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The Effects of Stellar Magnetic Activity and Variability on Observations of Exoplanets

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A dissertation
submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2019

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Abstract

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The search for life in the Universe outside of the Solar System focuses on the study of potentially habitable exoplanets. Exoplanets have been discovered principally via the transit method, which reveals planetary radii and orbital periods, among other things. In transiting multi-planet systems, we can measure the masses of exoplanets without expensive spectroscopy by using transit timing variations. The orbit of a single transiting planet around a single star would be (nearly) perfectly periodic, but if there's more than one planet in the system, the gravitational influence of each planet on each other changes the orbital shape and orientation. The apparent variation in the exoplanet transit times thus transmits information about the mass and orbit of the perturbing planet. Transits can also reveal the composition of exoplanet atmospheres via transmission spectroscopy. When the planet passes in front of the host star, it will appear largest at wavelengths where the planet's atmosphere is opaque, and smallest at wavelengths where the atmosphere is transparent. Thus by measuring the apparent radius of the planet as a function of wavelength, we can obtain a spectrum of an exoplanet's atmosphere. However, there are additional signals generated by magnetic activity and variability at the stellar surface which inject confounding time- and wavelength-dependent signals into the spectrophotometry of exoplanet host stars which complicate all of the aforementioned measurements. We must understand heterogeneous stellar surfaces in order to accurately answer astrobiological questions such as: does this planet have a surface,

and what is the composition of its atmosphere?

The goal of this dissertation is to explore stellar magnetic activity and variability and their impacts on measurements of exoplanets with implications for astrobiology. I used the transiting planet HAT-P-11 b to measure the size and latitude distributions of starspots on its active K4 dwarf host star, to find that its magnetic activity mirrors the Sun's. I measured the chromospheric activity of HAT-P-11 and compared it to stars of similar temperature and rotation period to find that it's the most active of its peers, perhaps suggestive of star-planet interaction. I directly measured starspot coverage on a sample of bright stars via TiO molecular band modeling. I identified the possibility of detecting stellar activity cycles of nearby stars using precision astrometry. I devised a technique for measuring robust exoplanet radii even in the presence of significant starspot distributions by reparameterizing the transit light curve of Mandel & Agol (2002). Finally, I devised a simulator for James Webb Space Telescope observations of transiting exoplanets, to explore the limits imposed by stellar magnetic activity on transit timing and transmission spectroscopy measurements for three systems with potentially habitable exoplanets.

TABLE OF CONTENTS

	Page
Chapter 1: Introduction	1
1.1 Overview	1
1.2 Astrobiology	5
1.3 Sunspots	7
1.4 The Magnetohydrodynamics of Sunspots	8
1.5 The Solar Dynamo	10
1.6 Short-Term Solar Variability	13
1.7 Outline	15
Part I: Solar Variability and Magnetic Activity	18
Chapter 2: The Solar Benchmark: Rotational Modulation of the Sun Reconstructed from Archival Sunspot Records	20
2.1 Introduction	21
2.2 The Solar Light Curve	22
2.3 Differential rotation	32
2.4 Discussion	33
2.5 Conclusion	35
Chapter 3: The Stellar Variability Noise Floor for Transiting Exoplanet Photometry with PLATO	36
3.1 Introduction	36
3.2 The HMI Instrument	39
3.3 Flux Variations of the Regions Occulted by the Planet	40
3.4 Flux Variations of the Unocculted Stellar Disk	46
3.5 Discussion	53
3.6 Conclusion	56

3.A	Typical posterior distributions	57
Chapter 4:	Generating Stellar Light Curves with Granulation and Oscillations . .	59
4.1	Introduction	59
4.2	Gaussian process kernel building	61
4.3	Scaling relations	62
4.4	Validation	64
4.5	Effect of oscillations on transit timing uncertainties	66
4.6	Discussion	67
4.7	Conclusion	68
Part II:	Stellar Magnetic Activity	69
Chapter 5:	The Active Latitudes of HAT-P-11: Evidence for a Solar-like Dynamo	71
5.1	Introduction	72
5.2	Starspot Modeling: Inputs for STSP	74
5.3	Detailed STSP Spot Occultation Model	88
5.4	STSP Results	96
5.5	Conclusions and discussion	111
Chapter 6:	The Chromospheric Activity of HAT-P-11: an Unusually Active, Planet- hosting K Dwarf	116
6.1	Introduction	117
6.2	Observations of the <i>S</i> -index	118
6.3	<i>Kepler</i> Full-frame image photometry	125
6.4	HAT-P-11 in context	126
6.5	Conclusion	135
Chapter 7:	Are Starspots and Plages Co-Located on Active G and K Stars?	138
7.1	Introduction	139
7.2	APO/ARCES Spectroscopy	140
7.3	Young G Star: KIC 9652680	142
7.4	Mid-K Dwarfs: EPIC 211928486 and EPIC 211966629	149
7.5	Discussion	157
7.6	Conclusions	158

Chapter 8:	Stellar Properties of Active G and K Stars: Exploring the Connection Between Starspots and Chromospheric Activity	160
8.1	Introduction	161
8.2	Stellar Parameters	162
8.3	TiO Molecular Band Modeling	174
8.4	Discussion	185
8.5	Conclusions	193
8.A	Stellar properties	194
8.B	Color combinations	196
8.C	M00G results	197
Chapter 9:	Possible Bright Starspots of TRAPPIST-1	198
9.1	Introduction	198
9.2	Rotational variability model	200
9.3	Simultaneous fits to the <i>Kepler</i> and <i>Spitzer</i> light curves	206
9.4	Correlation between bright spots and flares	208
9.5	Discussion	211
9.6	Conclusions	214
9.A	The effect of bright spots on transit light curves	214
9.B	Posterior distributions	215
9.C	Probability of spot occultations	215
Chapter 10:	Spotting Stellar Activity Cycles with Gaia	220
10.1	Introduction	220
10.2	Centroid estimating algorithm	221
10.3	Simulating starspot-induced astrometric jitter	224
10.4	Best targets for activity detection with Gaia	238
10.5	Conclusion and Discussion	241
Part III:	The effects of stellar activity on planet characterization	243
Chapter 11:	Robust Transiting Exoplanet Radii in the Presence of Starspots from Ingress and Egress Durations	244
11.1	Introduction	244

11.2 Self-contamination and the transit light curve	246
11.3 Constraining the radius ratio from durations of the transit and of ingress/egress	247
11.4 Validation on simulated light curves	252
11.5 Application to Observations	260
11.6 Discussion	276
11.7 Conclusions	281
11.A Planet radius from the duration of ingress/egress	283
11.B Limiting cases: Extreme spot distributions	284
11.C Uncertainties	284
Chapter 12: Robust Transiting Exoplanet Radii: Revisiting TRAPPIST-1	289
12.1 Introduction	289
12.2 Observations	290
12.3 Results	292
12.4 Conclusions	297
Chapter 13: The Limits of Transit Characterization with JWST/NIRSpec due to Stellar Variability: The Cases of TRAPPIST-1, Kepler-296 and Kepler-62	300
13.1 Introduction	300
13.2 Targets	302
13.3 Simulated Observations	303
13.4 Analysis of synthetic observations	313
13.5 Discussion	323
13.6 Conclusions	324
Part IV: Conclusions	325
Chapter 14: Conclusions	326
14.1 Summary	326
14.2 Concluding Thoughts	328
14.3 Future Work	332
Appendix A: astroplan: an Open Source Observation Planning Package in Python	371
A.1 Introduction	371
A.2 API	372

A.3 Documentation	379
A.4 Summary	380
Appendix B: aesop: The ARC Echelle Spectrograph Observation Pipeline	381
Appendix C: arcesetc: ARC Echelle Spectrograph Exposure Time Calculator	382

ACKNOWLEDGMENTS

There are not enough pages to properly acknowledge the people who made this dissertation possible. The author first needs to recognize the unrelenting, unconditional support of Shari, Scott and Michael Morris.

The author had the privilege of being taught science by the following teachers at Half Hollow Hills Central School District in New York: Mary Ann and Richard Sloan, Elaine Tozar, Janet Chan, Paul Travagianti, Dr. Daniel Moloney, Rick Russo, Thomas Page, Chrysi Notskas, Rose Suarez, and Dr. Michael Lake. The author owes special thanks to Thomas Carey and Thomas Affatigato, who gave the author a cathedral to work in; and to Dennis Grunbeck, who introduced the author to physics.

At the University of Maryland, the author was fortunate enough to have the guidance of Professors Chris Reynolds, Derek Richardson, who demonstrated infinite patience and incredible encouragement, and L. Drake Deming, who skillfully and joyfully transmitted invaluable skills, and gives special thanks to Elizabeth Warner for trusting him with her telescope. At NASA's Goddard Space Flight Center, Avi Mandell was a fierce advocate and tireless mentor.

While at the University of Washington, Professors Eric Agol, Suzanne L. Hawley and Leslie Hebb stewarded the author through challenges in life as well as science. Their patience, understanding and encouragement made this work possible.

The author acknowledges the traditional, ancestral territory of the Puget Sound Salish and Duwamish peoples, on which this work was completed.

DEDICATION

To Rebecca, my best friend, who came with me on this adventure;

to my family, who sent me out on it;

and to my friends, who were patient while I was gone.

Chapter 1

INTRODUCTION

1.1 Overview

When my parents gave me my first books on astronomy, the glossy pages were filled with fantastic color images from the Viking, Galileo, and Voyager missions, cataloging all of the known worlds beyond Earth. Everything there was to know about planets was wrapped up neatly into books about those (then nine) planets. At the same time – eleven months before I began kindergarten – the first planet orbiting a Sun-like star was discovered, 51 Pegasi b (Mayor & Queloz, 1995). This new world, called an exoplanet – or a planet that orbits a star other than the Sun – would be the first of many. In the following years, the number of known planets would rise at an exponential rate through to the present. I am a member of the first generation for whom there has never been a time in our lives when our age in years has exceeded the number of known planets.

The ultimate goals of this dissertation are to: (1) refine exoplanet characterization techniques with improved understanding of stellar magnetic activity and, (2) to identify exoplanet systems which advance the search for life in the Universe. Characterization of habitable exoplanets using starlight, as we will outline in Section 1.1.1, is a central component of the search for life in the Universe (Des Marais et al., 2008). We will find that our inferences about exoplanet properties are directly linked to measurements of their host stars in Section 1.1.2. We will introduce the implications of stellar magnetic activity for astrobiology in Section 1.2, before focusing on solar magnetic activity in Sections 1.3-1.5. We conclude our introduction with a discussion of the short-term variability of the Sun in Section 1.6, and an outline of the rest of the dissertation in Section 1.7.

1.1.1 *Exoplanets*

Exoplanets have been discovered principally via the transit method. This technique requires precise measurements of apparent system brightness, or photometry, to discover worlds. The arcs of some exoplanet orbits bring the planets between their host stars and the Earth – allowing us to see an eclipse of the host star by the exoplanet, an event known as a transit. Precision photometry can reveal the small decrease in apparent brightness of the host star during the eclipse.

Transit events transmit valuable information about exoplanets. The fraction of light missing during a transit event is simply the ratio of cross-sectional areas of the planet and star, $\Delta F/F \approx (R_p/R_\star)^2$, revealing the ratio of the planetary and stellar radii. For example, an Earth-sized planet orbiting a Sun-sized star only obscures 0.008% of the brightness of the star. The time between transit events is the orbital period of the planet, which is related to the distance between the planet and its host star, or the orbital semi-major axis, via Kepler’s third law. With the orbital separation, a bit of knowledge about the host star’s luminosity, and some critical assumptions about the exoplanet’s atmosphere, we can make a crude estimate of the equilibrium temperature of the planet – and thus whether or not it might be a world suitable for life.

In short order, we have already discovered that we can only know as much about a planet as we know about its host star. The planet’s radius is measured relative to the stellar radius, and the planet’s temperature is estimated relative to the stellar luminosity (and other terms). In order to make robust statements about exoplanets and their habitability, we must know several properties about their stars first.

Customarily, exoplanet-hosting stars are given cursory characterization upon discovery of their planets. This basic reconnaissance might include the use of broad-band photometry (color) to estimate the temperature of the star, and parallax distances to measure the stellar luminosity when available, in combination with expensive high resolution spectroscopy to identify the evolutionary state of the star. These measurements give an estimate of the

stellar mass and radius, allowing us to estimate the absolute radius of the planet – which is often used to confirm its nature as a planetary body, rather than a larger object like a brown dwarf or small star – and its surface temperature.

For a subset of these planets, we can also learn their masses using radial velocity measurements of the host star. If the planet is massive enough or close enough to its host star, and the host star isn't particularly magnetically active (more on this later), the gravitational acceleration of the star due to the planet is detectable via spectroscopy by looking for small Doppler shifts in the stellar spectrum. The acceleration of the star is related to the distance and mass of the exoplanet. If the planet is a transiting exoplanet, we know the orbital distance already via Kepler's third law, and thus we obtain an indirect measurement of the mass of the planet. Combining the mass and radius measurements, we can obtain bulk density measurements of an exoplanet, indicating perhaps whether it is rocky or gaseous (Seager et al., 2007).

In transiting multi-planet systems, we can measure the masses of exoplanets without expensive spectroscopy by using transit timing variations (TTVs) (Agol et al., 2005; Holman & Murray, 2005). The orbit of a single transiting planet around a single star would be perfectly periodic (barring relativistic effects), but if there is more than one planet in the system, the gravitational influence of each planet on each other changes the shape and orientation of the planets' orbits. The apparent early or late arrival of an exoplanet transit thus transmits information about the mass of the perturbing planet. This technique is especially promising for measuring the masses of small planets in the habitable zones of their Sun-like host stars – which are typically too far away and have too little mass to impart measurable radial velocities on their host stars with current high resolution spectroscopy.

Transits can also reveal the composition of exoplanet atmospheres via transmission spectroscopy (Seager & Sasselov, 2000). When the planet passes in front of the host star, the planet will appear largest at wavelengths where the planet's atmosphere is opaque, and smallest at wavelengths where the atmosphere is transparent. Thus by measuring the apparent radius of the planet as a function of wavelength, we can obtain a spectrum of an exoplanet's

atmosphere. Encoded in this spectrum are absorption features from the atoms and molecules in the planet’s upper atmosphere, yielding clues to the atmospheric composition, and the state of the planet’s climate.

1.1.2 Stellar magnetic activity

Thus far, our triumphant narrative of planet characterization has glided over some increasingly important details about the stars, which we have taken for granted as simple, uniform disks. One planet-hosting star has been studied for thousands of years: the Sun. Even before the invention of the telescope it was known that the Sun bears dark spots on its surface (Hayakawa et al., 2017). Sunspots are regions in the solar photosphere where strong magnetic fields inhibit convection of hot plasma from below, inhibiting heat transport and creating cool, dark spots on the Sun’s surface (Solanki, 2003). As the Sun rotates, sunspots roll into and out of view, subtly changing the light we receive from the Sun as a function of wavelength and time. Sunspots are one manifestation of the Sun’s magnetic activity.

Since the time of Copernicus, astronomical advances consistently remind us that the Earth is not at the center of the Universe, and that there is nothing particularly special about our location (Copernicus, 1543) – so perhaps it is no surprise that the Sun and Solar System are not unique. Multi-planet systems like ours are common (Burke et al., 2015; Coughlin et al., 2016; Dressing & Charbonneau, 2013). The processes which produce magnetic fields and drive magnetic activity on the Sun, or analogous ones for smaller stars, are also ubiquitous among planet-hosting stars. The evidence that stars have starspots comes to us from photometry – the same technique used to discover planets – revealing the changes in brightness as spotted planet-hosting stars rotate, for example, from NASA’s *Kepler* mission (Giles et al., 2017; McQuillan et al., 2013; Walkowicz & Basri, 2013).

Determining the sizes and temperatures of starspots is difficult. For main sequence stars, the angular resolution required for a telescope to spatially resolve starspots is beyond the diffraction limit for even the largest telescopes in the optical and infrared. Clever analysis of stellar spectral absorption features can reveal the positions of spots through Doppler imaging

(Barnes & Collier Cameron, 2001; Strassmeier, 2002; Vogt & Penrod, 1983), or its magnetic equivalent Zeeman Doppler imaging (Donati et al., 2003; Morin et al., 2010, 2008, 2011, 2013). Alternatively, one can measure the spot temperatures and covering fractions from high resolution spectra of active stars with molecular band modeling. The observed spectrum of a star is modeled as a linear combination of model or template stellar atmospheres with warmer and cooler components (Neff et al., 1995; O’Neal et al., 1998, 2004, 1996).

Another window into stellar magnetic activity was opened by *Kepler* transit photometry. During a transit event, when a planet occults a dark starspot, less light is missing than during occultations of brighter regions, creating a positive residual signal in transit light curves. One such planet has revealed more about its star’s spots than any other known to date, HAT-P-11 b (Bakos et al., 2010; Deming et al., 2011; Hirano et al., 2011; Sanchis-Ojeda & Winn, 2011; Winn et al., 2010).

Starspots directly affect our ability to make precise measurements of exoplanet properties. Their effect on the stellar flux adds signal of similar amplitude to the transit of an Earth-like planet for some Sun-like stars, making precise measurements of the transit depths (with photometry or transmission spectroscopy) and transit times (for TTVs) more challenging. To make matters worse, spots are cooler than the mean photosphere, introducing a wavelength-dependence to the variability in addition to time-dependence. Careful analyses of exoplanet properties must account for the effects of starspots in order to make reliable inferences.

1.2 Astrobiology

Astrobiology is the study of the origin and evolution of life on the Earth, and the search for conditions amenable to life elsewhere in the Universe. Life thrives in a bewildering variety of environments on Earth, from the bitter cold of Earth’s ice caps to the boiling heat of submarine hydrothermal vents (Cavicchioli, 2002; Rothschild & Mancinelli, 2001). It seems that one of the few criteria that life on Earth universally demands is the presence of some liquid water (Des Marais et al., 2002).

As a result, the search for life in the Universe thus far has focused on planets that reside

in their host star’s “habitable zone” – or the range of orbital distances at which a planet may sustain liquid surface water (e.g. Huang, 1959; Kasting et al., 1993; Kopparapu et al., 2013). The inner edge of the habitable zone is often defined as the orbital distance where a terrestrial planet’s atmosphere warmed by a runaway greenhouse-effect would create surface conditions too hot to sustain liquid water. The outer edge is often defined by the orbital distance where a dense atmosphere of greenhouse gases provides insufficient warming to maintain liquid water at the planet’s surface. For the purposes of this dissertation, planets which fall between these two orbital distances defined by climatic catastrophes will be referred to as “potentially habitable.”

Perhaps the first detections of life on another planet will come from searches for planets with global-scale biospheres that affect the entire atmosphere or surface of a planet, just as life shapes the present-day mixing ratios of the Earth’s atmospheric constituents, and Earth’s albedo (Lovelock, 1965; Sagan et al., 1993). Such a biosphere could be detected with modern technology via transmission spectroscopy or direct imaging of an exoplanet, for example. Both of these techniques rely upon transmitted or reflected light from the host star interacting with the atmosphere of the planet to spectroscopically reveal biosignatures, or signs of life. We will show in the following sections that signals generated by magnetic activity and variability of the host star may confound our best attempts to characterize exoplanet atmospheres.

TRAPPIST-1 is an exemplary system for demonstrating how uncertainties concerning a stellar atmosphere propagate into uncertainties regarding planetary atmospheres. TRAPPIST-1 is the M8V host star to at least seven transiting, Earth-sized planets in a resonant chain, some of which reside in the habitable zone (Gillon et al., 2016, 2017; Luger et al., 2017b). Spectrophotometry during transits has revealed little about the atmospheres of the TRAPPIST-1 planets (de Wit et al., 2016; Ducrot et al., 2018), due in part to significant contamination of the transmission spectra by the apparent presence of active regions on the stellar surface (Morris et al., 2018b; Wakeford et al., 2019; Zhang et al., 2018).

One of the goals of this dissertation is to understand the effects of stellar magnetic ac-

tivity and variability on observations of exoplanets, so that exoplanets may be characterized accurately in the presence of host stars with heterogeneous surfaces. A distant observer looking at the Solar System would be best prepared to accurately recognize the Earth as a potentially habitable exoplanet, for example, if they knew how to identify and remove the astrophysical signals generated by the Sun.

The Sun is our local laboratory for understanding stellar oscillations, magnetic activity and the dynamo which powers that activity. In the next three sections we briefly introduce the mechanisms responsible for the Sun’s long-term photometric variability from scales of months to years, by summarizing the history of sunspot observations in Section 1.3, the magnetohydrodynamics of sunspots in Section 1.4, and a description of the dynamo mechanism which gives rise to sunspots’ cyclic behavior in Section 1.5. In Section 1.6 we focus on the myriad short-term sources of solar variability from minutes to days, and we conclude the introduction with an outline of this dissertation in Section 1.7.

1.3 Sunspots

Sunspots have been observed on the Sun with the naked eye for millennia and with the telescope since Galileo. Since we can spatially resolve sunspots and study their substructure in detail, sunspots form the foundation of our understanding of starspots in general. In this section, we will briefly outline historical milestones in the study of sunspots.

We recently marked the 400th anniversary of Galileo’s telescopic observation that the Sun has dark spots on its surface, which rotate into and out of view (Galilei et al., 1613). Astronomers have monitored the dark spots on the solar surface from the mid-seventeenth century onwards, typically by counting the number of sunspots observed on the Sun. Thus the most enduring measurement in heliophysics is the “sunspot number” (SSN).

Incredibly, the cyclic nature of the SSN was discovered by a pharmacist-turned-astronomer who was in fact searching for a transiting planet in the Solar System. From 1826 to 1843, Samuel Heinrich Schwabe sketched observations of the Sun on every clear day, searching for solar transits of a hypothesized planet interior to Mercury. While no planet appeared,

Schwabe noted that the number of sunspots increases and decreases until no spots are visible, with an approximately period of 10 years (Schwabe, 1844). Spurred by Schwabe’s discovery of the solar activity cycle, J. Rudolf Wolf compiled all of the available records of sunspots in order to measure the cycle period, and found it to be 11 years long (Wolf, 1852).

Alexander Wilson recorded telescopic observations of sunspots as they traverse the solar surface due to rotation. He noted that spots appear largest at disk-center, and smaller at the solar limb. He discovered that geometrical foreshortening due to the spherical surface of the Sun was insufficient to explain the small size of the spots at the limb. He posited that sunspots are troughs in the solar photosphere, and their depth obscures part of the spot from view at extreme viewing angles, discovering what we now call the Wilson depression (Wilson & Maskelyne, 1774).

The observation that spots are highly magnetized was first made by Hale (1908). Hale went to great lengths to study the Zeeman effect – the apparent splitting of certain spectral lines in the presence of strong magnetic fields – both in the laboratory and using spectroscopic observations of the Sun. He found that sunspots often occur in pairs of opposite magnetic polarity, which today is known as Hale’s law (Hale & Nicholson, 1925).

1.4 The Magnetohydrodynamics of Sunspots

After Hale’s discovery that sunspots are magnetized, he and colleagues, notably Sir John Larmor, asked the question “how could a rotating body such as the Sun become a magnet?” (Larmor, 1919). This question is a vexing one as it requires three-dimensional magnetohydrodynamics to solve. In this section, we will briefly outline the mechanism by which sunspots arise.

The plasma in the outer convective zones of main sequence stars is conducting and mag-

netized, so its dynamics are dictated by Maxwell's equations:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (1.1)$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} \quad (1.2)$$

$$\vec{J}/\sigma = \vec{E} + \vec{v} \times \vec{B} \quad (1.3)$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B} - \eta \nabla \times \vec{B}) \quad (1.4)$$

Where $\vec{E}$ and $\vec{B}$ are the electric and magnetic field vectors, $\vec{J}$ is the current vector, $\vec{v}$ is the plasma velocity, and η is the magnetic diffusivity. The last relation, known as the induction equation, determines how the magnetic field evolves in time. On the right hand side, the first term, $\vec{v} \times \vec{B}$ is a source of inductance from bulk flow of the plasma, while the second term $\eta \nabla \times \vec{B}$ is a dissipative loss term due to resistance in the plasma.

In stars, the very high conductivity $\eta \rightarrow 0$ makes the dissipation term in the induction equation insignificant (Ossendrijver, 2003). In this regime we can apply the Alfvén's "frozen flux theorem" (Alfvén, 1942), which indicates that bulk flow of the plasma moves magnetic fields lines with it. This plays a critical role in the dynamics of plasma at the base of the convective zones in stars. The frozen flux theorem states that flux is conserved within an area A before (i) and after (f) some stretching of the magnetic flux tube

$$(BdA)_i = (BdA)_f, \quad (1.5)$$

which can be combined with the conservation of mass for plasma of density ρ in a flux tube of length ℓ

$$(\rho \ell dA)_i = (\rho \ell dA)_f, \quad (1.6)$$

to show that $B \propto \rho \ell$, or in words the magnetic field increases linearly with increasing length of the flux tube.

Now imagine a tube of plasma with magnetic field lines running along the length of it, at the base of the convective zone. Sun-like stars are differentially rotating – the Sun, for instance, rotates once in 25 days at the equator, and nearly 34 days at the poles. Differential

rotation of the star will stretch the plasma tube, making it longer and narrower, and since the frozen flux theorem applies, the plasma will drag the magnetic field lines with it, bringing the field lines closer together, i.e. amplifying the magnetic field in the flux tube. The pressure equilibrium between the plasma in the interior of the flux tube and the exterior medium is given by the plasma pressure in each region plus the magnetic pressure, $B^2/2\mu_0$, and using the ideal gas law, we can solve for the difference in density between the magnetic flux tube and its surroundings assuming $B_{\text{int}} \gg B_{\text{ext}}$:

$$p_{\text{ext}} + \frac{B_{\text{ext}}^2}{2\mu_0} = p_{\text{int}} + \frac{B_{\text{int}}^2}{2\mu_0} \quad (1.7)$$

$$P = \rho \frac{kT}{m} \quad (1.8)$$

$$\rho_{\text{ext}} - \rho_{\text{int}} = \frac{B_{\text{int}}^2}{2\mu_0} \frac{m}{kT} \quad (1.9)$$

We note that the term on the right hand side of the last equation is always positive for $B_{\text{int}} > 0$, and thus the magnetized plasma will have a lower density than its surroundings, causing it to become buoyant and to rise (Parker, 1955a).

In this classical picture, a portion of the rising magnetic flux tube now rises through the convective zone, where it is subject to stochastic convective turbulence and the consistent twist of the Coriolis force, before it finally rises through the photosphere (Cheung & Isobe, 2014; Rempel & Schlichenmaier, 2011). The magnetic field is very strong at the two locations where the flux tube intersects the photosphere, giving rise to two regions where the local magnetic field dominates over convection. These are called bipolar magnetic regions (BMRs), as observations of the magnetic polarity of each region show opposite polarity, i.e. Hale’s law (Hale & Nicholson, 1925) – a natural result of a single flux tube exiting (outward field) and entering (inward field) the photosphere. The halves of the BMRs are referred to as the leading and following components according to the direction of rotation. The twist of the Coriolis force causes BMRs to have a slight tilt with respect to a line of latitude, with the following component at higher latitudes than the leading component in the northern hemisphere (known as Joy’s Law, Hale et al. 1919). Since the upwelling of hot

plasma from convection is suppressed by the strong magnetic fields, an area just below the quiescent photosphere is evacuated, pushing the effective photosphere downwards, i.e. the Wilson depression. In regions of strong enough fields, the evacuated region cools and thus the cores of the BMRs are observed as dark sunspots.

In summary, dark starspots are the magnetic footprints of strong magnetic fields, which are concentrated in flux tubes that originate at the base of the convective zone and rise through the photosphere due to magnetic buoyancy in differentially rotating stars. Spots often occur in pairs of opposite polarity, known as bipolar magnetic regions, which are slightly tilted with respect to lines of latitude.

1.5 The Solar Dynamo

In the previous section, we described the process by which a plasma tube with a magnetic field may rise through the surface and produce starspots observed in the photosphere. There is a problem lurking in our description of stellar magnetic fields – stellar plasma is not in fact dissipationless, and in time, one might expect the bulk flows that give rise to amplified magnetic fields to decay due to resistance until fields are no longer produced. Or another challenge is the subject of how to construct a bulk flow of the plasma which remains magnetized, as it must not be axisymmetric in order to be sustained over millennia (known as Cowling’s Theorem, see Cowling 1933). In this section we’ll briefly outline the mechanism known as the $\alpha\Omega$ dynamo, which reproduces the observed solar magnetic activity cycle (Babcock, 1961; Charbonneau, 2014; Hathaway & Rightmire, 2010; Parker, 1955b).

Suppose we start the Sun with a strictly dipolar field, like a bar magnet – see Figure 1.1. The real Sun does have a dipolar field at solar minimum. Field lines in the convective zone run along meridional lines in this initial condition – or in other words the field is strictly poloidal. Since the Sun is differentially rotating, and the frozen flux theorem applies, the field lines near the equator are dragged ahead of the field lines near the poles. After several rotations, the originally meridional field lines have been twisted around the Sun several times, wound up like a spring at the mid-latitudes, until a significant component of the magnetic

field is running along lines of latitude – or in other words, there is a significant toroidal component of the magnetic field. The twisting of the meridional (poloidal) magnetic field lines into azimuthal (toroidal) ones due to differential rotation is known as the Ω -effect.

Now we have the magnetic field lines wrapped around the star and concentrated (amplified) at the mid-latitudes. As differential rotation continues to stretch the plasma and amplify the magnetic field, the flux tubes eventually become unstable and rise through the photosphere, producing starspots via the mechanism described in the previous section. Some of the magnetic flux tubes have a twist imparted on them by the Coriolis effect and by convective turbulence (Parker, 1955a,b), which together create loops in the twisted magnetic flux tubes. Magnetic reconnection occurs, liberating the magnetic field loops, which due to the earlier twist now contain a poloidal component. This is known as the α -effect.

Now the simultaneously present toroidal and poloidal field components interact with each other, causing bands of magnetic flux tubes to migrate from the mid-latitudes towards the equator, creating the observed dynamo wave of starspots that first emerge at mid-latitudes (near 30°) and drift towards the equator throughout the solar activity cycle (Babcock, 1961; Parker, 1955a,b).

It has been observed that meridional flow exists on the solar surface which flows from the equator to the poles at the surface, and via continuity it is thought that meridional flow must also exist at the base of the convective zone from the poles to the equator. The inferred flow at the base of the convection zone is slow, about 1 m/s, which is roughly the speed needed for bulk flow of plasma to migrate from 30° latitude to the equator in 11 years – causing some to speculate whether flux transport via the meridional flow is responsible for the 11 year periodicity of the solar activity cycle (Dikpati & Gilman, 2006; Hathaway & Rightmire, 2010).

1.6 Short-Term Solar Variability

The previous two sections summarize the emergence and dynamics of the Sun’s magnetic active regions throughout the solar activity cycle, which drive photometric variability on

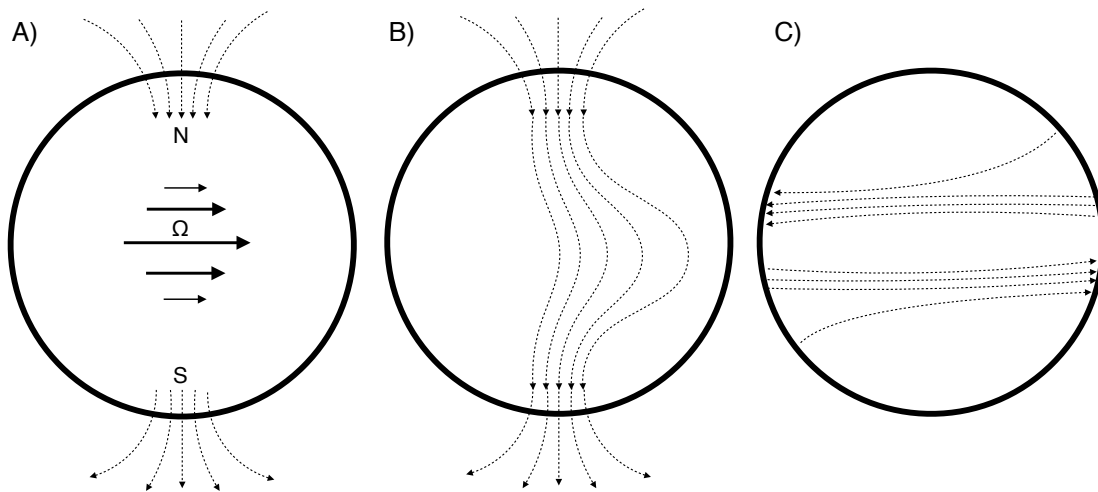


Figure 1.1: The conversion of poloidal to toroidal magnetic fields (dashed arrows) in a differentially rotating star (solid arrows). The star begins at A with a strictly poloidal field, like a bar-magnet. Since Alfvén’s “frozen flux theorem” applies, magnetic field lines are frozen into the plasma. The star is differentially rotating, meaning it rotates faster at the equator than at the poles, causing the magnetic field lines that were originally poloidal (A) to begin to twist after many rotations (B). After many more rotations (C), the magnetic field is tightly wound around the star several times and concentrated at the mid-latitudes. The progression from mostly poloidal (A) to mostly toroidal field (C) takes about five years.

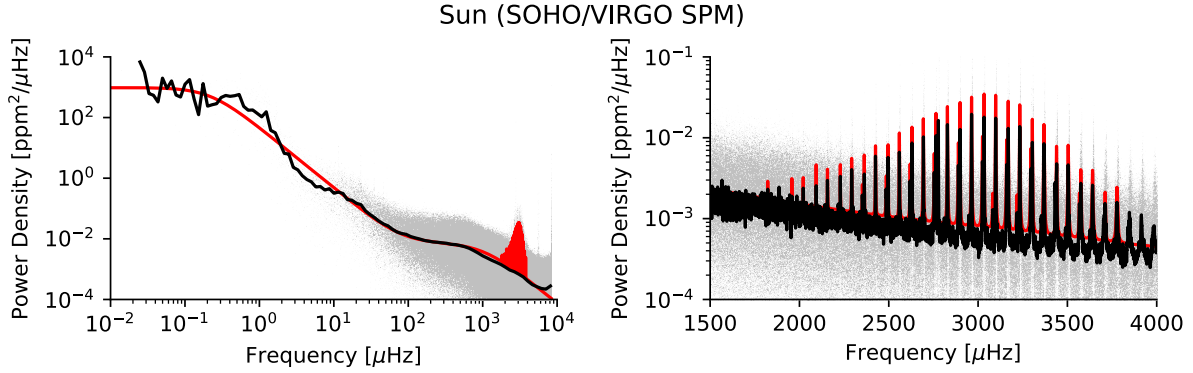


Figure 1.2: Solar variability as a function of frequency, measured by SOHO VIRGO/SPM (Fröhlich et al., 1997a). For the periodically inclined, we note: $10^{-2} \mu\text{Hz}$ is equivalent to periods of 1150 days, $1 \mu\text{Hz}$ is 11.5 days, $3000 \mu\text{Hz}$ is 5.5 minutes.

timescales of months to years. The Sun is also variable on shorter timescales ranging from minutes to days. Figure 1.2 shows the power spectrum of solar broadband photometry taken over 20 years by the SOHO VIRGO/SPM instrument (Fröhlich et al., 1997a). There are three features in the solar power spectrum that we will encounter elsewhere in this dissertation (specifically in Chapters 3 and 4), which we summarize here (see review by Nordlund et al., 2009).

First we note the “comb” of peaks in the power spectrum in Figure 1.2 between 1000 and $4000 \mu\text{Hz}$, with the greatest power near $3100 \mu\text{Hz}$ (period of 5.5 minutes) to the far right of the left panel and the center of the right panel. These peaks represent *p*-mode oscillations, or standing waves in the solar plasma for which the restoring force is pressure. The detection of these *p*-mode oscillations gave rise to the field of helioseismology, which makes use of the waves propagating throughout the solar atmosphere to measure fundamental properties of the Sun, including its internal structure (Christensen-Dalsgaard, 2002). Using simple scaling laws based on the solar *p*-mode oscillations, it is possible to predict properties of distant stars including their masses, radii, densities and ages using short-cadence photometry alone

(e.g. Huber et al., 2011, 2012; Kallinger et al., 2014; Kjeldsen & Bedding, 1995, 2011).

The next feature to note is the “knee” with near-constant power 10^{-2} at mid-frequencies $10^2 - 10^3 \mu\text{Hz}$ that begins to slope downward near $10^3 \mu\text{Hz}$ – this is the signal of granulation. Granulation is the small-scale convective motion which gives rise to the numerous convective “granules” which tile the surface of the Sun. These granules are a few times the local scale height in horizontal extent, spanning a few Megameters (Mm). Granules produce power predominantly at periods $\lesssim 30$ min.

The knee at the lowest frequencies near $10^{-1} \mu\text{Hz}$ is due to supergranulation. Supergranulation is the signature of large-scale, slow convective motions which are generated by bulk flows roughly 20-40 Megameters (Mm) in size on the solar surface. Supergranules have the longest coherence timescale, giving rise to power in the power spectrum at periods $\lesssim 10$ days.

Each of these short-period solar photometric phenomena occur on other stars, and thus we can expect these signals to be present in short-cadence photometry of exoplanet host stars. In particular, we note that the ingress duration of an Earth orbiting a Sun-like star is roughly 10 minutes. Thus the periodic power generated by granulation and p -mode oscillations on timescales of order 10 minutes may affect the precision of observations of transiting Earth-like exoplanets, especially measurements such as transit timing variations which depend on precision at ingress and egress.

1.7 Outline

In Part I we study the magnetic activity and variability of the Sun itself, and the impact of stellar variability and magnetic activity on observations of Earth-like exoplanets orbiting Sun-like stars. Part I addresses the first main goal of this dissertation, understanding of stellar magnetic activity and variability and its impact on observations of transiting exoplanets, by studying our closest stellar neighbor: the Sun. In Chapter 2, we use archival observations of sunspots to produce a *Kepler*-like light curve of the Sun spanning 68 years at one-day cadence, and show that differential rotation is impossible to detect from rotational modulation

observations alone. In Chapter 3 we investigate the effects of short-term solar variability on the precision of measurements of exoplanet radii with applications to observations by the PLANetary Transits and Oscillations (PLATO) mission. We find that solar oscillations and a degeneracy in the light curve between the impact parameter and the transit depth each contribute significantly to the radius uncertainties of Earth-like planets transiting Sun-like stars. Finally in Chapter 4, we introduce an efficient technique for generating long-duration, short-cadence light curves of oscillating stars based on the solar light curve.

In Part II we present detailed studies of the magnetic activity of distant stars, examining the effects of activity on transit photometry, high resolution spectroscopy and astrometry, addressing the first goal of this dissertation, understanding *stellar* magnetic activity, by examining the properties of spots on stars other than the Sun. In Chapter 5 we conduct the most detailed survey of starspots on a distant star to date, for the very spotted star K4V star HAT-P-11. We use *Kepler* observations to deduce that HAT-P-11: has active latitudes like the Sun near 15° latitude; has spots with radii similar to sunspots at solar active maximum; and has spot coverage roughly two orders of magnitude greater than the Sun. We supplement the *Kepler* observations with ground-based spectroscopy of HAT-P-11 in Chapter 6. We find that HAT-P-11 likely has an activity cycle with a similar period to the Sun’s activity cycle, and we measure a somewhat elevated average chromospheric emission from HAT-P-11, which may suggest that HAT-P-11 is more active than its peers of similar rotation period and mass, perhaps due to tides raised by its close-in exoplanet.

In Chapters 5 and 6, we observed the photospheric (starspot) activity and chromospheric (plages) activity of HAT-P-11 at different times. In Chapter 7 we attempt to simultaneously observe chromospheric and photospheric activity of stars to resolve the longitudinal distribution of starspots and plages, and find that starspots and plages are co-located for a young, active G star, while two active K stars likely have uniformly-distributed plages, which are not concentrated near the biggest starspots that drive photometric rotational modulation. In Chapter 8 we measure stellar properties (temperatures, surface gravities and metallicities) and absolute starspot coverages for a sample of 55 active G and K stars using

a high-resolution spectroscopic technique. We show that the method is only sensitive to very large spot coverages, and that there is a weak correlation between spot coverage and chromospheric activity.

In Chapter 9 we present a two-bandpass photometric analysis of the ultracool dwarf TRAPPIST-1, which provides some of the earliest evidence for bright surface regions on TRAPPIST-1. To conclude the part, in Chapter 10 we introduce an astrometric technique for detecting starspots on nearby active stars using observations from the Gaia mission. We show that the technique is sensitive enough to detect the presence of large spot coverages on the nearest stars.

In Part III we take advantage of our knowledge of stellar magnetic activity and exoplanet characterization to prepare for observations of planets orbiting active host stars, addressing both goals of this dissertation – identifying exoplanet systems which advance the search for life in the Universe, and refining exoplanet characterization techniques. In Chapter 11 we devise a technique for measuring the radii of transiting exoplanets even in the presence of significant starspot coverages. We apply the new exoplanet radius measurement technique to observations of the TRAPPIST-1 planets in Chapter 12. We conclude the part by simulating observations of three exoplanet systems, Kepler-62, Kepler-296 and TRAPPIST-1, using the NIRSpec instrument on the James Webb Space Telescope, while including as many stellar variability effects as possible in the simulations. We show that with realistic observations, it is possible to measure the masses of the habitable exoplanets of Kepler-62 to 10% precision using transit timing variations, and that transmission spectra of TRAPPIST-1 b may reveal the climate state of the exoplanet.

We summarize our conclusions and outlook for future work in Part IV.

Part I

SOLAR VARIABILITY AND MAGNETIC ACTIVITY

Starting from fish-shape Paumanok where I was born...

How curious! how real!

Underfoot the divine soil, overhead the sun.

— Walt Whitman

For the foreseeable future, an astronomer’s only available tool for studying an exoplanet is light. It may be light that disappears from the host star during an exoplanet transit, transmitting information via the planet’s silhouette. It may be starlight that has filtered through the planet’s atmosphere, such as the light used in transmission spectroscopy. It might be starlight that has reflected off of the planet in the case of the secondary eclipse or direct imaging. It may even be the apparent spatial shifts in starlight indicating the presence of the planet, as in astrometric planet detection.

Each of these techniques make use of the light of the exoplanet’s host star to study the properties of the exoplanet. Our reliance on stars to illuminate their exoplanets has led to the oft-repeated mantras “one only knows as much about a planet as one knows about its host star,” and “know thy star, know thy planet” (attributed to David Ciardi). If we are to have any hope of understanding the detailed properties of exoplanets, we must first thoroughly understand the light sources which make the planets visible to us.

Stars are not pristine light sources – they change in brightness with time, they have surface brightness variations like dark starspots or bright facular regions, and each of these surface components has different spectral properties. The deviations in brightness are often generated by strong magnetic fields affecting the stellar plasma; these effects are grouped into the broad category of “stellar magnetic activity”. The Sun and Sun-like stars also vary in brightness due to *p*-mode oscillations, granulation and super-granulation.

In this Part, we will explore the magnetic activity and variability on our nearest star, the Sun. The Sun is remarkable for several reasons – it is the only star for which spatially resolved telescopic observations have been recorded for more than 400 years; it is the only star for which we have minute-cadence space-based photometric observations spanning decades; it is the only star known to host a planet with extant life. In Chapter 2 we reconstruct the light curve of the Sun spanning 68 years of observations, showing clear signals of solar rotational modulation and the 11 year solar magnetic activity cycle. In Chapter 3 we investigate the effects of stellar oscillations and granulation on transit photometry of Sun-like stars using solar brightness observations of the Sun with a (fake) superimposed transiting exoplanet. This has applications and implications for the PLANetary Transits and Oscillations (PLATO) mission. In Chapter 4 we devise an efficient method for producing light curves of solar-like stars that include p -mode oscillations, granulation and super-granulation variability based on scaled-solar relations. Taken together, the Chapters of this Part form a foundation for understanding the Sun as a star, and for understanding the types of stellar variability that we can anticipate observing on Sun-like exoplanet host stars.

Chapter 2

THE SOLAR BENCHMARK: ROTATIONAL MODULATION OF THE SUN RECONSTRUCTED FROM ARCHIVAL SUNSPOT RECORDS

The *Kepler* Mission was a spacecraft devoted to the search for exoplanets, which recorded precision photometry of 150,000 stars every 30 minutes for four years (Borucki et al., 2010). *Kepler* recorded the brightness variations of thousands of stars as they rotated. In *Kepler*'s red-optical bandpass, dark starspots caused stars to periodically decrease in brightness when their most spotted hemisphere was facing *Kepler*, and then increase when the less spotted hemisphere faced *Kepler*. The amplitudes and morphologies of rotational modulation in *Kepler* data have revealed trends with age and spectral type (e.g. Basri & Nguyen, 2018; Basri et al., 2011; Giles et al., 2017; McQuillan et al., 2013, 2014; Notsu et al., 2013). However there is one critically important benchmark star which *Kepler* did not observe: the Sun.

The modern era of high cadence, space-borne solar observations began in earnest with the SOHO mission, launched in 1995, and continued with the SDO mission, launched in 2010 (Domingo et al., 1995; Pesnell et al., 2012). These spacecraft record resolved images of the surface of the Sun in pseudo-continuum light, as well as magnetograms and dopplergrams. However neither mission obtained directly analogous measurement to the disk-integrated, red-optical photometry observed on stellar targets with *Kepler*. This may lead one to ask: what would the rotational modulation of the Sun look like if observed with *Kepler*?

To answer this question, we turn to ground-based solar observations. For more than 100 years, observers at the Mount Wilson Observatory have faithfully recorded hand-drawn sketches of the Sun's photosphere in visible light. These sketches were recorded in the base of the Mount Wilson 150 Foot Solar Tower (Hale, 1912; van Maanen, 1917), marking the

area of umbrae and penumbra, and their positions on the solar surface. In 1984, three heliophysicists took up the arduous task of digitizing the sunspot positions and areas for the purpose of measuring solar differential rotation from the motions of sunspots across the solar disk (Howard et al., 1984). In this chapter we will use their sunspot catalog to reconstruct a historical light curve of the Sun, and measure basic properties of the Sun such as its rotation period and activity cycle period using the same techniques which are applied to *Kepler* stars.

This chapter was first published in Monthly Notices of the Royal Astronomical Society (Morris et al., 2019), and is printed here with permission from MNRAS.

2.1 Introduction

For decades astronomers have endeavoured to study the “Sun as a star”, measuring properties of the Sun that we typically measure on distant stars, with the goal of putting the Sun into context (e.g.: Bertello et al., 2012; Chaplin et al., 2004; Egeland et al., 2017; Hall, 2015; Hall et al., 2009; Livingston, 1991; Livingston et al., 2007; Tayler, 1996). These efforts are valuable, for example, for understanding the Sun’s activity through time, by observing Sun-like stars of different ages or at different phases in their activity cycles.

We are entering a new era for the study of rotational modulation of stars. *Kepler* has measured rotational modulation of tens of thousands of stars for four consecutive years, and K2 has measured rotation periods for many more stars, albeit over a shorter baseline. TESS will measure precision light curves for bright nearby stars, for a maximum duration of 355 consecutive days near the ecliptic poles in the primary mission (Ricker et al., 2014; Sullivan et al., 2015). *Gaia* will measure rotation periods for $> 10^5$ stars (see, e.g. Lanzafame et al., 2018). ESA’s PLANetarty Transits and Oscillations (PLATO) mission may observe targets for up to 8 years (Rauer et al., 2014), potentially allowing us to probe variations in the stellar rotational modulation of stars as a function of phase in their activity cycles. Having a solar benchmark light curve to compare these future, long-term light curves will be an important data product for the community.

Morris et al. (2018a) developed tools for measuring the apparent stellar centroid offsets

due to starspots that affect *Gaia* astrometry. In particular, a framework was developed for reconstructing archival spot maps of the Sun using the Mount Wilson Observatory (MWO) spot coverage catalog published in Howard et al. (1984). The MWO spot catalog is a digitized representation of “white light” photographic plate images of the solar disk taken from 1917-1985, denoting the apparent positions (latitude and longitude) and areas of penumbrae in sunspot groups. In this work, we use the same software and spot coverage archive as Morris et al. (2018a), to reconstruct artificial time-series photometry of the Sun with one-day cadence.

In Section 2.2 we introduce our approximation of the solar rotational light curve, and measure its properties as though it were a distant star. We will then recover several properties of the Sun using the reconstructed light curve. First and foremost we seek to recover the solar rotation period and activity cycle period, which are 25-34 days and 10.9 years respectively (Hathaway, 2015; Howe et al., 2000).

We also follow the technique of Giles et al. (2017) to estimate the sunspot lifetimes. High resolution observations of sunspots show that they have lifetimes ranging from hours to months (Solanki, 2003). There is a roughly linear relationship between active region areas and their lifetimes, as described by Gnevyshev (1938) and Waldmeier (1955) (see also, for example, Petrovay & van Driel-Gesztelyi, 1997).

The broad range of possible rotation periods for the Sun is the result of differential rotation – the Sun rotates faster at the equator than at the poles (Miesch, 2005). The pursuit to detect differential rotation from photometric rotational modulation of Sun-like stars in *Kepler* light curves has proven very difficult (Aigrain et al., 2015). Setting the perils aside, we will naively attempt to search for differential rotation by its effect on the solar light curve in Section 2.3.

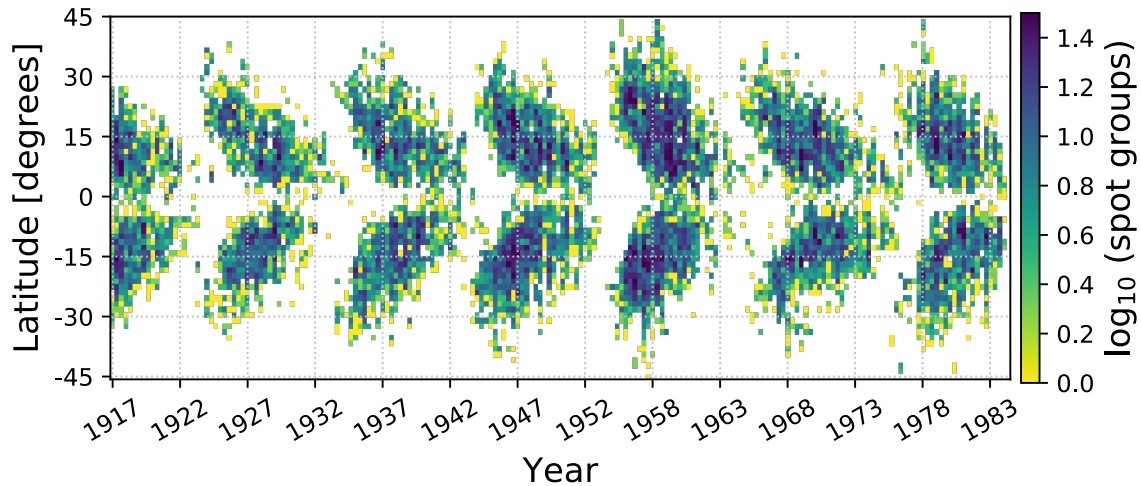


Figure 2.1: Butterfly diagram (after Maunder 1904) showing spot density as a function of time and solar latitude with the spot archive of Howard et al. (1984).

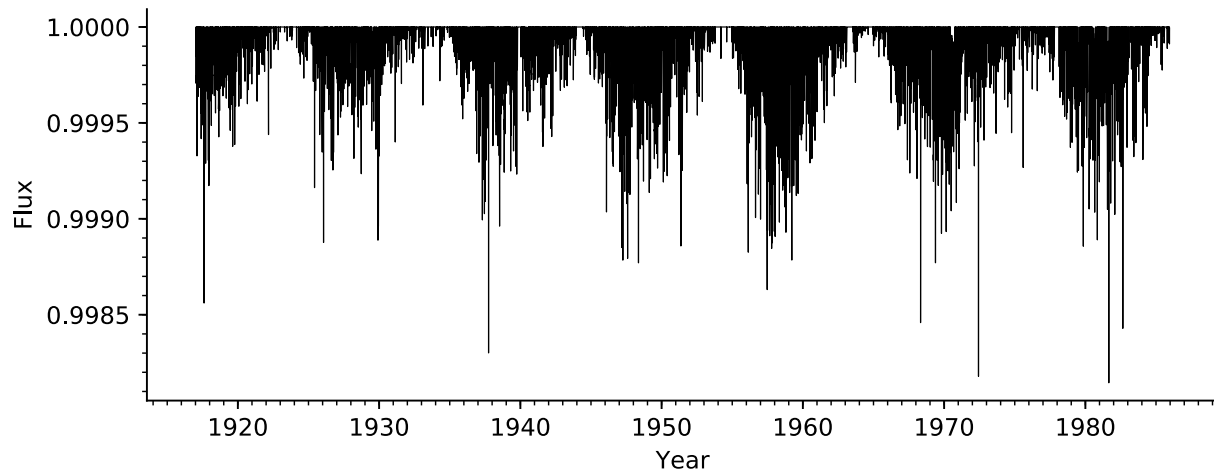


Figure 2.2: Reconstructed solar light curve from the spot area coverage archive of Howard et al. (1984). The standard deviation of the full light curve is 150 ppm. The mean flux is 80 ppm less than the maximum flux. See Figure 2.3 for a close-up view of one cycle and further description.

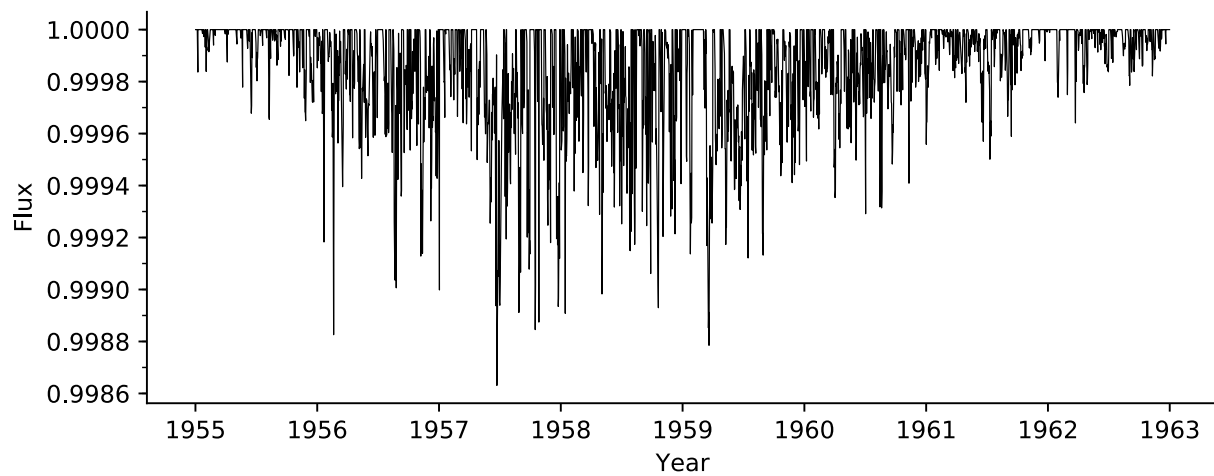


Figure 2.3: Reconstructed solar light curve zoomed into cycle 19 to show fine structure. This light curve is unlike *Kepler* light curves for several reasons: our reconstruction has no photon noise, no p-mode oscillations, no granulation “flicker”, and no instrumental artifacts. In addition, unlike *Kepler* targets, we know the true unspotted flux of the Sun in these reconstructed light curves (i.e. we know when the Sun was truly spotless), so the light curve has a maximum of unity, rather than a median of unity.

2.2 The Solar Light Curve

2.2.1 Constructing the light curve

As in Morris et al. (2018a), we integrate the total flux of the unspotted, limb-darkened Sun,

$$F_{\odot, \text{unspotted}} = \frac{1}{d^2} \int_0^{R_\star} 2\pi r I(r) dr, \quad (2.1)$$

where $I(r)$ is a quadratic limb-darkening law, r is in units of angle, and d is the distance to the target, so that $2\pi r dr$ is solid angle.

We define Cartesian sky-plane coordinates (x, y) , with the origin placed at the center of the star, $\hat{x}$ aligned with the stellar equator, and $\hat{y}$ aligned with the stellar rotation axis. We describe each starspot with an ellipse with centroid $\mathbf{r}_i = (x_i, y_i)$, and $r_i = |\mathbf{r}_i|$. We can compute the negative flux contribution from each spot by computing the approximate spot area and contrast. A circular spot will be foreshortened near the stellar limb. The foreshortened circular spot can be approximated with an ellipse with semi-major axis R_{spot} and semi-minor axis $R_{\text{spot}} \sqrt{1 - (r_i/R_\odot)^2}$.

Since these spots are small compared to the solar radius ($R_{\text{spot}}/R_\odot < 0.1$), we adopt one limb-darkened contrast for the entire spot, $c_{ld} = (1 - c)I(r)$, where c is the flux contrast in the spot relative to the photosphere flux.

The integrated spot flux is

$$F_{\text{spot}, i} = -\frac{\pi}{d^2} R_{\text{spot}}^2 c_{ld} \sqrt{1 - (r_i/R_\odot)^2}, \quad (2.2)$$

and accounting for all N spots, the spotted flux of the star is

$$F_{\odot, \text{spotted}} = F_{\odot, \text{unspotted}} + \sum_{i=1}^N F_{\text{spot}, i}. \quad (2.3)$$

This approximation is valid for spots that are small compared to the solar radius, or small compared to the scale of limb-darkening variation across the solar disk.

The spot group coverage catalog of Howard et al. (1984) describes the daily areas and positions of sunspot groups from 1917-1985, see Figure 2.1. We approximate each spot group

as a single circular spot with the area of the entire spot group. We fix the spot contrast in the *Kepler* band at $c = 1 - I_{\text{spot}}/I_{\text{phot}} = 0.7$, which is the mean sunspot intensity averaged over the penumbra and umbra, assuming their typical penumbra covers a factor of 5 more area than the umbra (Solanki, 2003).

The reconstructed solar light curve is shown in Figures 3.3 and 2.3. This very long-term view of the solar light curve shows periods of high variance separated by relatively quiet times, corresponding to the phase in the activity cycle. During solar maximum, there can be as many as 14 spot groups on the visible hemisphere of the Sun at once, leading to typical dips in flux of order ~ 500 ppm. Near solar minimum, the spotless solar surface had no spot groups, and we have filled in those dates with no spot group entries with flux equal to unity.

The full reconstructed solar light curve is available online (Morris, 2018)¹.

2.2.2 Constraining the Effects of Faculae

The Mount Wilson Observatory sunspot catalog only tracked the positions and areas of dark sunspots, but did not measure the positions or sizes of faculae, which are small *bright* regions of concentrated magnetic flux. We reconstruct the solar light curve due to facular brightening using the same technique as in the previous section, but this time using faculae positions and areas from the Greenwich Photo-Heliographic Plate archive, digitized in 1999 by the NOAA Environmental Data Rescue Program, which provides facular positions and areas.

Unlike the starspots, we do not choose a fixed contrast for the faculae, since facular intensity varies as a function of position on the Sun. Therefore we compute a contrast for each facula individually given their position according to

$$\Delta T_{\text{fac}} = 250.9 - 407.7\mu + 190.9\mu^2, \quad (2.4)$$

where ΔT_{fac} is the temperature excess of the faculae relative to the local photosphere, $\mu = \cos \theta$, and θ is the angle between the stellar surface normal and the observer's line of sight

¹ <https://doi.org/10.5281/zenodo.1476637>

(Dumusque et al., 2014; Meunier et al., 2010). The contrast of each facula is thus the integrated blackbody flux with the photospheric temperature plus the temperature excess, normalized by the blackbody flux with the temperature of the photosphere (5777 K). We integrate the blackbodies over the *Kepler* bandpass, but the choice of bandpass has little effect on the results (see, for example, Figure 2 of Morris et al. 2018a).

The resulting light curve of excess solar flux due to faculae is shown in Figure 2.4. Typical brightening in the *Kepler* band due to faculae is small ($\lesssim 20$ ppm) compared to the darkening due to sunspots ($\lesssim 200$ ppm). Despite their large relative area coverage compared to starspots, the typical facular intensity contrast ($c \sim 1.05$) is relatively small compared with sunspots ($c \sim 0.7$), so we expect spots to dominate the rotational modulation of the Sun in the *Kepler* band, in agreement with Shapiro et al. (2016), for example.

The dominance of sunspots over faculae in the rotational light curve of the Sun is not to be confused with the fact that the Sun is considered “faculae dominated” on timescales of the activity cycle. That is, near solar maximum the Sun is bolometrically brighter than it is at solar minimum (Solanki et al., 2013). What we refer to as the solar light curve in this work is *not* the bolometric flux of the Sun, rather it is the flux integrated over a bandpass like those of *Kepler*, TESS, or *Gaia*. As such, we choose to ignore the effects of faculae in the remainder of this work, since spots dominate the rotational modulation, which is our primary focus.

2.2.3 Measuring the solar rotation and activity cycle periods

An astronomer’s first instinct is likely to measure periodicities upon seeing a light curve such as Figure 2.2. In this section, we examine the autocorrelation function and Lomb-Scargle periodogram of the solar light curve to establish benchmark measurements of the rotation and activity cycle periods.

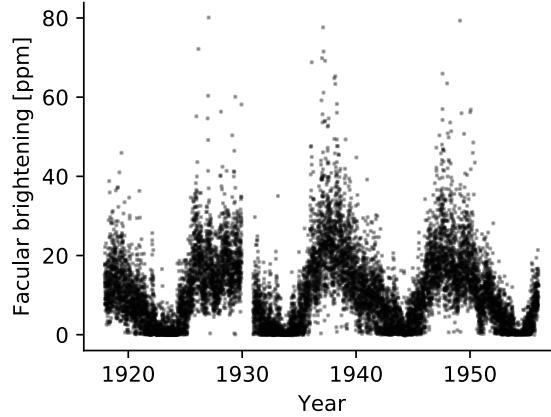


Figure 2.4: Facular brightening of the Sun from the Greenwich Photo-Heliographic archive spanning three activity cycles. Note that the scale of facular brightening in the *Kepler* band is small ($\lesssim 20$ ppm) compared to the darkening due to sunspots ($\lesssim 200$ ppm).

Gaussian Process regression

The autocorrelation function of the solar light curve is shown in Figure 9.6. There is short-term variation peaking at 26 days – approximately the rotation period of the Sun at the photosphere near the active latitudes (Howe et al., 2000). There is also a long-term decaying cosine-shaped correlation with its first peak at 10.6 years, corresponding to the magnetic activity cycle period of ~ 11 years (Hathaway, 2015). Finally, there is a cosine-shaped correlation with a period of 365 d, corresponding to the orbital period of the Earth. This systematic crops up because the Earth’s orbit is inclined with respect to the solar equator by 7.25° (Meeus, 1991), causing starspots to drift slightly towards and away from the solar equator throughout each year, injecting a small correlated signal into the reconstructed light curve.

For a more rigorous measurement of the solar rotation and activity cycle period, we model

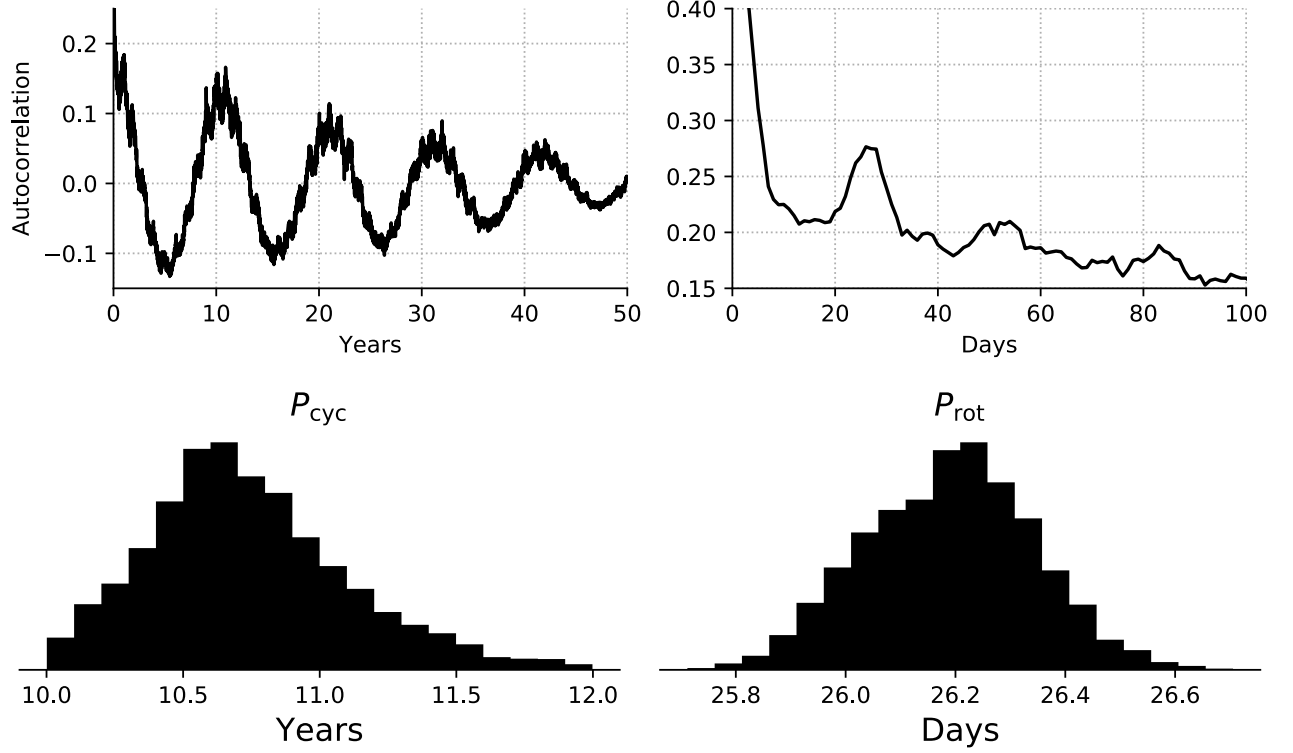


Figure 2.5: *Upper left*: long-term autocorrelation function of the solar light curve in Figure 3.3. The first peak is ~ 10.5 years. *Upper right*: short-term signals in the autocorrelation function of the solar light curve, with a peak at 26 d. This estimate of the rotation period is approximately consistent with the rotation period at the active latitudes (Howe et al., 2000). See Section 3.3.3 for a more robust rotation period measurement using Gaussian process regression with a quasi-periodic kernel. *Lower*: Posterior distributions for the the magnetic activity cycle period P_{cyc} and the solar rotation period P_{rot} measured with a quasi-periodic Gaussian process regression to the synthetic photometry from 1917-1985 (see Figure 3.3). We measure $P_{\text{rot}} = 26.32 \pm 0.14$ days and $P_{\text{cyc}} = 10.61 \pm 0.23$ years.

the light curve with a quasi-periodic Gaussian process with a kernel of the form:

$$\begin{aligned}
 k(\tau) = & a_0 e^{-c_0 \tau} \cos\left(\frac{2\pi\tau}{P_{\text{cyc}}}\right) + \\
 & a_1 \cos\left(\frac{2\pi\tau}{P_{\oplus}}\right) + \\
 & a_2 e^{-c_2 \tau} \left[\cos\left(\frac{2\pi\tau}{P_{\text{rot}}}\right) + 1 \right]
 \end{aligned} \tag{2.5}$$

τ is the difference in times (units of days). The exponential term allows for deviations from a perfectly periodic activity cycle signal with decay timescale $c_0 > 0$. P_{rot} is the rotation period and P_{cyc} is the activity cycle period. $P_{\oplus}$ is the orbital period of the Earth, which imprints itself on these data because the Earth’s inclination with respect to the solar equator gives rise to a periodic systematic shift in the positions of sunspots. We fit for $a_0, a_1, a_2, c_0, c_2, P_{\text{rot}}, P_{\text{cyc}}$ using Markov Chain Monte Carlo via **emcee** with **celerite** (Foreman-Mackey et al., 2017, 2013). We measure $P_{\text{rot}} = 26.3 \pm 0.1$ d – see the posterior distributions in Figure 9.6. We note that this is consistent with the asteroseismic rotation period of the solar photosphere at $\sim 15^\circ$ latitude (Howe et al., 2000) – as one would hope, it seems the quasi-periodic Gaussian process properly recovers the rotation period at the active latitudes where the most spots are emerging. Thus, at high enough S/N, a light curve will show the rotation period at the active latitudes, rather than the equatorial rotation period, as has been potentially observed in tidally synchronized binaries (see e.g. Lurie et al., 2017).

We also measure activity cycle period $P_{\text{cyc}} = 10.61 \pm 0.23$ years. This is consistent with canonical cycle period measured by taking the dates of the minima of cycle 1 and cycle 23 and dividing by 22, yielding an average cycle period of 10.9 years (131.7 months, Hathaway 2015).

Lomb-Scargle Periodogram

Next, we use the Lomb-Scargle (LS) periodogram to compare its ability to pick out the quasi-periodic peak – see Figure 2.6. The dominant period is 27 d, just longer than the rotation period measured by Gaussian process regression in the previous section. The difference in

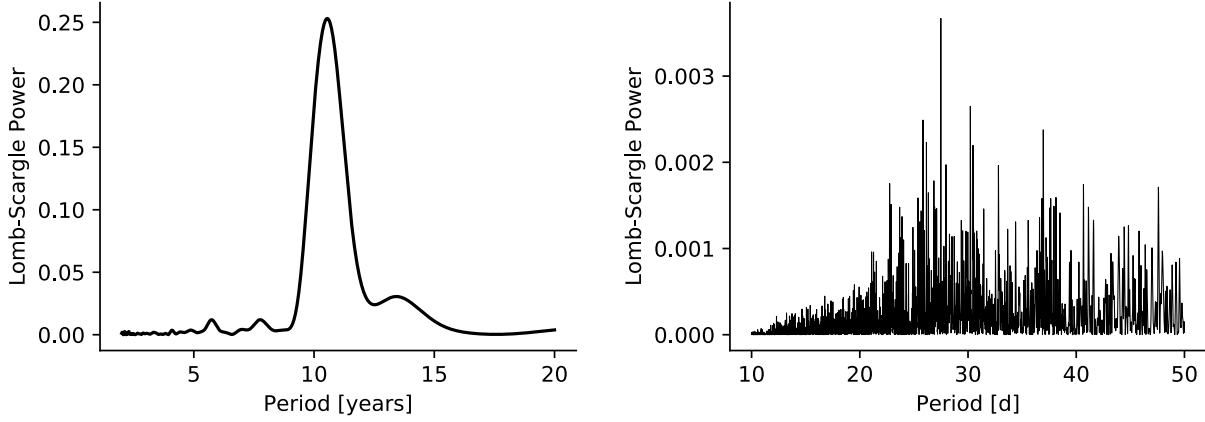


Figure 2.6: Lomb-Scargle periodogram of the solar light curve in Figure 3.3 on long (*left*) and short (*right*) timescales. Like the autocorrelation function in Figure 9.6, the Lomb-Scargle periodogram has a peak at the oft-quoted activity cycle period of 11 years, and the rotational peak at 27 days.

rotation periods measured with each technique is an artifact of the intrinsically quasi-periodic nature of the Gaussian process kernel in the previous section, and the strict periodicity enforced by the LS periodogram. In addition, the uncertainty in the periodicity measured with the LS periodogram is not well defined, so it is not possible to do a robust comparison between the LS and Gaussian process period measurements. Turning to longer periods, the activity cycle peak is prominent at 10.6 years – this result is consistent with the Gaussian process regression measurement.

We prefer the value from the quasi-periodic Gaussian process analysis for the apparent rotation period rather than the LS period because: (1) we know from high resolution observations that there’s more than one frequency at play – for example, starspots emerge and decay on timescales similar to the stellar rotation period; and (2) the Gaussian process regression provides us with robust uncertainties on the apparent rotation period. For these reasons, we encourage observers of distant stars to consider using Gaussian process regression

over the LS periodogram when searching for the rotation period at the mean active latitudes (VanderPlas, 2018).

2.2.4 Measuring active region evolution timescales

The autocorrelation function in Figure 9.6 has a peak at the rotation period of the star, and smaller peaks at integer multiples of the rotation period with decreasing amplitudes. Giles et al. (2017) developed a technique for measuring active region evolution timescales by modeling the autocorrelation functions of active stars with a underdamped simple harmonic oscillator (uSHO), which we apply here to the autocorrelation function of the reconstructed solar light curve to estimate active region lifetimes.

We attempt to measure the sunspot lifetimes from the autocorrelation function. However the form of the autocorrelation function (Figure 9.6) is slightly different to those seen in Giles et al. (2017), which typically follow the pattern of an underdamped simple harmonic oscillator. In Figure 9.6 there is an additional decreasing trend which causes the subsequent peaks to be significantly lower than the central peak, which arises from the much longer timescale activity cycle pattern. This effect is persistent whether we generate the autocorrelation function for the light curve as a whole, or cut it up into smaller portions and combine the autocorrelation functions.

Although the uSHO fits were unsuccessful, we can still make some qualitative statements from inspection of the autocorrelation function at short lags. The signal of rotation peaking at 26 days has repeated aliases at twice and possibly at three times the rotation period, each with diminished amplitude, before the aliases of the rotation signal appear to decay away at large lags ($\gtrsim 3P_{\text{rot}}$). This suggests that the typical spot decay timescale is similar to the rotation period, and only occasional spots survive more than one or two solar rotations. This observation is in agreement with spatial resolved observations which show that the longest-lived sunspots live of order several rotations (Howe et al., 2000; Pettit, 1951), but most only survive for less than one rotation (Petrovay & van Driel-Gesztelyi, 1997).

2.3 Differential rotation

Many efforts have been made to quantify differential rotation in *Kepler* light curves of stars, most notably in Aigrain et al. (2015), where several groups of observers attempted to measure the differential rotation rate in synthetic light curves. The authors found that there was little relation between the injected and recovered differential rotation rates, indicating that *Kepler* detections of solar-like differential rotation ought to be treated with caution.

In this Section, we set out to mimic this perilous exercise by measuring the solar rotation period in consecutive one year bins, using the quasi-periodic Gaussian process technique that we used in Section 3.3.3 to measure the rotation period of the full light curve. We choose one year bins so that there is sufficiently long baseline to get a fit for the period, but the duration is short compared to the activity cycle period (11 years). If the rotational modulation contains the signature of differential rotation, we expect to find that the apparent rotation period changes slightly from one year to the next, as spots emerge at different latitudes throughout the activity cycle, and due to differential rotation, the spots rotate with slightly different periods.

Ideally, we would observe that at the beginning of each activity cycle, the spots emerge at high latitudes and therefore the apparent rotation period is long. Then as the activity cycle progresses, spots emerge at lower latitudes, revealing shorter rotation periods.

The rotation period recovered from fitting the quasi-periodic Gaussian process to one-year bins of the solar light curve is shown in black points in Figure 2.7. The red curve shows the rotation period at the mean area-weighted spot latitude averaged into yearly bins, and shows the small differential rotation signal imparted by the activity cycle which we are attempting to measure. In practice, we observe a spread in measured rotation periods much larger than the variance due to the activity cycle, with similarly large uncertainties. Activity minima can be identified in this figure by the large uncertainties on the rotation period, when few spots are present to drive rotational modulation. In between these points of large uncertainties are intervals where the rotation period is measured more precisely, though

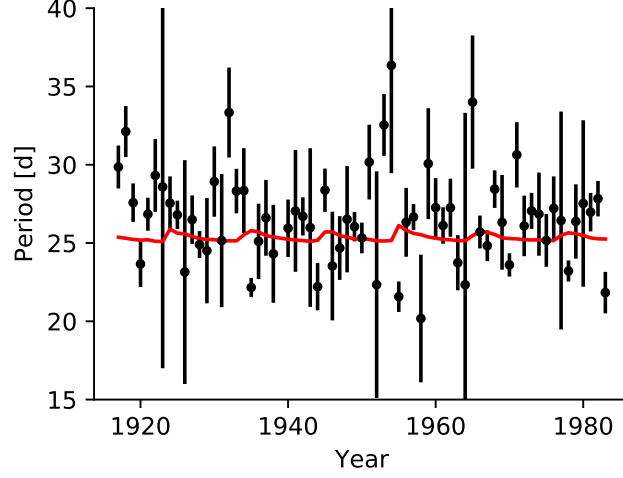


Figure 2.7: Measured solar rotational period inferred from quasi-periodic Gaussian process regression to one year-long bins of the solar light curve (black circles), compared with the rotation period at the mean area-weighted spot latitude averaged in one year bins (red curve). As spots emerge at different latitudes with differential rotation, we hoped to find that the rotation period varied from year to year with the phase of the activity cycle – with spots emerging at high latitudes and long rotation periods, and the rotation period appearing to decrease as spots emerge closer to the solar equator. It appears that due to spots emerging at a broad range of latitudes at all phases of the activity cycle, the apparent rotation period remains largely constant, irrespective of the activity cycle phase.

it is roughly consistent with a 26.3 d rotation period throughout all phases of the activity cycle. Assuming the rotation period is 26.3 d throughout, the reduced $\tilde{\chi}^2 = 8$, indicating that the variance is indeed greater than expected for Gaussian-distributed errors. However, the stochastic nature of the measurements make it impossible to recover the true differential rotation rate from these rotation measurements. Therefore even at “infinite” signal-to-noise, we arrive at the same conclusion as Aigrain et al. (2015) – measuring differential rotation shear from rotational modulation alone is a fraught exercise.

2.4 Discussion

The detection of differential rotation from the solar light curve eludes us in Section 2.3. One reason for this is made clear by the butterfly diagram in Figure 2.1 – the distribution of spots within active latitudes of the Sun are broad; spots are distributed within $\pm 8^\circ$ of the mean “active latitude” at each phase of the activity cycle. The spots at multiple latitudes each contribute to the rotational modulation with their own rotation period, imprinting the mean rotation period on the light curve, rather than the specific rotation period at a high or low latitude. We are encouraged by recent work by Benomar et al. (2018) which may hold the key to measuring differential rotation from stellar photometry via asteroseismology for at least a small subset of stars.

One limitation of this reconstruction approach is that the Howard et al. (1984) spot archive only cataloged spots within 60° longitude of the central solar meridian, meaning that spots on the limb were not logged. If spots near the limb were included in this time series, the overall flux trends might be smoother, and there would be fewer days with flux equal to unity. However, the net effect on the rotation period and activity cycle measurements is likely small, since spots on the limb are geometrically foreshortened, and due to the Wilson depression, they have smaller contrasts than spots at disk center (Solanki et al., 1993).

2.5 Conclusion

We reconstructed a one day-cadence light curve of the Sun using the sunspot archive of Howard et al. (1984). We compared the amplitude of variability due to dark sunspots to the amplitude of brightening from faculae, and found that the dark sunspots dominate the rotational modulation.

With the noise-free light curve, we measured rotation period and activity cycle period of the Sun with both the Lomb-Scargle periodogram and a quasi-periodic Gaussian process regression. The rotation periods and activity cycle periods measured with both techniques are consistent with the rotation period at the active latitudes, and the duration of a typi-

cal activity cycle. We showed that differential rotation cannot be detected even from this idealized reconstructed light curve.

Chapter 3

THE STELLAR VARIABILITY NOISE FLOOR FOR TRANSITING EXOPLANET PHOTOMETRY WITH PLATO

In the previous chapter, we devised a technique for reproducing the solar light curve as though it were a *Kepler* target. One successor to the *Kepler* mission which will observe thousands of Sun-like stars is the PLANetary Transits and Oscillations (PLATO) mission (Rauer et al., 2014). PLATO is a space-based planet-search survey lasting four years with the goal of searching for Earth-like planets orbiting Sun-like stars, while observing at a short cadence to measure stellar oscillations for asteroseismology. PLATO seeks to use these asteroseismic measurements of its newly-discovered exoplanet host stars to precisely characterize stellar radii, which propagates forward into precision radii of exoplanets.

The photometric signal which allows asteroseismologists to measure a star’s properties is also a source of noise which limits the precision of measurements of an exoplanet’s radius. In this chapter, we will measure the effects of stellar oscillations and granulation on observations of transiting exoplanets by superimposing transits of an Earth-like planet on resolved images of the Sun. This chapter has been submitted for publication in Monthly Notices of the Royal Astronomical Society.

3.1 Introduction

The detection of Earth-like planets around Sun-like stars is a long-standing goal of astronomy. The *Kepler* spacecraft set out to discover Earth-Sun analogs, and its most promising discovery was a transiting planet on an orbit similar to Earth around a star similar to our Sun, Kepler-452b (Jenkins et al., 2015), although the statistical significance of this detection has been debated (Burke et al., 2019; Mullally et al., 2018).

In addition to the orbital period, the radius-ratio of the planet to the star may be inferred from the transit depth after accounting for limb-darkening. When coupled to estimates of the radius of the star, this yields an estimate of the planet radius, which is an indicator of the possible composition of the planet, as revealed by transiting planets at shorter orbital periods (Fulton et al., 2017; Rogers, 2015). The planet Kepler-452b has a radius about 60% larger than Earth, which may imply a different composition (Rogers, 2015). Other promising candidates exist with shorter periods and/or larger radii than Earth, as well as host stars which are different from our Sun; we have not detected a true Earth-Sun analog.

Yet, the transit technique still holds promise for the detection of Earth-Sun analogs. The ESA PLANetary Transits and Oscillations (PLATO) mission aims to discover transiting exoplanets among 15,000 dwarf and sub giant stars with $V < 11$ with 25 second cadence photometry collected over 4.5 years (Rauer et al., 2014). One of the main scientific motivations for PLATO is to measure Earth-like exoplanet transit radii with 3% precision. To achieve this ambitious goal for planets orbiting Sun-like stars, the host stars likely must have little stellar activity in the form of starspots or flares, and the stellar variability must be accounted for in the transit analysis.

Here we examine the noise floor on measuring the planet-star radius ratio which is caused by stellar inhomogeneity and variability coupled with stellar limb-darkening. Two forms of variability during transits may affect transit measurements: variability caused by non-uniformity in the surface brightness of the star which is being occulted by the planet, and variability due to temporal variations in the total flux emitted by the unocculted star. Limb-darkening affects the depth of the transit depending on how close the path of the transit passes with respect to the center of the star. These three effects limit how well we can measure the planet-star radius ratio.

In principle, space-based photometry of transiting exoplanets contains information about the host star as well as the exoplanet. Light curves of transiting exoplanets have been used to map stellar surface brightness variations within the transit chord, occasionally revealing maps of starspots (see e.g. Bonomo & Lanza, 2012; Davenport, 2015a; Désert et al., 2011;

Morris et al., 2018a, 2017b; Sanchis-Ojeda & Winn, 2011). As a result, one must be careful to account for stellar surface inhomogeneities when measuring the radius of an exoplanet (Morris et al., 2018d).

The Sun and Sun-like stars exhibit photospheric granulation, a small-amplitude surface inhomogeneity observable in transit photometry (Chiavassa et al., 2017). Stellar granulation is the pattern of bright upwelling convective plasma surrounded by dimmer down-flowing plasma which tiles the photosphere of a Sun-like star. Granulation occurs on a variety of size scales. The most prominent in typical continuum images of the Sun are granules with radii ~ 1 megameter (Mm) in size (see Figure 3.1), or roughly $0.2R_{\oplus}$; less obvious is the structure of supergranules, which span ~ 16 Mm in radius, or roughly $2.5R_{\oplus}$ (Rast, 2003).

The degree to which granules and supergranules affect transit light curves depends on their size scales. Several granules are occulted by an Earth-sized planet – 6.37 Mm in radius – at any instant during an exoplanet transit event. However, only a portion of a supergranule is occulted during an exoplanet transit. As a result, transits of Earth-sized exoplanets could in principle reveal the pattern of stellar supergranulation in the residuals of extremely high precision transit photometry. However, as we show in this paper, this will be swamped by temporal stellar variability.

The Sun and Sun-like stars also exhibit p -mode oscillations (Christensen-Dalsgaard, 2002). Spatially-resolved Doppler velocity and photometric measurements of the Sun reveal p -mode oscillations with a maximum power near period $P = 5.39 \pm 0.05$ minutes (Fröhlich et al., 1997a; Huber et al., 2011), often referred to as the solar “five-minute oscillations.” These oscillations are omnipresent in solar and stellar photometry, injecting a continuous source of correlated astrophysical noise into transiting exoplanet light curves, which imposes a noise floor on transit depths – and therefore planet radii – measured from photometry.

There is modest literature on simulating space-based transit photometry along with realistic stellar variability, see for example Aigrain et al. (2004a); Aigrain & Irwin (2004); Carpano & Fridlund (2008); Hippke & Angerhausen (2015). In this paper, we seek to build on those works by studying the specific case of an Earth-sized planet transiting using actual

observations of the Sun, and by examining the fundamental noise limits on the measurement of the radii of planets from transits by Earth-Sun analogs.

The continuum intensity image time series from the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) aboard the Solar Dynamics Observatory (SDO) provides us with a useful dataset for simulating transits of exoplanets on observations of the Sun. We discuss the HMI instrument in Section 3.2. There are two stellar contributions to the uncertainty in a transit measurement: spatial variations in the surface brightness of the star which is occulted by the planet (§3.3) and temporal variations in the brightness of the unocculted star (§3.4). In this work, we artificially superimpose an exoplanet on HMI continuum intensity images to create simulated transits of the real Sun. We then analyze these transits, which contain the signatures of solar granulation and p -mode oscillations, and, in Sections 3.3 and 3.4, we quantify the impact of each component on the exoplanet radius uncertainty. We discuss the results in Section 11.6 and summarize in Section 11.7.

3.2 The HMI Instrument

The HMI instrument aboard SDO takes a series of images in 6 wavelengths, centered on the Fe I spectral line at 6173 Å, and 4 polarizations, which are then processed together to derive physical observables (Schou et al., 2012). One observable is the continuum intensity (see Figure 3.1), which is derived by reconstructing the solar line from the Doppler-shift, line-width, and line-depth estimates following Equation 14 of Couvidat et al. (2016), who show that the continuum intensity derived in this manner differs from the true continuum intensity by less than 1%.

Photon noise accounts for approximately 0.01% of these continuum intensity measurements (Couvidat et al., 2016); similarly, systematic variations in the flat field on the order of 100 ppm add an additional source of noise to the data. These numbers exceed the performance specifications for the instrument.

As with any telescope, optical limitations also affect the image quality. Ideally, the light from a singular point on the Sun corresponds to a singular point on an image of the Sun.

In practice, diffraction and imperfect optics cause light from a singular point on the Sun to spread over many points on an image of the Sun (Couvidat et al., 2016). This spread is characterized by a Point Spread Function (PSF). To mitigate the effects of diffraction and imperfect optics, we deconvolve HMI continuum intensity images of the Sun with the PSF (modeled as an Airy function; for details, see Wachter et al. 2012). This process increases the granular contrast by a factor of two (see Figure 27 of Couvidat et al., 2016), and ensures that optical artifacts play a small role in the following simulated transits.

We also remove the diurnal variation in the amplitude of the HMI continuum intensity measurements, which appear due to the orbital velocity of the SDO spacecraft (see Section 2.10 of Couvidat et al., 2016), that would otherwise dominate over the small-scale perturbations we are trying to measure in this work. We discuss our methods for removing this signal in Sections 3.3 and 3.4.

All the HMI data are publicly available at <http://jsoc.stanford.edu>.

3.3 Flux Variations of the Regions Occulted by the Planet

In this section we simulate the variation in transit depth due to spatial variations of the stellar surface brightness which is occulted by the planet.

3.3.1 Simulating transits

To simulate transits, we first select a single, static continuum intensity image. We then create a time series of fluxes by first creating a synthetic exoplanet, equal to the projected size of the Earth, and summing the flux within this circular disk. We then subtract this sum from the total solar disk intensity. The projected size of the Earth is computed from the HMI image headers, which record the apparent solar radius, in units of pixels, for each image.

We ignore the effects of the Moon or other planets on the orbit of Earth, and we also neglect the eccentricity of Earth’s orbit for simplicity. We advance the planet incrementally across the solar surface and compute the time of each integration assuming a circular orbit

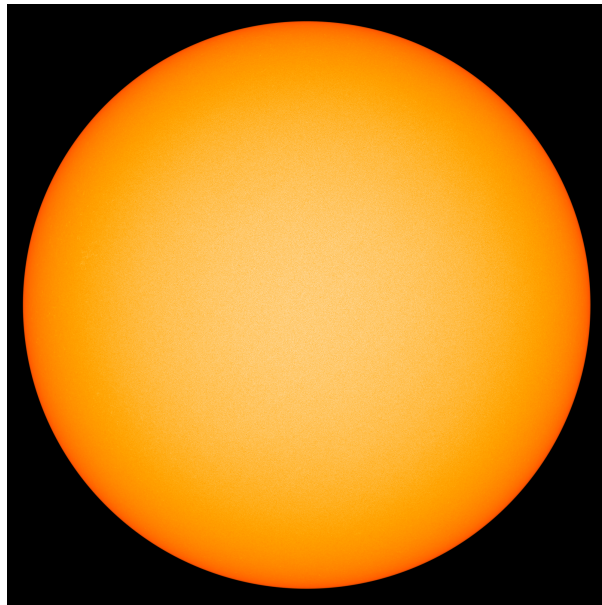


Figure 3.1: Deconvolved SDO/HMI continuum intensity image of the quiet Sun on 21 January 2018 at 19:34 TAI shown in the Helioprojective Cartesian coordinate system with the color table scaled from 0 to 65000 DN/s.

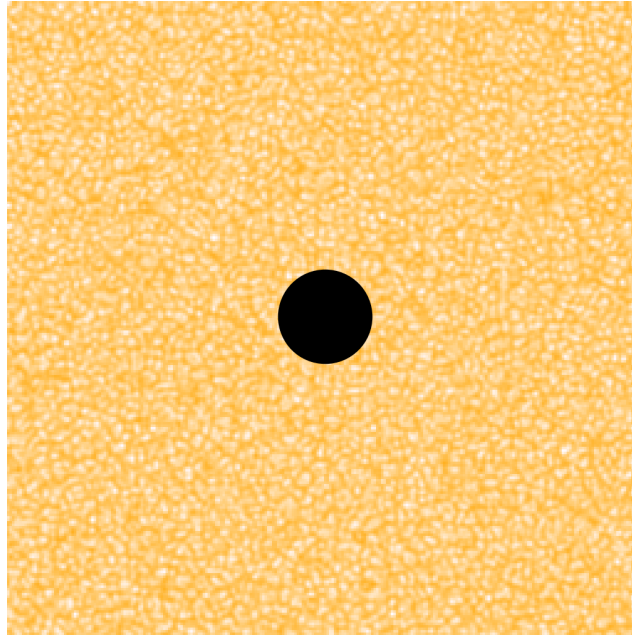


Figure 3.2: Same as Figure 3.1, but zoomed in on a 128 x 128 arcsecond patch of the the quiet Sun at disk center. The black circle shows the scale of a simulated Earth-sized exoplanet.

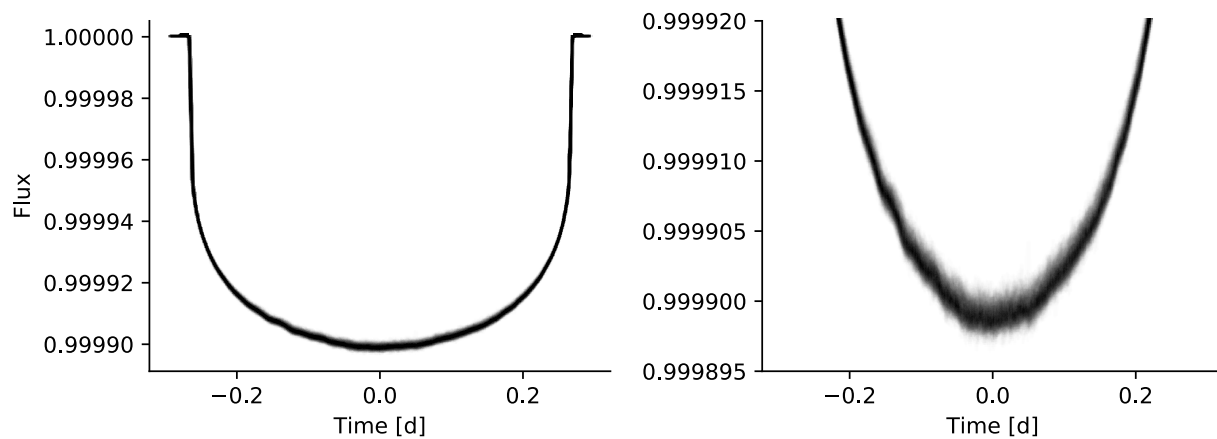


Figure 3.3: 282 simulated transit light curves of an Earth-sized planet transiting the SDO/HMI images of the Sun (left: full transit, right: zoom into mid-transit). The spread at flux minimum is due to solar surface brightness variations due to activity and granulation.

with $P_{\text{orb}} = 365$ days. We create this time series across a single, static image to avoid the diurnal variation in the amplitude of the intensity measurements. This has the added benefit of eliminating the effects of photon noise (since the entire time series is across one realization of photon noise), which allows us to probe the effects of photospheric granulation at a ppm level.

We simulate transits across 282 deconvolved continuum intensity images taken on days in 2018 that show the least magnetic activity. This ensemble of transits is shown in Figure 3.3. We only simulate transits with an impact parameter of $b = 0$. Selecting $b = 0$ ensures that the planet is unlikely to occult magnetically active regions, which rarely occur near the solar equator, and maximizes the granulation contrast. The software for these simulations is available online¹.

3.3.2 Granulation and supergranulation noise in the transit residuals

We fit the Mandel & Agol (2002) transit model to each of the simulated light curves, implemented by the Python package `batman` (Kreidberg, 2015). For each light curve, we simultaneously fit for the planet radius, mid-transit time, orbital inclination and four nonlinear limb-darkening parameters, while fixing the orbital period, semi-major axis, and radius of the star at the known values, assuming a circular orbit for the Earth. We then examine the residuals of each transit fit (an example is shown in Figure 3.4) and reject any transits contaminated by magnetic elements (transits containing residual flux values > 5 ppm). We used nonlinear limb-darkening parameters here to be sure to remove any symmetric trends in the light curve. To remove imperfections in the HMI deconvolved image flat field, which we discussed in Section 3.2, we subtract the residual flux at each time by the median of all transit residuals. The resulting transit residuals typically have standard deviations of 0.5 ppm, and a typical range is 2 – 4 ppm.

¹ Open source software: <http://github.com/bmorris3/stash>

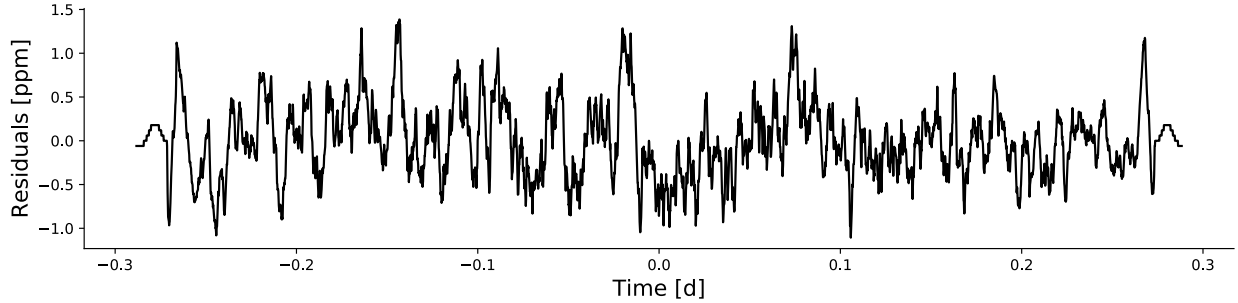


Figure 3.4: Transit residuals of a particular realization of the solar granulation, showing residual amplitude ~ 2 ppm.

3.3.3 Radius uncertainty due to granulation and supergranulation

Granulation occurs on a variety of size scales – granules with radii of ~ 1 Mm, which are clearly visible in the HMI continuum intensity images (see Figure 3.1), and supergranules, with radii of ~ 16 Mm, which are not easy to see in the continuum intensity images (Nordlund et al., 2009). Granules and supergranules appear stochastically over time, but their length scales and turnover times stay roughly constant. Therefore, we can model our ensemble of 282 transit residuals as an autocorrelated signal with noise.

We model the autocorrelated signal with Gaussian process regression – for more information on Gaussian processes, see Rasmussen & Williams (2006). We use a simple harmonic oscillator kernel implemented by the Python package `celerite` (Foreman-Mackey et al., 2017), which has the following power spectrum:

$$S(\omega) = \sqrt{\frac{2}{\pi}} \frac{S_0 \omega_0^4}{(\omega^2 - \omega_0^2)^2 + \omega_0^2 \omega^2 / Q^2}, \quad (3.1)$$

where S_0 is the amplitude, ω_0 is the characteristic oscillation frequency, and $Q = 1/\sqrt{2}$ is the quality factor of the oscillation. We use a Markov Chain Monte Carlo method, implemented by the Python package `emcee` (Foreman-Mackey et al., 2013), to simultaneously fit for the simple harmonic oscillator kernel hyperparameters S_0 and ω_0 as well as the Mandel & Agol (2002) transit model parameters for the orbital inclination i_o , quadratic limb darkening

parameters u_1 and u_2 , mid-transit time t_0 , and $R_p/R_\star$, the ratio of the exoplanet radius, R_p , to the stellar radius, $R_\star$.

We find a typical uncertainty on the exoplanet radius is 0.02% R_p . We consider this a noise floor, or a lower limit, since we modelled the granulation pattern from a synthetic transit across a single, static image.

We also find that the transit residuals are roughly periodic with timescale $P = 18 \pm 1$ minutes. We can use this periodicity to measure the characteristic length scale for supergranulation. Assuming a supergranule is large compared to the planet, the duration of a supergranule occultation τ by a small transiting exoplanet (with an impact parameter $b = 0$) is approximately

$$\tau \approx \frac{2R_{\text{sg}}}{v} = \frac{R_{\text{sg}}P_{\text{orb}}}{\pi a} \quad (3.2)$$

where R_{sg} is the radius of the supergranule, v is the orbital velocity of the planet, P_{orb} is the orbital period of the planet, and a is the semimajor axis of the planet's orbit. Rearranging Equation 3.2 for the supergranule radius, we find $R_{\text{sg}} = 16 \pm 1$ Mm, similar in horizontal scale to supergranules observed both in radial velocity maps of the solar surface (Hathaway et al., 2000) as well as in continuum intensity (see for example Goldbaum et al., 2009; Meunier et al., 2008; Rieutord & Rincon, 2010). Modelling the granulation across a time-varying background would account for the convective motions of the granules and therefore introduce a more complex pattern for the granulation noise. However, supergranulation imprints itself in patterns on the Sun with characteristic lifetimes of ~ 20 hours (Rast, 2003), which is longer than a typical Earth transit of a Sun-like star (~ 12 hours), and so the static approximation should be adequate.

Comparison with previous results

Chiavassa et al. (2017) simulated transits of Earth-like planets on three-dimensional radiative hydrodynamical simulations from the STAGGER grid models of Sun-like stars and found the

residual signal in the transit due to granulation had RMS amplitude 3.5 ppm in the bandpass 7600-7700 Å, which is similar to our estimate using HMI continuum intensity images (2 – 4 ppm).

Expectations for other stars

Numerical simulations of stellar granulation for stars across the main sequence show that granule size scales inversely with the stellar surface gravity (see review by Kupka & Muthsam, 2017; Nordlund et al., 2009). As a result, one might expect that stars smaller than the Sun will have smaller granules. The smaller the granules, the more granules occulted by an Earth-sized planet in a given exposure, and therefore the smaller the in-transit signal of granulation on the light curve.

Numerical simulations of granulation for stars from spectral type F7-K3 dwarfs by Trampedach et al. (2013) all have characteristic horizontal scales of granules of order 1 Mm. These scales grow as stars evolve and their $\log g$ decreases (see also Trampedach et al., 2017). Therefore the small-scale granulation signal should be most significant for evolved stars.

Solar supergranulation, in contrast with small scale granulation, is difficult to measure due to its small amplitude, and difficult to simulate due to its vast physical extent (Rieutord & Rincon, 2010). Thus we caution the reader to only use the results of this analysis for Sun-like stars.

3.4 Flux Variations of the Unocculted Stellar Disk

In Section 3.3 we studied the effect of stellar brightness variations due to granulation within the transit chord of an Earth-like exoplanet on the transit light curve. We assumed that the disk-integrated brightness of the star was unchanging, and only the spatial surface brightness variations within the transit chord were responsible for perturbations to the transit residuals. While this was a pedagogically interesting exercise, it was fundamentally one step removed from real photometry of stars: p -mode oscillations, magnetic activity and granulation inject time variability into the disk-integrated flux of a Sun-like star. In this Section, we measure

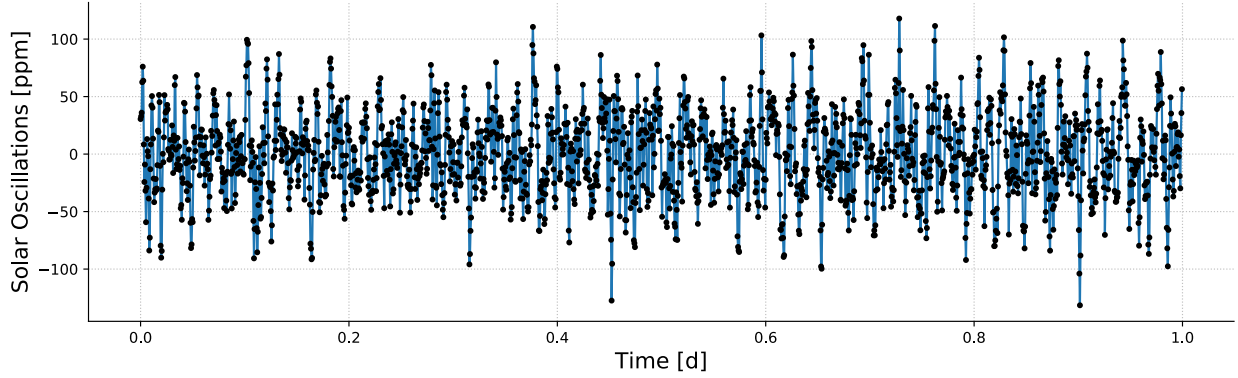


Figure 3.5: Twenty-four hours of 45-second cadence photometry of the Sun from SDO/HMI continuum intensity images, with the mean intensity removed to show the small amplitude variability of the Sun on these timescales (black circles). The error bars on the fluxes from each measurement are smaller than the points. The blue curve is the maximum-likelihood Gaussian process fit to the light curve with a simple harmonic oscillator kernel.

the amplitude of the variability of the unocculted star. Given that the transit depth is of order 0.01%, the planet only occults a small fraction of the stellar disk, and so this variability will be present at the same level both in transit and out of transit.

3.4.1 *Simulating transits*

First, we measure the total brightness of the Sun using 45-second cadence HMI continuum intensity images throughout four sets of 24-hour observations, each separated by one year. The four sets of observations represent one transit observation for each of the four years of the nominal PLATO mission. This disk-integrated variability will affect both in- and out-of-transit photometry observed by PLATO. We compute the total intensity of each HMI image taken on 21 January 2018, a day with little magnetic activity near solar minimum, as well as the same day in 2015, 2016, and 2017.

The resulting photometry has a strong diurnal signal, due to the orbital velocity of the

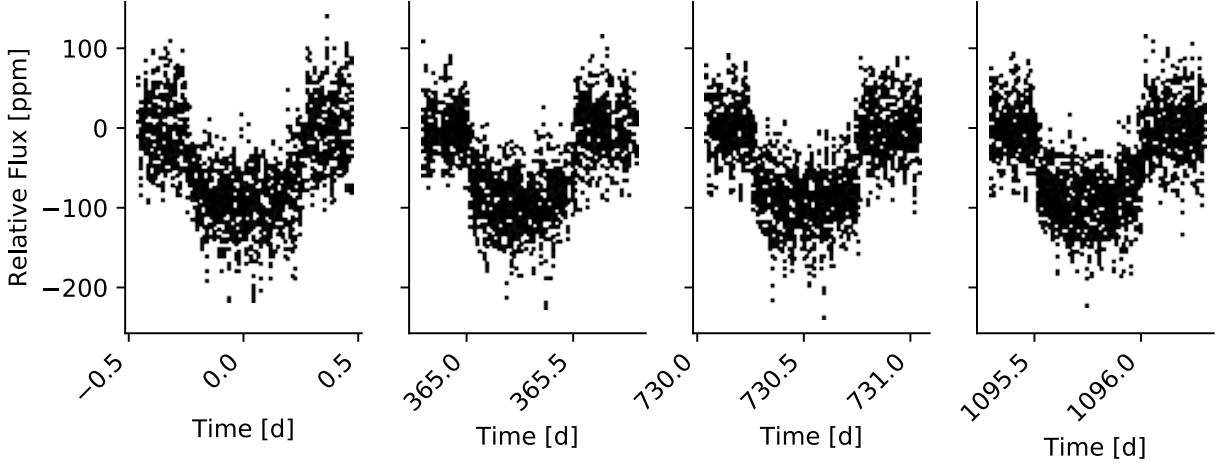


Figure 3.6: Transits of an Earth-sized planet across the solar surface, including the disk-integrated variability due to p -mode oscillations and granulation. Clearly the disk-integrated variability is greater than the in-transit granulation signal discussed in Section 3.3 (1 ppm).

SDO spacecraft (see Section 2.10 of Couvidat et al., 2016), which dominates over the small-scale perturbations we are trying to measure in this work. Our second step is to remove this trend by modelling the light curve with a smooth Gaussian process using a Matérn 3/2 kernel (Rasmussen & Williams, 2006), and divide the light curve by the maximum-likelihood fit, which had $\sigma = 0.00409$ and $\rho = 15$ hours.

The resultant systematics-corrected HMI photometry for 21 January 2018 is shown in Figure 3.5 (black circles), with the mean flux from the time series removed. The amplitude of the variability in the 45-second cadence photometry is ~ 100 ppm. We also show the maximum-likelihood Gaussian process fit with a simple harmonic oscillator kernel (blue curve).

Next we inject exoplanet transits with Earth’s size and orbit (with $e = 0$), shown in Figure 3.6, into the four 24-hour sets of systematics-corrected photometric time series measurements. To do this, we could superimpose a synthetic planet on each image, as we did for a single, static image in Section 3.3, compute the total intensity per image, and remove the

diurnal signal by modelling the light curve with a smooth Gaussian process using a Matérn 3/2 kernel. However, this approach may remove the small-scale perturbations we are trying to measure. Instead, we use a model to construct a synthetic (Mandel & Agol, 2002) transit model and we multiply this with each of the four 24-hour sets of systematics-corrected photometric time series measurements as observed by HMI.

These simulated transits indicate what PLATO might observe if it discovers a true Earth-analog orbiting a Sun-like star. The scatter in the plots in Fig. 3.6 is due to solar oscillations and granulation. The amplitude of the oscillations is similar to the transit depth of the Earth. In the HMI photometry, the error bars are similar in scale to the size of the points in the plot. We have not added additional noise to these simulations, and so the photometric variability is the fundamental limit on the precision of the transit model.

3.4.2 *Radius uncertainty*

To determine the uncertainty in an exoplanet’s radius due to solar oscillations and granulation, we follow the same procedure as in Section 3.3.3. We simultaneously fit a Mandel & Agol (2002) transit light curve and a Gaussian process with a simple harmonic oscillator kernel to the transit photometry in Figure 3.6 to measure the uncertainty in the exoplanet radius while accounting for the correlated noise due to oscillations and granulation. In the previous section, the periodicity measured by the kernel arose from the synthetic planet spatially crossing bright convective upflows and dark inter-granular lanes. In this case, the periodicity measured by the kernel is due to p -mode oscillations and granulation. In this section, we also let the orbital period float, so as to let its uncertainty propagate into the uncertainties on other parameters since the period will be unknown for newly discovered transiting planets.

The posterior PDF for the planet radius is shown in Figure 3.7, for which the uncertainty in the planet radius is 3.6%. This uncertainty is the combined effect of three contributions: the degeneracy with the unknown impact parameter, and the signals of stellar granulation and oscillations. The square-root of the maximum depth of transit, $D^{1/2}$, is measured with

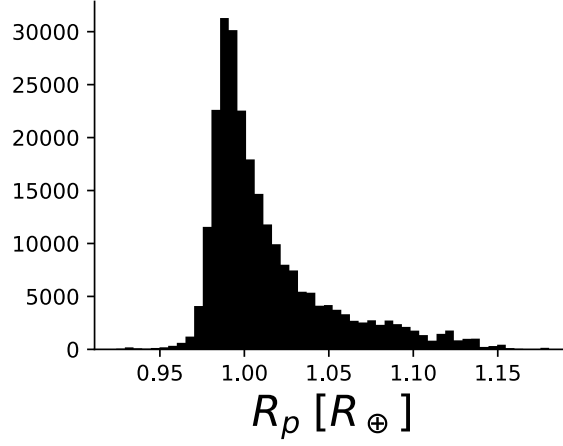


Figure 3.7: Posterior distribution of the radius of the Earth-sized planet, in units of Earth radii. The uncertainty is 3.6%, accounting for the full noise budget of the PLATO mission, before any instrumental or systematic effects are accounted for. The dominant contributor towards this uncertainty is degeneracy with impact parameter in the presence of noise due to stellar oscillations and granulation (see Appendix 3.A for full posterior distributions).

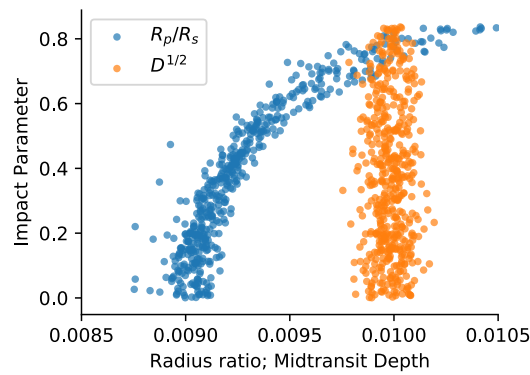


Figure 3.8: Posterior distribution of radius-ratio, R_p/R_* , versus impact parameter (blue) and the square root of depth, $D^{1/2}$ versus impact parameter (orange). The uncertainty on $D^{1/2}$ is 0.73%

much higher precision, about 0.73%, as shown in Figure 3.8, where depth is defined as:

$$D = \frac{R_p^2}{R_*^2} \frac{1 - u_1(1 - \sqrt{1 - b^2}) - u_2(1 - \sqrt{1 - b^2})^2}{1 - \frac{u_1}{3} - \frac{u_2}{6}}, \quad (3.3)$$

where R_p is the planet radius, R_* is the stellar radius, u_1 is the linear limb-darkening parameter, u_2 is the quadratic limb-darkening parameter, and b is the impact parameter mid-transit (in units of the stellar radius). The significant limb-darkening of the star in the PLATO passband, which we have approximated with the limb-darkening coefficients in the *Kepler* band given by $u_1 = 0.45$ and $u_2 = 0.19$ (Sing, 2010), is the origin of the degeneracy between impact parameter and radius ratio, which is responsible for the long tail in radius-ratio seen in Figure 3.7. The simulation was created with an edge-on orbit, corresponding to $b = 0$, while in the presence of stellar noise, the recovered impact parameter varies from 0 to 0.8 (Figure 3.8). At larger values of the impact parameter, the duration of the transit shortens and the depth of transit becomes shallower due to the lower surface brightness of the star. However, the *shape* of the trough of the transit is very similar shape as zero impact parameter. Thus, at higher impact parameter, very good fits to the data are obtained by adjusting the duration of the transit (this comes from adjusting the ratio a/R_*), and by increasing the radius ratio of the planet to the star to maintain the same transit depth, as well as a very slight change in the limb-darkening coefficients.

The one quantity that changes significantly at higher impact parameters is the duration of ingress and egress, which is smaller than the transit duration by a factor of $(R_p/R_*)(1 - b^2)^{-1}$. Although the higher impact parameters have a longer duration of ingress and egress, the uncertainty on the measurement of this duration from the data is significant due to the noise caused by stellar oscillations and granulation variability, which have a similar characteristic timescale. It is only at very large impact parameter, $b \approx 0.8$, that the ingress/egress duration becomes sufficiently long that the data can rule out the model with a large impact parameter; this is why the posterior distribution cuts off at high impact parameter. Unfortunately there is a significant variation in the radius ratio as a function of impact parameter, and so the lack of constraint upon the impact parameter yields a much larger uncertainty on the radius

ratio compared with the uncertainty on the square root of transit depth, $D^{1/2}$.

To further isolate the contributions of the uncertainty in impact parameter/inclination, we fixed the impact parameter to $b = 0$ and refit the light curve. This yielded a radius uncertainty of 0.5%, which is a *much* smaller uncertainty than in the variable inclination fit. This indicates that the majority of the measured uncertainty in the radius ratio actually arises from degeneracy with the impact parameter in the presence of noise due to granulation and oscillations.

The degeneracy between the planet radius and the unknown impact parameter may present a significant obstacle to precision exoplanet radius characterization with PLATO, but it still may be possible to mitigate the impact of this degeneracy. As with the procedure presented in Morris et al. (2018d), asteroseismic analysis of the light curve can yield precise estimates of the mean stellar density, which constraints $a/R_\star$ via Kepler’s third law. The measured duration of the transit in turn constrains the impact parameter via

$$b = a/R_\star \cos(i) \left(\frac{1 - e^2}{1 + e \sin \omega} \right) \quad (3.4)$$

(Winn, 2010a), with some uncertainty due to the unknown eccentricity of the orbit, e , and longitude of pericenter, ω . Therefore by measuring the asteroseismic signal of the star, as PLATO is designed to do, better precision on the impact parameter, and thus the planet radius, could be achieved with a prior on the eccentricity. Another means of characterizing the stellar density would be to use the transits of other planets in the system (Kipping, 2014), which would similarly constrain the impact parameter. If the eccentricity of the orbit could be measured through other means, such as radial-velocity monitoring of the star, then the constraint upon the impact parameter could be tightened, and the full precision of the radius ratio recovered.

The limb-darkening parameters contribute to the radius uncertainty, as the limb-darkening in a broad optical bandpass like PLATO’s will be significant. Our fits to simulated photometry show that the posterior PDFs of the limb-darkening parameters are somewhat constrained (see Appendix 3.A for full posterior distributions), and are not strongly covariant with the

impact parameter, and so the degeneracy between impact parameter (or inclination) and limb-darkening remains. If follow-up observations were obtained in the infrared, where limb-darkening is much less significant, then the exoplanet radius can be measured with less dependence upon the impact parameter. An additional advantage of observing in the infrared would be quieter variability of the star, and a stronger variation of the transit light curve at ingress and egress, which may yield a further constraint upon the impact parameter based upon the shape of the light curve.

The predicted uncertainty, due to degeneracy between impact parameter and exoplanet radius in the presence of stellar granulation and oscillations, amounts to the full error budget in the mission specifications for PLATO. Marginal improvements on the precision of the transit light curves may be obtained by modeling more of the out-of-transit light curve, or with an extended mission which observes the same field for more transits.

3.5 Discussion

The PLATO mission seeks to measure Earth-analog exoplanet radii with 3% precision. We have demonstrated, using simulated photometry from HMI continuum intensity images, that stellar oscillations and granulation coupled to degeneracy between the planet radius and orbital impact parameter caused by limb-darkening will be important contributors to the uncertainty in exoplanet radii, of order 3%. In order to reach 3.6% precision, we took advantage of the extremely high signal-to-noise of the HMI observations and fit a Gaussian process to the solar oscillations and granulation.

The HMI photometry detrending strategy in Section 3.4 used to remove the continuum intensity trends with orbital phase likely also removed solar variability on timescales greater than a few hours. As a result, there may be additional sources of correlated noise that are not incorporated into the radius uncertainties we report in this work. Primarily, we note that super- and meso-granulation are sources of correlated noise on the hours-to-days timescales similar to the transit of an Earth across a Sun (Aigrain et al., 2004a; Fröhlich et al., 1997a). As such, the 3.6% radius uncertainty noise floor that we present here should be understood

as a lower limit – incorporating the longer timescale sources of variability will increase the radius uncertainty.

We carried out a test of whether the detrending technique is removing significant signals that will affect the exoplanet radius uncertainty. We downloaded four complete days of continuous, 1-minute cadence continuum intensity images taken by the Michelson Doppler Imager (MDI; Scherrer et al. 1995) aboard the Solar and Heliospheric Observatory (SoHO). MDI took data from 1996 until 2010 from the L1 Lagrange point, and thus its continuum intensity data does not show the orbital phase variations present in the SDO data. Therefore, the MDI observations² are an ideal control data set for comparison against the detrended HMI continuum intensity photometry. We find that after injecting transits into the MDI observations, the posterior distributions for the exoplanet radius have a similar uncertainty as the detrended HMI observations (4%). This indicates we do not significantly underestimate the uncertainty in the exoplanet radius due to the HMI detrending process.

In our analysis of the Earth-like transit light curves, we assumed the period was known perfectly $P_{orb} = 365.25$ d, and that no transit timing variations occurred. In real observations of the Earth, the uncertain period and transit timing variations would introduce larger uncertainties on the impact parameter, and therefore the radius ratio.

3.5.1 Wavelength dependence of variability

In the calculations presented above, we assumed that the variability that PLATO will observe is similar to the “psuedo-continuum” variability observed by SDO/HMI. However, HMI continuum intensity is observed over a narrow ~ 1 Å bandpass centered on 617.3 nm, whereas PLATO will observe in a broad bandpass from 500-1050 nm. Therefore we must verify that the variability observed in the narrow HMI bandpass is not significantly different from the variability extrapolated into the PLATO bandpass. We can approximate the ratio of variability in the HMI bandpass to the variability in the PLATO bandpass as follows.

² MDI observations are publicly available at <http://jsoc.stanford.edu>

Ignoring limb-darkening, let's say a fraction $f_c \ll 1$ of the star is covered by the cool portion of granules with temperature T_c , while the remainder of the star we take as having a constant temperature, T_s . Then, the flux from the star is given by:

$$F_\nu = \Omega [f_c I_\nu(T_c) + (1 - f_c) I_\nu(T_s)] \quad (3.5)$$

where the flux can vary in the *Kepler* band is via variations in either T_c or f_c . The specific intensity is $I_\nu(T)$ for an atmosphere at temperature T , while Ω is the solid angle of the star. We Taylor expand the intensity in terms of temperature:

$$I_\nu(T_c) = I_\nu(T_s) + (T_c - T_s) \left. \frac{\partial I_\nu}{\partial T} \right|_{T_s}, \quad (3.6)$$

giving

$$F_\nu \approx \Omega \left[I_\nu(T_s) + f_c (T_c - T_s) \left. \frac{\partial I_\nu}{\partial T} \right|_{T_s} \right] \quad (3.7)$$

Then, integrating over the SDO/HMI (subscript H) and PLATO (subscript P) bands:

$$\dot{N}_H = \int d\nu \frac{F_\nu}{h\nu} T_{H,\nu} \quad (3.8)$$

$$\dot{N}_P = \int d\nu \frac{F_\nu}{h\nu} T_{P,\nu} \quad (3.9)$$

where $T_{H,\nu}$ is the SDO/HMI throughput at frequency ν , and $\dot{N}_H$ is the photon count rate ($\text{cm}^2 \text{ s}^{-1}$).

When F_ν varies, this causes variation in $\dot{N}_H$ and $\dot{N}_P$, but both of these just depend on $f_c(T_c - T_s)$. Since the amplitude of variation is small, we approximate

$$\frac{d\dot{N}_H}{df_c} \frac{1}{\dot{N}_H|_{f_c,0}} \approx (T_c - T_s) \frac{\int d\nu \left. \frac{\partial I_\nu}{\partial T} \right|_{T_s} \nu^{-1} T_{H,\nu}}{\int d\nu I_\nu(T_s) \nu^{-1} T_{H,\nu}} \quad (3.10)$$

where the approximation assumes $f_c \ll 1$ and $T_c - T_s \ll T_s$. A similar relation holds for the PLATO bandpass. Thus, the ratio of the fractional amplitude of variation in PLATO to that in SDO/HMI, α , is given by:

$$\alpha \equiv \left(\frac{d\dot{N}}{df_c} \frac{1}{\dot{N}_P|_{f_c,0}} \right) \left(\frac{d\dot{N}_H}{df_c} \frac{1}{\dot{N}_H|_{f_c,0}} \right)^{-1} \approx \frac{\int d\nu \left. \frac{\partial I_\nu}{\partial T} \right|_{T_s} \nu^{-1} T_{P,\nu} \int d\nu I_\nu(T_s) \nu^{-1} T_{H,\nu}}{\int d\nu \left. \frac{\partial I_\nu}{\partial T} \right|_{T_s} \nu^{-1} T_{H,\nu} \int d\nu I_\nu(T_s) \nu^{-1} T_{P,\nu}}, \quad (3.11)$$

where, conveniently, the dependence upon f_c and T_C has disappeared.

Approximating the Solar spectrum as a blackbody, we estimate that the variability of a Sun-like star with $T_{\text{eff}} = 5777$ K as observed in the PLATO bandpass will have 86% of the variability observed in the SDO/HMI bandpass. We therefore assume that the variability due to granulation estimated by SDO/HMI is a fair proxy for the variability that will be observed by PLATO, or slightly overestimated.

3.5.2 Limb-darkening parameters

Given that the design of the PLATO instrument has yet to be finalized, we have used the limb-darkening parameters computed for the *Kepler* bandpass as a stand-in for the limb-darkening in the PLATO band. We justify this by estimating the expected quadratic limb-darkening parameters in the PLATO band.

We utilize the radiation hydrodynamic “stagger-grid” models of Magic et al. (2015) to estimate the limb-darkening in the PLATO bandpass. We assume that the PLATO transmission is constant over the 500-1050 nm, and we integrate the photon-weighted specific intensity from the averaged models of Magic et al. (2015)³. Note that this model has been calibrated to the Sun, and gives limb-darkening which closely approximates the Sun (Magic et al., 2015).

We find best-fit quadratic limb-darkening parameters for the Solar model over this wavelength range of $u_1 = 0.24$ and $u_2 = 0.36$. This compares favorably with the *Kepler* limb-darkening parameters which we have used in our simulations; the stagger-grid surface brightness only differs from the quadratic *Kepler* surface brightness by a few percent over the range of observed inclination angles.

³ Downloaded as an IDL .sav file, mmu_t5777g44m00v05.flx, from <https://staggergrid.wordpress.com/clv/>.

3.6 Conclusion

We have constructed photometry of the Sun using HMI continuum intensity time series images to study the effects of solar p -mode oscillations and granulation on transit photometry. The short timescale (< 1 hour) scatter in a transit light curve of an Earth-like planet transiting a Sun-like star has two components. First, both the in- and out-of-transit residual scatter show disk-integrated temporal brightness fluctuations driven by p -mode oscillations and granulation, of order 100 ppm in amplitude with a five-minute period.

Second, maps of stellar surface brightness variations within the transit chords of exoplanets are encoded in the residuals of transit photometry. We find that the brightness variations due to granulation impart only a slight additional scatter, of order 2-4 ppm, to the in-transit photometry, in good agreement with studies of simulated stellar atmospheres by Chiavassa et al. (2017).

We demonstrate that transiting exoplanet radius uncertainties of 3.6% are possible with photon noise-limited photometry from HMI continuum intensity images by accounting for the correlated disk-integrated p -mode and granulation signals with a Gaussian process. This uncertainty on Earth-like exoplanet radii due largely to degeneracy with impact parameter accounts for the full error budget for the PLATO mission, and perhaps motivates: (1) careful propagation of the stellar density measured via asteroseismology into the measurement of the exoplanet’s orbital parameters; (2) auxiliary observations of PLATO targets in the infrared where stellar variability and limb-darkening are weaker to measure precision exoplanet radii and orbital parameters; and (3) a longer extended mission to improve upon the radius measurement uncertainties. We emphasize that these simulated observations focus on observations near solar minimum, and therefore represent conservative estimates on the noise contributed by the Sun and Sun-like stars.

In general, the radius-impact parameter degeneracy discussed in Section 3.4.2 should affect smaller planets more strongly than large planets. The duration of ingress and egress in the limit of small impact parameter scales linearly with the radius ratio $R_p/R_\star$, so the

shape of the light curve, and thus the constraint on the planet radius, is weaker for smaller planets. Thus, we expect that our results will apply more generally for observations of small transits at wavelengths with strong limb-darkening.

3.A Typical posterior distributions

In Section 3.4.2 we injected a Mandel & Agol (2002) transit model with the properties of Earth (impact parameter $b = 0$) into the SDO/HMI continuum intensity photometry of the Sun, whose scatter is dominated by p -mode oscillations (see Figure 3.6). We fit simultaneously for the transit light curve parameters $R_p/R_\star$, i_o , a , t_0 , u_1 and u_2 , in addition to the simple harmonic oscillator kernel hyperparameters S_0 and ω_0 , fixing $Q = 1/\sqrt{2}$. In Figure 9.11 we show the posterior PDFs for each of the parameters.

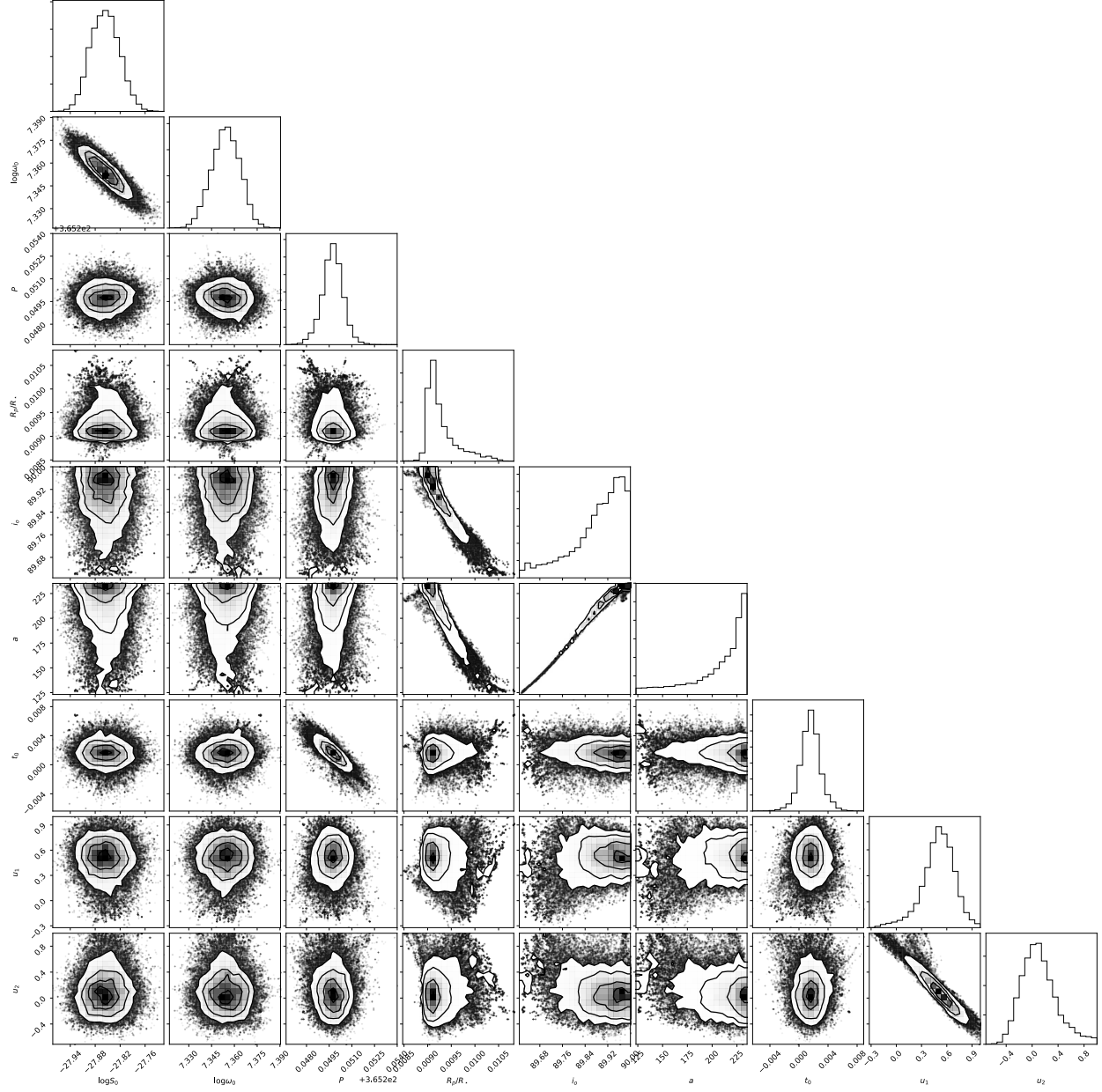


Figure 3.9: Posterior distributions for the Gaussian process hyperparameters and the Mandel & Agol (2002) transit model parameters in a typical fit to a simulated transit. The periodicity in the residuals has timescale $P = 5.83 \pm 0.10$ minutes, and the uncertainty in the planet radius is 3.6%

Chapter 4

GENERATING STELLAR LIGHT CURVES WITH GRANULATION AND OSCILLATIONS

In the Chapter 3 we found that stellar granulation and oscillations will affect precision photometry of exoplanet host stars for the PLATO mission. Stellar granulation and oscillations should occur on all planet-hosting stars, simultaneously allowing for precision measurements of stellar properties via asteroseismology while unfortunately also limiting the precision of planet radius measurements.

PLATO is one of several missions which stands to measure planetary radii and stellar oscillations; others include the Transiting Exoplanet Survey Satellite (TESS), and the CHaracterizing ExOPlanets Satellite (CHEOPS), and the James Webb Space Telescope (JWST) (Beichman et al., 2014; Broeg et al., 2013; Ricker et al., 2014). In this chapter, we devise a novel technique for simulating photometry of stars with oscillations and granulation, in preparation for these missions. This technique allows for efficient computation of long-duration, short-cadence, noiseless light curves of Sun-like stars. We first reproduce the solar variability power spectrum, and then we use established asteroseismic scaling relations to generate light curves of other stars. This chapter has been submitted for publication in Monthly Notices of the Royal Astronomical Society.

4.1 *Introduction*

The Sun varies in brightness on a multitude of timescales and amplitudes. Perhaps one of the best platforms for observing these total solar irradiance variations is with the Solar and Heliospheric Observatory (SOHO)/Variability of Solar Irradiance and Gravity Oscillations (VIRGO) PMO6 radiometer, which has measured the irradiance of the Sun every minute

for more than 20 years (Fröhlich et al., 1995; Fröhlich et al., 1997b; Jiménez et al., 2002). The power spectrum of the solar irradiance variations reveals signals of supergranulation, granulation, and p -mode oscillations.

Granulation is the pattern of upwelling and down-flowing plasma which tiles the solar surface, giving rise to correlated disk-integrated solar irradiance variations (near 1000 μHz , see review by Nordlund et al., 2009). Supergranulation is a large-scale analog to small-scale granulation, which varies on longer timescales (near 10 μHz) and over larger spatial extents on the solar surface (Goldbaum et al., 2009; Meunier et al., 2008; Rieutord & Rincon, 2010). p -mode oscillations (~ 3000 μHz) are standing sound waves in the solar plasma, with the restoring force provided by pressure (see review by Christensen-Dalsgaard, 2002). p -mode oscillations are also known as the famous “five-minute oscillations” observed in spatially resolved radial velocity measurements of the solar surface, as well as photometry.

The myriad photometric variations of the Sun and sun-like stars are about to be observed with unprecedented precision. The TESS mission is currently observing solar-like stars at two-minute cadence (Ricker et al., 2014), ESA’s PLATO mission will observe targets at 45 second cadence (Rauer et al., 2014), CHEOPS will observe bright targets at 60 second cadence (Broeg et al., 2013; Moya et al., 2018). If sufficient precision is attained, each of these observations will contain the signals of stellar granulation and oscillations.

One way to parameterize the power spectrum of the total solar irradiance light curve is with a Gaussian process (GP; Rasmussen & Williams, 2006). For our purposes, Gaussian process models describe how photometric measurements are correlated in time, assuming Gaussian uncertainties for each photometric measurement. The correlations in time are parameterized by a kernel function $\kappa(\tau)$. Recent work by Foreman-Mackey et al. (2017) takes advantage of the properties of kernels expressed as mixtures of complex exponentials in order to compute GP models that scale linearly with the size of the data set via efficient Cholesky decomposition of the covariance matrix. This GP toolkit called *gplearn* enables fast computation of GP models, which is scalable for large data sets such as those one might create for simulated observations from TESS, PLATO, CHEOPS, etc.

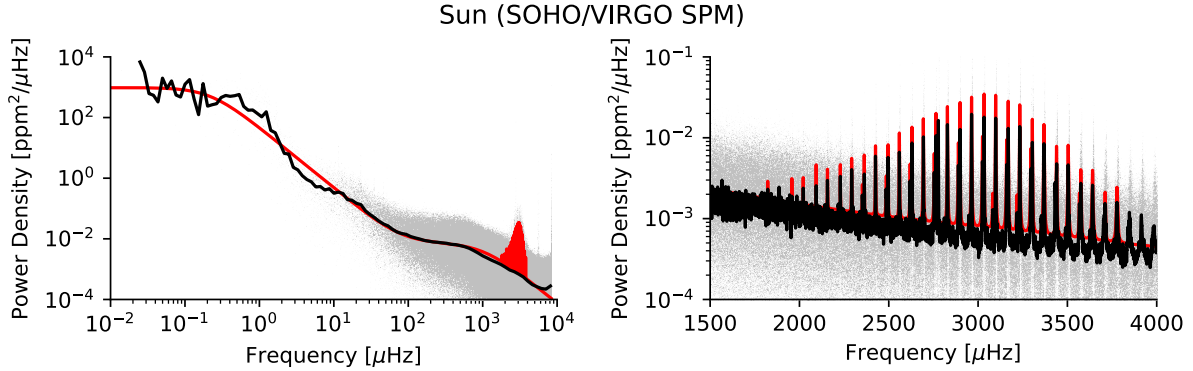


Figure 4.1: Power spectral density of the SOHO/VIRGO PMO6 observations of solar photometry (black points) compared with the maximum-likelihood kernel’s power spectrum (red curve). The kernel has 42 components: one for supergranulation, one for granulation, and 40 for the comb of p -mode oscillation frequencies between 2000-4000 μHz .

In this work, we will use a Gaussian process to describe the covariance of the total solar irradiance light curve from SOHO/VIRGO PMO6 measurements, and then with the kernel function defined by the VIRGO measurements, we will generate simulated solar irradiance observations in Section 4.2. Then in Section 4.3 we will take advantage of simple asteroseismic and granulation scaling relations to generalize the solar kernel function for stars of other masses, effective temperatures, radii and luminosities. In Section 4.4 we validate this PSD-inversion technique against bright *Kepler* targets, and we wrap up with discussion and conclusions in Sections 4.6 and 4.7.

4.2 Gaussian process kernel building

We model the autocorrelated signals in the total solar irradiance light curve with Gaussian process regression – for more information on Gaussian processes, see Rasmussen & Williams (2006). We use the following simple harmonic oscillator (SHO) kernel implemented by the

Python package (Foreman-Mackey et al., 2017):

$$S_i(\omega) = \sqrt{\frac{2}{\pi}} \frac{S_{0,i} \omega_{0,i}^4}{(\omega^2 - \omega_{0,i}^2)^2 + \omega_{0,i}^2 \omega^2 / Q_i^2}. \quad (4.1)$$

which has three parameters, amplitude S_i , critical frequency $\omega_{0,i}$, and damping term Q_i . We describe the kernel function $\kappa(\tau)$ as a mixture of simple harmonic oscillators,

$$\kappa(\tau) = \sum_{i=1}^N S_i(\omega). \quad (4.2)$$

In this work, $N = 42$ – there is one SHO component for large-scale granulation, another SHO component for small-scale granulation, and 40 SHO components which each represent small peaks in the comb of p -mode frequencies between 2000-4000 μHz . We chose 40 components for the p -mode frequencies to assign one to each p -mode frequency identified in Table 2 of Broomhall et al. (2009).

One desirable feature of is its straightforward computation of the power spectral density (PSD) for a given kernel. We vary the parameters S_i , $\omega_{0,i}$, and Q_i for each component in the kernel to fit the SOHO/VIRGO PMO6 PSD, shown in Figure 4.1 in black. The resulting kernel PSD is the red curve – a composite of 42 maximum-likelihood SHO kernels which approximate the solar variability on frequencies from $10^{-2} - 10^4$ μHz .

4.3 Scaling relations

4.3.1 p -modes

For computation of stellar p -mode oscillation frequencies, we use the scaling relations found in Huber et al. (2011, 2012) and references therein (e.g. Kjeldsen & Bedding 1995). In particular, we solve for the relative maximum frequency ν_{max} with Equation 2 of Brown et al. (1991)

$$\nu_{\text{max}} \propto MR^{-2}T_{\text{eff}}^{-1/2}, \quad (4.3)$$

and the spacing between frequencies $\Delta\nu$ from Ulrich (1986)

$$\Delta\nu_{\text{max}} \propto M^{1/2}R^{-3/2}. \quad (4.4)$$

The amplitude scaling of the p-mode oscillations is given by Equation 9 of Huber et al. (2011)

$$A \propto \frac{L^s}{M^t T_{\text{eff}}^{r-1} c(T_{\text{eff}})}, \quad (4.5)$$

where $r = 2$, $s = 0.886$ and $t = 1.89$; and finally,

$$c(T_{\text{eff}}) = \left(\frac{T_{\text{eff}}}{5934\text{K}} \right)^{0.8}. \quad (4.6)$$

in the *Kepler* bandpass.

4.3.2 Granulation

One limitation of assuming SHO kernels is that the slope of the PSD curves at frequencies greater than the critical frequency approaches -2 . This is similar to the power law form of the PSD assumed by Harvey (1985), which was later generalized in Aigrain et al. (2004b) and others for slopes other than -2 . As a result of the fixed slope implied by our sum of SHO kernels, we are unable to exactly reproduce the low frequency PSD fits of Aigrain et al. (2004b), which use more extreme slopes in order to include a component for mesogranulation near periods of 12 hours ($\nu \approx 20 \mu\text{Hz}$). Instead, we fit one “large scale granulation” component which encapsulates the net variability due to supergranulation and mesogranulation (see Figure 4.1). We note that this simplified parameterization makes conservative estimates of the variability due to granulation at all scales, as it generally agrees with the variability observed at long periods when compared with SOHO/VIRGO PMO6 observations (see Figure 4.1).

For computation of large and small scale stellar granulation frequency, we use the scaling relation found in Kallinger et al. (2014):

$$\tau_{\text{eff}} \propto \nu_{\text{max}}^{-0.89}, \quad (4.7)$$

where τ_{eff} is the characteristic granulation timescale. According to Kjeldsen & Bedding (2011), the amplitude of the granulation scales as

$$A \propto \nu_{\text{max}}^{-2}. \quad (4.8)$$

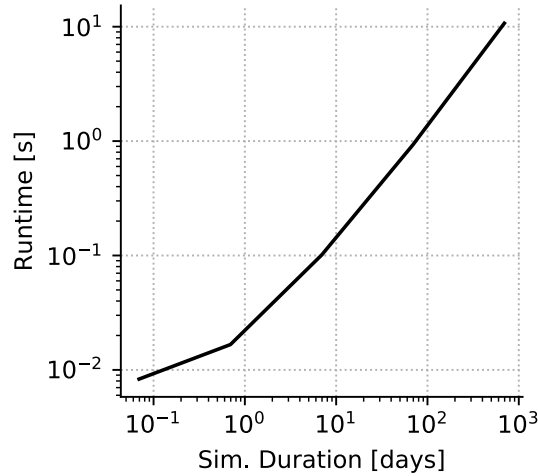


Figure 4.2: Runtime required to generate samples spanning different simulation durations using the efficient kernel technique on a 2.5 GHz Macbook Pro. For large N the runtime increases linearly with the number of data points.

4.3.3 Runtime

One advantage of using the efficient computation by is that computational expense scales linearly with the size of the data set. Figure 4.2 shows how the runtime of the algorithm which generates simulated stellar fluxes scales with the duration of the simulation requested. One million simulated fluxes can be computed in about 10 seconds on a typical laptop. The open source Python implementation of the kernel and scaling relations is available on GitHub¹.

4.4 Validation

We test our scaling relations against the observed power spectra of several bright solar-type stars observed by the NASA *Kepler* mission, listed in Table 4.1, and shown in Figure 4.3. The simulated PSDs are calculated given stellar masses from Mathur et al. (2012) and other

¹ <https://github.com/bmorris3/shocksgo>

Star	T_{eff} [K]	M [$M_{\odot}$]	L [$L_{\odot}$]	R [$R_{\odot}$]	K_P
KIC 3656476	5581	1.09	1.627	1.36	9.516
KIC 5184732	5766	1.25	1.952	1.40	8.165
KIC 6116048	5980	1.12	1.851	1.27	8.418
KIC 6106415	6034	1.12	1.897	1.26	7.179

Table 4.1: Stellar masses from Mathur et al. (2012) and other properties from Andrae et al. (2018); Gaia Collaboration et al. (2018a).

stellar properties from Andrae et al. (2018); Gaia Collaboration et al. (2018a).

The general shapes of the power spectra produced by our scaled kernels match the observed *Kepler* power spectra reasonably well over eight orders of magnitude in power density and six orders of magnitude in frequency. The precise position of the comb frequencies near ν_{max} often does not align perfectly with the expectation from the kernel, but the overall shape of the frequency comb and spacing between peaks scales quite well given the simplicity of the assumptions in Equations in Section 4.3.

4.5 Effect of oscillations on transit timing uncertainties

Correlated noise in stellar photometry increases the uncertainties of exoplanet transit times, which are largely constrained by the sharp flux deviations during ingress and egress. Ingress and egress last for duration τ for a planet with period P , impact parameter b , normalized semimajor axis $a/R_{\star}$,

$$\tau_{\text{ing}} \approx \frac{P}{\pi\sqrt{1-b^2}} \frac{R_{\star}}{a} \frac{R_p}{R_{\star}}, \quad (4.9)$$

which is a valid approximation if the orbit has small eccentricity $e \rightarrow 0$, the planet is small and distant from its host star $R_p \ll R_{\star} \ll a$, and the transit is not grazing $b \ll 1 - R_p/R_{\star}$ (Winn, 2010b).

We can rephrase the scaling relation for ν_{max} in Equation 4.3 in terms of the timescale

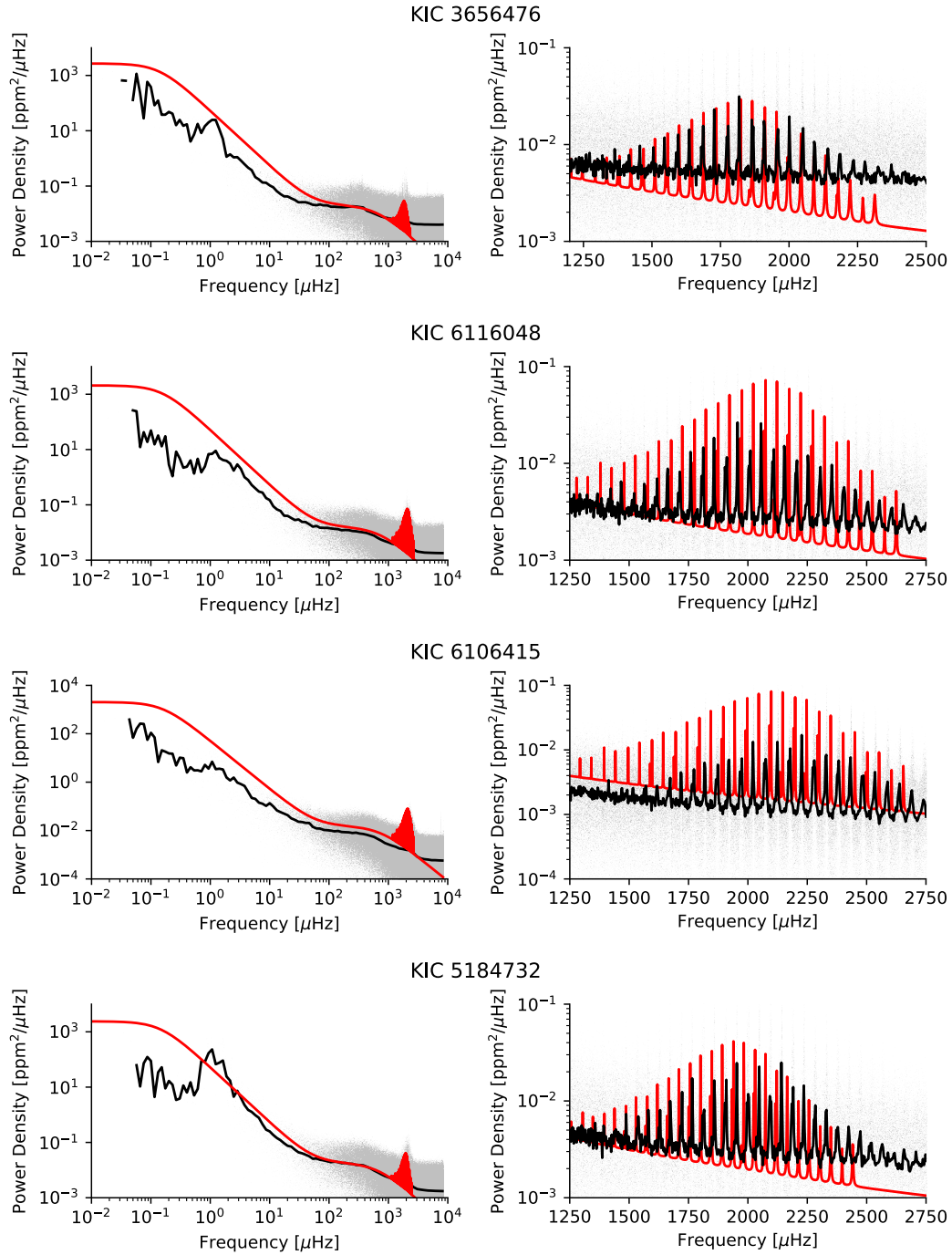


Figure 4.3: Power spectral densities of *Kepler* observations of several Sun-like stars (gray points), PSDs median binned (black curves), compared with the kernels' power spectra (red curve; stellar properties listed in Table 4.1).

maximally affected by p -mode oscillations $\tau_{\max}$ given that $\tau_{\max} = \nu_{\max}^{-1}$, so

$$\tau_{\max} \approx \frac{M_{\odot}}{M_{\star}} \left(\frac{R_{\star}}{R_{\odot}} \right)^2 \left(\frac{T_{\text{eff}}}{T_{\text{eff},\odot}} \right)^{1/2} \tau_{\max,\odot} \quad (4.10)$$

where $\tau_{\max,\odot} = 5.39$ minutes.

To examine the effect of the p -mode oscillation signal on the uncertainty of transit timing measurements, we generate 100 simulated transit light curves for 100 different orbits with varying orbital periods, all with the same transit depth (and $b = 0, e = 0$). At each orbital period, we added the solar oscillation signal to 50 of the light curves, and added white noise with the same standard deviation as the solar oscillation signal to the other 50 light curves. For each light curve, we fit for SHO kernel hyperparameters S_0 , and ω_0 , and the mid-transit time, fixing all other parameters.

In Figure 4.4, the median mid-transit time uncertainty for the 50 light curves with solar oscillations is shown in blue, as a function of the ingress duration τ_{ing} normalized by the maximum oscillation period $\tau_{\max}$. The black points show the median transit time uncertainty for the 50 light curves with white noise only. For ingress durations longer than the exposure time (45 s), the typical uncertainty for solar oscillations (blue) is about 60% greater than the uncertainty for a similar light curve with white noise (black).

4.6 Discussion

In the power spectra of *Kepler* stars in Figure 4.3, we typically over-predict the power at short frequencies, which may be a consequence of detrending of the observations which removes power at these frequencies. For example, $0.1 \mu\text{Hz}$ is equivalent to a period of 115 days, which is similar in timescale to a *Kepler* quarter. We also under-predict the power at high frequencies, which is a result of white noise in the observations. Therefore it is necessary to add white noise to their simulated observations generated with the inversion technique in order to approximate real observations.

The PSD approximation technique described in this work is best suited to dwarf stars. In particular, we emphasize that it will not work well for sub-giant stars because the dipole

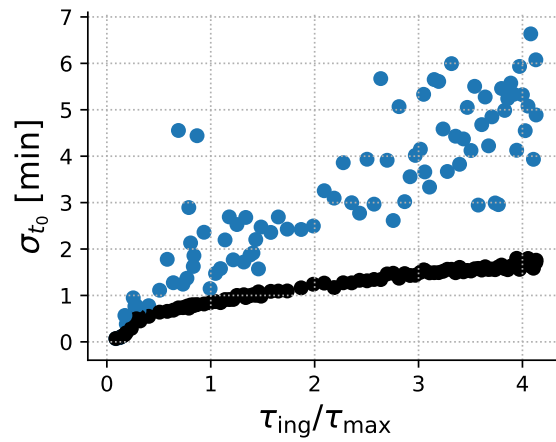


Figure 4.4: Mid-transit time uncertainty σ_{t_0} as a function of the ingress duration τ_{ing} normalized by the maximum oscillation period τ_{max} for simulated observations with p -mode oscillations (blue) compared with observations that have white noise with the same standard deviation as the p -mode oscillations. Typical realizations of the p -mode oscillations produce 60% larger mid-transit time uncertainties than the equivalent white noise realization.

p -modes and g modes begin to blend for sub-giants, as p -modes shift to lower frequencies.

4.7 Conclusion

We constructed a kernel from a sum of simple harmonic oscillators which approximates the solar power spectrum as observed by SOHO/VIRGO PMO6, including terms for supergranulation, granulation and a comb of 40 frequency peaks representing the p -mode oscillations. We used asteroseismic scaling relations to generalize the solar kernel to stars with other fundamental properties (masses, radii, effective temperatures or luminosities), and validated the scaling relations against *Kepler* light curves of bright, Sun-like stars.

We showed that p -mode oscillations are a source of correlated noise which increase the uncertainties of mid-transit time measurements by about 60% when compared with white noise of similar amplitude, for exoplanets with ingress durations longer than the p -mode oscillation timescale. This estimate is an important factor to incorporate when planning for observations of transit timing variations, which are used to estimate the masses of exoplanets.

Part II

STELLAR MAGNETIC ACTIVITY

I believe a leaf of grass is no less than the journey work of the stars.

— Walt Whitman

In the previous Part, we studied solar variability and magnetic activity, as it is the cornerstone of our understanding of stellar variability and magnetic activity. In this Part, we turn our attention to the magnetic activity of other stars. Due to the tremendous distances to even nearby stars, we need to make use of several indirect techniques to infer the presence of surface features attributed to stellar activity.

In Chapters 5 and 6 we present a detailed investigation into the properties of stellar magnetic activity on the star HAT-P-11, a star with a similar rotation period to the Sun, but 20% less massive. We find that the starspots of HAT-P-11 cluster into active latitudes like the Sun's near $\pm 15^\circ$ latitude, though the star is covered by substantially more spots than the Sun. In Chapter 7 we investigate whether a few Sun-like stars exhibit Sun-like magnetic activity, and find that a young G dwarf behaves like the Sun while two young K dwarfs do not. In Chapter 8 we measure the effective temperatures, metallicities and surface gravities for 55 bright stars, and experiment with a technique for measuring the presence and extent of stellar magnetic activity via stellar spectroscopy. We discover that there is a dearth of stars with large spot coverages but inactive chromospheres. In Chapter 9 we probe the magnetic activity of a star quite different from the Sun, the very low-mass dwarf star TRAPPIST-1. We show that the reported stellar rotation period of TRAPPIST-1 may instead be the lifetime of active regions, and that the flares of TRAPPIST-1 are correlated with the flux of the star. Finally, in Chapter 10 we introduce a novel technique for measuring stellar activity using astrometry. This may allow us to probe the magnetic activity of the

nearest stars.

Chapter 5

THE ACTIVE LATITUDES OF HAT-P-11: EVIDENCE FOR A SOLAR-LIKE DYNAMO

In the Introduction we introduced the solar dynamo and activity cycle, and how magnetic activity is expressed on the solar surface in the form of sunspots. The physical mechanisms which give rise to the solar dynamo and activity cycle surely act on other Sun-like stars as well, though our ability to study the latitude- and size distributions of starspots is hindered by their great distance from the Earth. Even with the world’s largest telescopes and interferometry, it is not yet possible to directly spatially resolve starspots in images of nearby dwarf stars. Thus, indirect methods must be employed.

In this chapter, we will use a transiting exoplanet to study the starspots on a star seven million times farther away from the Earth than the Sun, the K4 dwarf star HAT-P-11. The exoplanet HAT-P-11 b transits its host star in a nearly polar orbit, crossing from near the south stellar rotational pole to the north pole, across many latitudes. As the planet blocks out starlight during transit events, it passes over dark starspots. When the planet occults a quiescent region of the stellar photosphere, up to 0.3% of the starlight is obscured by the planet. When the planet occults a dark starspot, less light goes missing than during an occultation of a bright region – imprinting a positive flux excursion onto the transit light curve. The amplitude of the change in flux during a spot occultation is proportional to the size of the spot and the contrast of the spot relative to the mean photosphere. The timing of the spot occultation encodes the latitudes of the occulted spots. Using this technique, we can reconstruct a map of the starspots of HAT-P-11 during transit events over the four-year *Kepler* mission. This is the most comprehensive starspot map for a Sun-like dwarf star ever produced, and presents the best evidence for small scale field resembling a Sun-like dynamo

on another dwarf star to date.

This chapter was first published in the *Astrophysical Journal* (Morris et al., 2017b).

5.1 Introduction

The Sun is our local laboratory for understanding stellar magnetic activity. Centuries of sunspot observations and recent helioseismology results point towards the $\alpha\Omega$ dynamo mechanism as the source of solar magnetic activity. Solar magnetic fields are stored and amplified in poloidal and toroidal components, in the tachocline beneath the convective zone, until magnetic buoyancy causes them to rise. The buoyant magnetic flux tubes become visible as sunspots where they intersect with the photosphere (Babcock, 1961; Parker, 1955a,b; see reviews by Charbonneau, 2010; Cheung & Isobe, 2014; Hathaway, 2015).

Magnetic activity on slowly rotating Sun-like stars is difficult to measure (Saar, 1990) because the Sun has dark spots spanning only $\lesssim 0.5\%$ of its surface area at its most active, while spot areas of at least $\gtrsim 10\%$ are required to detect high S/N molecular absorption or Zeeman splitting. Polarization can characterize spots on resolved stars such as the Sun, but the opposite polarities in bipolar magnetic regions cancel one another in unresolved spot pairs, yielding little net polarization. As a result, most of our measurements of stellar activity come from stars much more active than the Sun (see reviews by Berdyugina, 2005; Reiners, 2012).

Initial observations of a small sample of Sun-like stars show that the fraction of magnetic energy stored in the toroidal field decreases as rotation period increases (Petit et al., 2008). Spot temperatures and area covering fractions have been inferred from molecular absorption by TiO and OH in cool starspots of Sun-like stars (Neff et al., 1995; O’Neal et al., 2004, 2001, 1996). The properties of sunspots that are most informative for constraining dynamo theory, such as the physical sizes and latitude distributions of spots, are typically highly degenerate with these observing techniques.

Transiting exoplanets enable measurements of spot sizes and positions on their host stars. During an exoplanet transit, the flux lost at any instant is proportional to the intensity of the

occulted portion of the stellar surface. Occultations of starspots by exoplanets are observed as positive flux anomalies in transit light curves, which are resolved in time by *Kepler* short-cadence photometry. Hebb et al. (2017) develop a photometric model for spotted stars which computes the observed light curve for spots of a given size and position on the stellar surface. STSP simulates times during transit – when the planet may or may not be occulting a spot – and during the rest of the planetary orbit when the stellar rotation drives photometric variability.

In this work, we will make a direct comparison between the Sun and an exoplanet host star using the occultation mapping method. We measure starspot positions and sizes using the photometric model STSP developed in Hebb et al. (2017). STSP simulates photometric time series measurements for stars with spotted surfaces and transiting planets. If we know the stellar orientation relative to the planet’s orbit, the timing and morphology of spot occultations can be transformed into precise positions of starspots with the forward-modeling approach of STSP.

The active, transiting planet host star HAT-P-11 produces many spot occultations in its *Kepler* light curve – see Figure 5.1 for examples. It is a K4 dwarf with a hot Neptune planet with orbital period $P = 4.88$ d, mass $M_p = 0.08M_J$, and radius $R_p = 0.4R_J$ (Bakos et al., 2010). Observations of the Rossiter-McLaughlin effect revealed that HAT-P-11 b likely orbits over the poles of its host star (Hirano et al., 2011; Sanchis-Ojeda & Winn, 2011; Winn et al., 2010). Therefore the transit chord of the planet sweeps a path across one stellar longitude over many latitudes. The stellar rotation period and the orbital period of the planet are nearly commensurate at 6:1, which causes transits to occur near the same six stellar longitudes (Béky et al., 2014a).

Spot crossings of HAT-P-11 in the *Kepler* observations can be used to search for active stellar latitudes. Sanchis-Ojeda & Winn (2011) and Deming et al. (2011) noted that the first few quarters of *Kepler* observations show spot occultations predominantly at two orbital phases, which they attribute to starspots which are concentrated into two active latitudes. Béky et al. (2014b) constructed a spot occultation model which they applied to HAT-P-11,

and they estimate spot contrasts and sizes.

We introduce the STSP model and solve for the inputs it requires in Section 5.2, and measure spot positions and sizes in Section 5.3. We compare the spot sizes, active latitudes, and spotted area coverage of HAT-P-11 to the Sun in Section 5.4. Finally, we discuss the properties of HAT-P-11’s activity in Section 11.7.

5.2 Starspot Modeling: Inputs for STSP

Hebb et al. (2017) developed a flux model for spotted stars with transiting planets called STSP, which leverages spot occultations during planetary transits to break the spot position degeneracies. They illustrated the mapping technique on the young solar-like star Kepler-17. The alignment of the stellar spin and planetary orbit in that system confine the spot occultation observations to one narrow band of stellar latitudes. This alignment allowed them to probe the time evolution of spots, since the same spot was occulted multiple times in consecutive transits. In the HAT-P-11 system, the near-perpendicular misalignment of the stellar spin and planetary orbit alternatively allows us to probe spot positions as a function of latitude.

We first need to determine several input parameters that will be fixed in the STSP flux model, enabling us to solve for the spot properties. In Section 5.2.1, we fit for the orbital properties of the planet from the transit light curves. We solve for the initial spot positions with a simplified spot model in Sections 5.2.2-5.2.3, which enables us to measure the approximate stellar inclination in Section 5.2.4, re-evaluate the spin-orbit obliquity in Section 5.2.5, and to test our assumptions about spot contrasts in Section 10.2.4. With the approximate starspot positions derived from the simplified model fits, we explore the spot latitude-longitude-radius parameter space with the full STSP forward model in Section 5.3.

STSP is a pure C code for calculating the variations in flux of a star due to spots, both in- and out-of-transit (Hebb et al., 2017). We use STSP because its prescription for the shapes of spot occultations are more realistic than the simple model in Sections 5.2.2-5.2.3, and the correlations between MCMC parameters allow us to properly explore the degeneracies

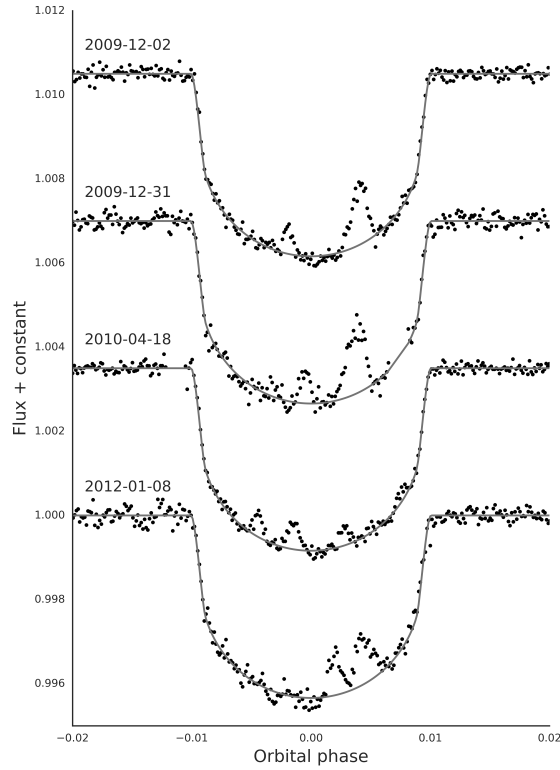


Figure 5.1: Typical transit light curves of HAT-P-11 b. The points are *Kepler* fluxes, the curves are the best-fit transit model (Mandel & Agol, 2002). The positive anomalies during transit are occultations of starspots by the planet.

between starspot positions and sizes. STSP can also solve for the properties of spots driving out-of-transit flux modulations, however in this work we consider only the spots detected in-transit, since the spot occultations yield tighter constraints on the spot properties than the out-of-transit flux variations.

5.2.1 Orbital Properties of HAT-P-11 b

To study the signal imparted by starspots on the transit light curve residuals, we must first remove the transit of HAT-P-11b from each light curve. It is non-trivial to derive the transit parameters for HAT-P-11 b since nearly all of the transits appear to be affected by starspots

to some extent. We acknowledge that the most robust measurement of the transit properties would be obtained by fitting the light curve simultaneously for the transit and the occulted starspots, but the number of parameters in that fit is prohibitively large. Therefore, we opt to fit for the transit parameters on a subset of transits with minimal starspot anomalies, and to fix those transit parameters later when we fit for the starspot properties. In the next two sections, we outline the procedure for finding the orbital properties of HAT-P-11 b in spite of the abundant starspots.

Light Curve Normalization

For the transit depths to be consistent in each transit light curve, an appropriate normalization for each transit must be chosen. Transit light curves are often normalized by the flux immediately before ingress and after egress. However, each transit light curve will have different relative depths if the total flux of the star is varying due to unocculted starspots (Carter et al., 2011; Csizmadia et al., 2013; Czesla et al., 2009). For example, if unocculted starspots dim the host star’s flux by a factor $0 < \epsilon < 1$, the flux lost during transit ΔF is unaffected, but the total flux ϵF is smaller, so the relative depth $\delta = \Delta F / (\epsilon F)$ is larger for the spotted star than for the unspotted star. The transits of HAT-P-11 likely have many occulted and unocculted starspots, and the transit depths would vary in time if simple out-of-transit flux normalization was used. In this section, we outline a normalization procedure that ideally yields transits of constant depth for stars with unocculted starspots, so that we can use a single depth parameter for all transits which corresponds to the square of the ratio of radii, $\delta \propto (R_p/R_s)^2$.

We assume that the peak flux of HAT-P-11 over a few stellar rotations is close to the unobscured brightness of the unspotted star¹. We then normalize all transit fluxes by: (1) fitting and subtracting a second-order polynomial to the out-of-transit Simple Aperture Photometry (SAP) fluxes near each transit; (2) adding the peak quarterly flux to each

¹ This assumption is revisited in the discussion in Section 5.4.4

Parameter	Measurement
Orbital period [d]	$4.88780258 \pm 0.00000017$
Mid-transit [JD]	$2454605.89146 \pm 0.000020$
Depth $\approx \left(\frac{R_p}{R_*}\right)^2$	0.00340 ± 0.00002
Duration, T_{14} [d]	0.0980 ± 0.0001
b	$0.141^{+0.052}_{-0.080}$
$q_1 = (u_1 + u_2)^2$	0.48 ± 0.01
$q_2 = \frac{u_1}{2(u_1 + u_2)}$	0.46 ± 0.01

Table 5.1: Transit light curve parameters for HAT-P-11 from the ten transits in Figure 5.2. T_{14} is the duration between first and fourth contact; q_1 and q_2 are the limb-darkening parameters of Kipping (2013); u_1 and u_2 are the standard quadratic limb-darkening parameters. These parameters are fixed in the starspot fits.

polynomial detrended transit; and (3) dividing each transit by the peak flux of each quarter. The subtraction by a second-order polynomial removes trends in flux due to stellar rotation, and the addition and division by the peak flux normalizes the out-of-transit fluxes to near-unity, while keeping the transit depths consistent between transits (Hebb et al., 2017). We must use the SAP flux because it is the unnormalized flux in units of electrons per second, rather than the PDCSAP flux which is already normalized.

“Spotless” Transits

We select the ten transits with the fewest measurable starspot crossings to fit for the transit parameters. To identify the transits least perturbed by starspots, we fit a Mandel & Agol (2002) transit light curve to each of the 205 normalized short-cadence transits in the full *Kepler* light curve. We hold the light curve parameters fixed, except for the depth which is allowed to vary, and optimize the light curve parameters using Levenburg-Marquardt least-

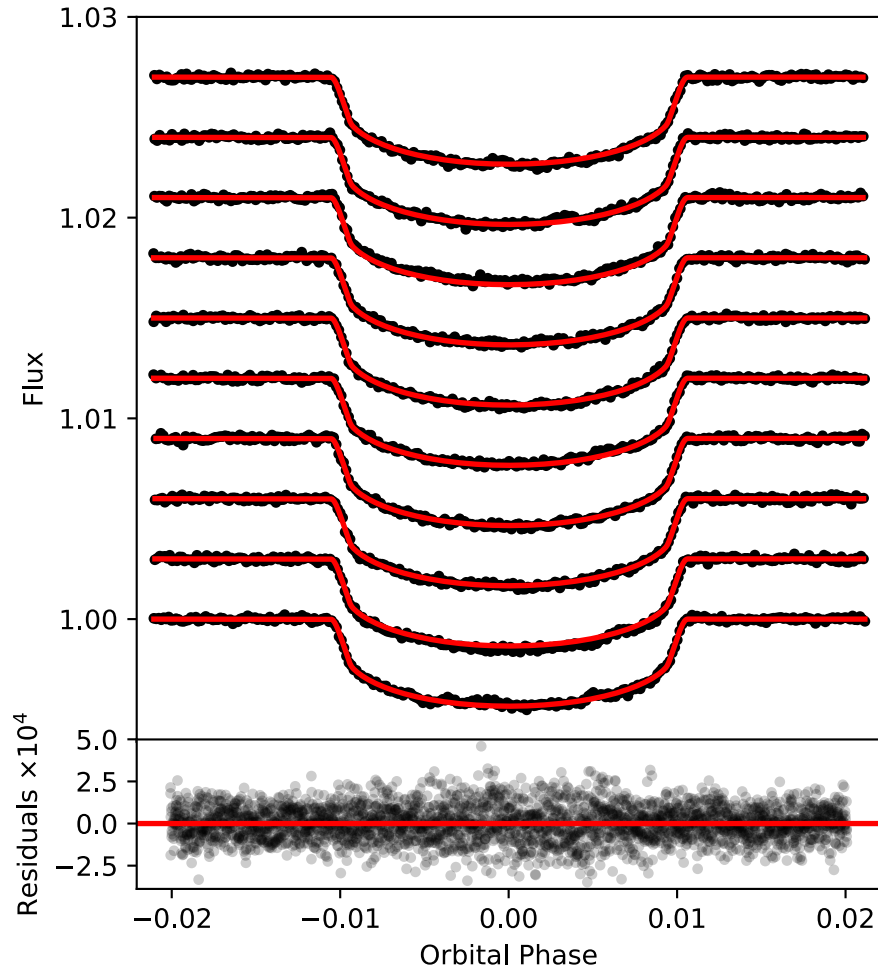


Figure 5.2: The ten transits least affected by starspot crossings, which we fit for the planet orbital parameters listed in Table 5.1.

squares minimization. We allow depth to vary because fits to transits with spot occultations (positive flux anomalies) will be biased towards smaller transit depths and higher χ^2 . We then select the ten transits with the smallest χ^2 . There are no significant starspot crossings visible by eye after this selection process, see Figure 5.2.

We fit the ten transits for the orbital parameters and the stellar limb-darkening coefficients. We compute transit light curves with the `batman` package (Kreidberg, 2015), and sample the parameter posterior distributions with the affine-invariant Markov Chain Monte Carlo (MCMC) package `emcee` (Foreman-Mackey et al., 2013). The best-fit transit parameters are listed in Table 5.1.

The maximum likelihood planet-to-star radius ratio is $R_p/R_\star = 0.058 \pm 0.004$. This measurement is in agreement with Deming et al. (2011) (0.0589 ± 0.0002), Southworth (2011) (0.058 ± 0.001), and Bakos et al. (2010) (0.0576 ± 0.0009).

Measurements of the mean stellar density of HAT-P-11 via asteroseismology and transit light curves have been reported by Christensen-Dalsgaard et al. (2010) and Southworth (2011), respectively. Using our transit parameters for HAT-P-11 b, we constrain the mean stellar density $\rho_s = 1.81 \pm 0.04 \rho_\odot$, which is similar to the preliminary asteroseismic measurement of $\rho_s = 1.7846 \pm 0.0006 \rho_\odot$, and smaller than the previous photometric measurement, $2.415 \pm 0.097 \rho_\odot$.

5.2.2 Spot Position Initial Conditions

We observe starspot occultations as positive flux anomalies during transit events. The amplitudes, durations and timing of the spot occultations constrain the spot locations and radii. If the starspot is a uniformly dark circular region on the star, and the planet passes over the edge of the spot in a grazing occultation, the resulting flux anomaly is an inverted “v” shape, analogous to the shape of an inverted eclipsing binary light curve. If the planet completely occults the spot or the spot completely circumscribes the planet, the resulting flux anomaly is an inverted “u” shape, like an inverted exoplanet transit event. There are many more grazing spot occultations (“v”-shaped, roughly approximated by Gaussians) than complete

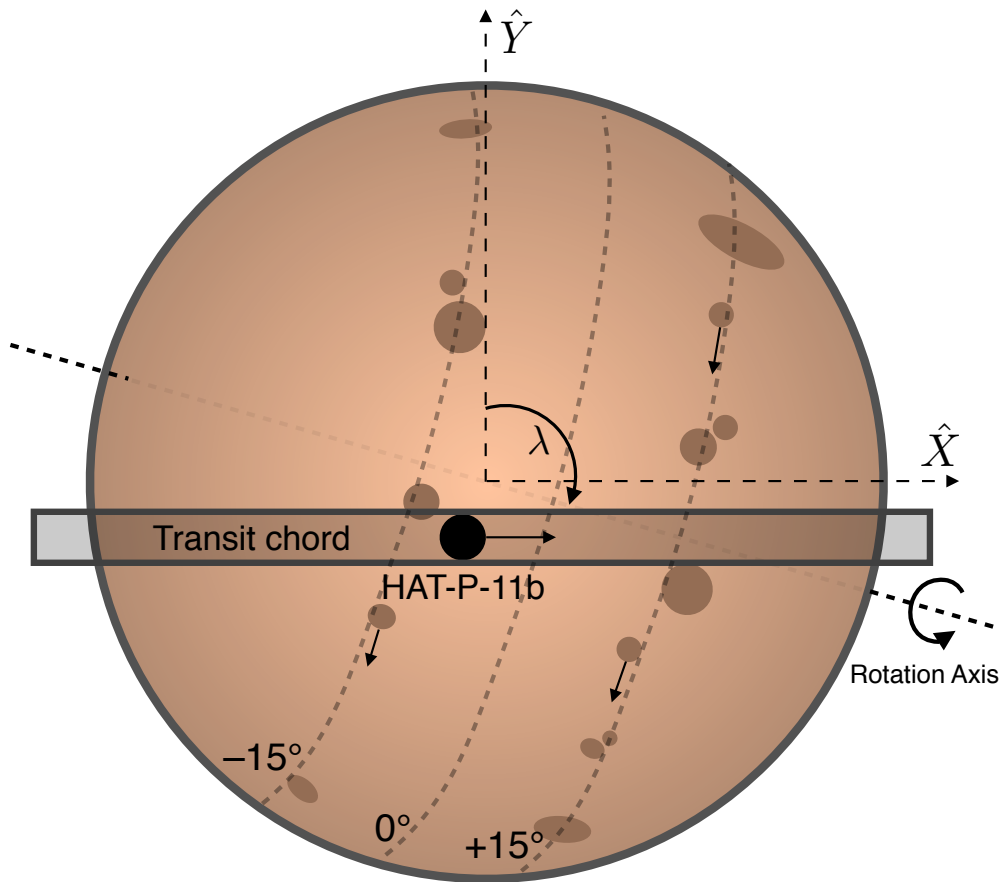


Figure 5.3: The HAT-P-11 system in the observer-oriented coordinate system of Fabrycky & Winn (2009), roughly to scale. The planet’s orbit is misaligned from the stellar rotation axis by the projected spin-orbit angle $\lambda = 106^\circ$ (Sanchis-Ojeda & Winn, 2011), and the north rotational pole of the star is inclined away from the observer by $i_s = 100^\circ$.

spot occultations. In most *Kepler* transits of HAT-P-11, there are between one and four spot occultations with amplitudes more than a few times the noise.

It is notoriously difficult to measure starspot positions robustly, because they are described by several degenerate quantities. For example, the occultation of a small, very dark spot is often degenerate with a larger spot of less extreme intensity contrast. These degeneracies can be broken for host stars of transiting exoplanets like HAT-P-11. The orientation of the planet’s orbit is measured from the transit light curve, and the orbital phase of the planet at each time maps to a position on the projected stellar surface that is being occulted. We can measure the orientation of the star with two angles – the spin-orbit angle which is measured via the Rossiter-McLaughlin effect, and the stellar inclination. We need to assume a stellar inclination, since the spectroscopic $v \sin i$ is consistent with zero (Bakos et al., 2010) due to this star’s long rotation period. Sanchis-Ojeda & Winn (2011) found that active latitudes are evident in the spot positions recovered from the *Kepler* photometry, and they measure the stellar inclination by assuming that the active latitudes are symmetric with respect to the stellar equator. Using the same technique, we can then map the flux measured at a given time to the brightness of the stellar surface at a particular latitude and longitude. Then when the planet occults a dark starspot, the timing and shape of the positive flux anomaly in the transit light curve can be transformed into the position and radius of the starspot.

Figure 5.3 depicts the orientation of the system. HAT-P-11 b’s orbit normal is nearly perpendicular to the host star’s spin – in other words, it nearly orbits over the host star’s poles. Thus each transit cuts a chord across the stellar surface from pole to pole, across most latitudes and over a narrow range in longitude. The transit chords start near the southern rotational pole of the star in the eastern hemisphere, pass over the sub-observer meridian in the northern hemisphere, and end to the northwest of where the chord began. The most complete latitude coverage is from the equator to $\pm 50^\circ$, with no transits occulting near the poles. The north rotational pole of the star is tilted into the sky-plane by $\sim 10^\circ$.

We cannot say definitively whether or not the starspots of HAT-P-11 are occulted in

consecutive transits. Since the stellar rotation period is roughly $P = 29.2$ d and the orbital period is $P = 4.8878$ days, the planet occults the same longitude once per stellar rotation, which appears to be longer than the lifetime of spots on HAT-P-11 (Sanchis-Ojeda & Winn, 2011) and similar to the lifetimes of sunspots (Solanki, 2003). The search for repeated spot occultations is made more difficult by the fact that there are active latitudes on the star, so one would expect to find spot occultations at similar orbital phases in each transit. We therefore assume that each spot occultation belongs to only one spot, and fit each transit light curve independently.

Starspot photometry models are difficult to optimize. The starspot occultations impart only small anomalies to a few flux measurements per transit, so the region of spot latitude-longitude-radius space that produces an improvement in likelihood is often very small and computationally expensive to find with a blind search. Preliminary experiments by Hebb et al. (2017) showed that unseeded MCMC fits required very long integration times to fully explore the parameter space before converging into likelihood maxima. However, the spot occultations of HAT-P-11 have quite high signal-to-noise owing to the star’s brightness ($K_p = 9.17$), which makes them relatively simple to locate using peak-finding algorithms. We therefore devise a heuristic spot occultation model in Section 5.2.3, which provides us with sensible initial conditions for the full STSP forward model, which we discuss in Section 5.3.

5.2.3 Initial, Heuristic Spot Occultation Model

We need initial guesses for spot positions in stellar latitude and longitude, and the stellar inclination angle i_s to seed our STSP model. We find spot occultations in the transits in a two-step process. First, we subtract the light curve by the transit model from Section 5.2.1, which produces residuals near zero except near spot occultations. We then smooth the flux residuals by convolving them with a Gaussian kernel, and apply a local-maximum peak-finding algorithm to find the times and amplitudes of spot occultations in the residuals. We exclude any peaks detected within 5% of the transit duration of ingress or egress, since we are not able to measure reliable spot properties for these highly foreshortened spots near the

stellar limb.

We approximate the residuals of each transit as the sum of Gaussian perturbations, with one Gaussian per spot. We marginalize over the Gaussian amplitude, mid-occultation time and width using the affine-invariant MCMC method. We assign a positive prior to the amplitude to search only for occultations of dark spots, and a flat prior to the mid-spot occultation time to exclude spots occulted within 5% of the transit duration from ingress or egress. We apply a flat logarithmic prior to the spot-occultation width σ to include only real occultations of small spots. We set priors on the spot occultation width to limit our spots to the regime $1.5 < \sigma < 8.6$ minutes – the lower limit prevents the model from choosing very narrow Gaussians that affect single fluxes, which are typically outliers. The upper limit of the prior prevents the model from choosing very long duration spot occultations, which we do not observe in the *Kepler* data. We also apply a significance cut which excludes any spot occultations with significance $\Delta\text{BIC} < 20$. This yielded 294 spots, on 138 of the 205 complete transits in the full *Kepler* light curve.

We also ran a null test to verify that false-positives are not being incorrectly identified as spots. We offset the mid-transit time by one quarter of an orbital phase and set $R_p/R_\star = 0$ to search for false-positive spot-occultations in regions of the light curve where no transit is occurring. If there was significant correlated noise in the HAT-P-11 light curve with amplitudes and time-scales similar to the spot-occultation signals, those fluctuations would be detected as candidate spot occultations. No such false-positive spot occultations were detected by the peak-finding algorithm. We therefore conclude that correlated noise is not a significant source of false-positive detections of spot occultations on the scales relevant to this work.

5.2.4 Stellar Inclination

The starspot positions that we extract depend on the stellar orientation that we assume when computing the spot positions. Two angles define the orientation of the stellar rotation axis: (1) the stellar inclination i_s , which is the angle between the observer, the center of

the star, and the rotation axis of the star; and (2) the projected spin-orbit angle λ , which is the tilt of the stellar rotation axis on the sky-plane with respect to the orbit normal of the planet. See Figure 1 of Fabrycky & Winn (2009) for a graphical representation of these angles.

The projected spin-orbit angle λ has been constrained with the Rossiter-McLaughlin effect (Hirano et al., 2011; Winn et al., 2010), but the stellar inclination i_s is more difficult to measure. In principle, it can be calculated for systems with known stellar rotation periods and spectroscopic rotational velocities ($v \sin i_s$), but Bakos et al. (2010) found only a weak constraint on the projected rotational velocity. Using a different approach, Sanchis-Ojeda & Winn (2011) noted that the distribution of starspots on HAT-P-11 resembled active latitudes like those of the Sun. The authors fitted the spot latitude distribution to solve for the stellar inclination by requiring the active latitudes to be symmetric across the stellar equator. They discussed two possible stellar orientations that explain the apparent active latitudes which they called the “pole-on” and “equator-on” solutions. In this paper, we reject the “pole-on” solution, because high-latitude spots viewed from a pole-on orientation would not move into and out of view sufficiently to produce the observed $\sim 3\%$ rotational variability. We adopt the “equator-on” solution hereafter.

Sanchis-Ojeda & Winn (2011) estimated the stellar inclination with observations from *Kepler* Quarters 0-2. Here, we carry out a similar analysis with the complete *Kepler* light curve from Quarters 0-17, which yields a stronger constraint on the stellar inclination. We proceed by constructing a probabilistic model for the distribution of the spot latitudes. We model the probability distribution of spots as a function of latitude using a Gaussian mixture model $p(\ell)$, which is the sum of two normal distributions with mean latitudes m_1 and m_2 , standard deviation σ , and relative amplitudes a and $(1 - a)$,

$$p(\ell) = a \exp\left(-\frac{(\ell - m_1)^2}{2\sigma^2}\right) + (1 - a) \exp\left(-\frac{(\ell - m_2)^2}{2\sigma^2}\right). \quad (5.1)$$

The time-dependent mean latitudes m_1 and m_2 are

$$m_1(t) = \bar{\ell} + \ell' t + \Delta i_s \quad (5.2)$$

$$m_2(t) = -(\bar{\ell} + \ell' t) + \Delta i_s \quad (5.3)$$

where the mean latitude is $\pm\bar{\ell}$,² and Δi_s is the difference between the stellar inclination measured by the probabilistic model and the stellar inclination published in Sanchis-Ojeda & Winn (2011).

We allow the mean latitudes m_1 and m_2 to vary in time since the Sun’s active latitudes migrate from high to low latitudes throughout the solar activity cycle. The parameter ℓ' therefore tests whether or not we can detect evolution in the mean spot latitudes throughout the four years of the *Kepler* mission. The Sun’s activity cycle is ~ 11 years long, and significant migration in mean spot latitude can be detected over four year intervals. If the activity cycle of HAT-P-11 is long compared to four years, the slower latitude evolution could be reflected in small values of ℓ' .

We force the mean latitudes to be symmetric about the stellar equator, and allow the northern and southern hemisphere distributions to have independent amplitudes. We assume the distribution is symmetric about the equator because: (1) on few-year time-scales the mean latitudes of the solar active latitudes are approximately symmetric; and (2) we have no more robust measurement of the stellar inclination to assert that the active latitudes are asymmetric.

We maximize the likelihood of the observed distribution of spot latitudes from our simple model for values of a , σ , $\bar{\ell}$, ℓ' and Δi_s with the MCMC package **emcee** (Foreman-Mackey et al., 2013). We find the maximum-likelihood slope of the mean active latitudes is $\ell' = 0.9 \pm 0.8$ degrees per year, consistent with no latitude evolution. This may indicate that the activity cycle of HAT-P-11 is long compared to four years. Since there is no evidence for time-

² We use the symbol ℓ to represent stellar latitudes, rather than λ as is used in the sunspot literature, to avoid confusion with the projected spin-orbit angle, which by the convention of Ohta et al. (2005) is also called λ .

evolution of the active latitudes, we fix $\ell' = 0$ and fit the model again.

The maximum-likelihood solution for the stellar inclination is $i_s = 100 \pm 2^\circ$, following the angle definition in Fabrycky & Winn (2009) (i_s is the angle between the observer’s line of sight, the center of the star, and the stellar rotation axis), which we adopt as fixed throughout the rest of this work. This stellar inclination angle is consistent with the inclination reported in Sanchis-Ojeda & Winn (2011), though the values differ due to their choice of coordinate system. We will revisit the distribution of spot latitudes with solutions from the more detailed spot model in Section 5.4.2.

5.2.5 *Spin-orbit misalignment*

We can measure the obliquity – or the de-projected spin-orbit misalignment – of HAT-P-11 with our revised measurements of i_o and i_s . We solve Eqn. 9 of Fabrycky & Winn (2009) for the obliquity ψ

$$\cos \psi = \sin i_s \cos \lambda \sin i_o + \cos i_s \cos i_o, \quad (5.4)$$

and find $\psi \approx 106^\circ$, consistent with the obliquity reported by Sanchis-Ojeda & Winn (2011). This provides another check on our coordinate system which follows the definitions of Fabrycky & Winn (2009) and differs from Sanchis-Ojeda & Winn (2011), but yields the same obliquity angle.

5.2.6 *Spot contrasts*

In this work, STSP approximates starspots as circular features with homogeneous contrast. We can define the spot intensity contrast relative to the local photosphere c as

$$c = 1 - I_{spot}/I_{phot} \quad (5.5)$$

where I_{spot} is the mean intensity inside the dark spot, I_{phot} is the intensity of the local photosphere, and $I_{spot} < I_{phot}$. Spots with temperatures and intensities similar to the local photosphere $I_{spot} \approx I_{phot}$ are “low contrast”, i.e. $c \rightarrow 0$, and spots with extreme temperature

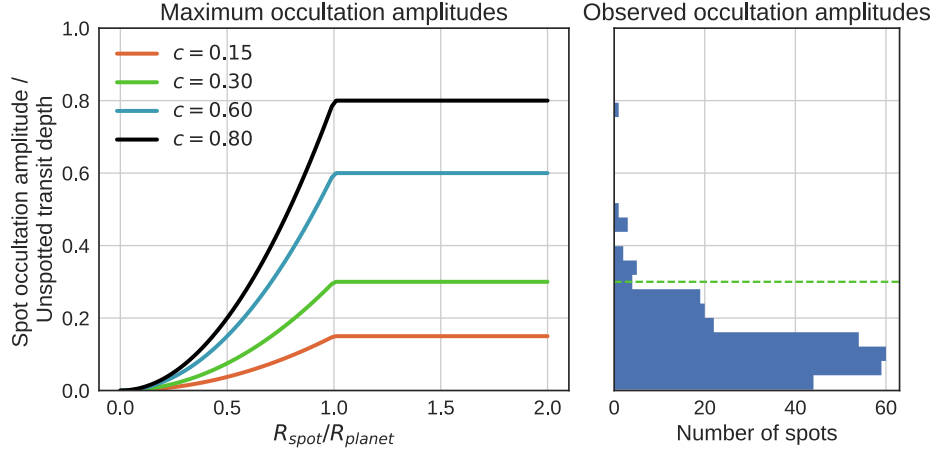


Figure 5.4: *Left*: amplitudes of positive flux anomalies during spot occultations, normalized to the unspotted transit depth, as a function of the spot size and contrast. *Right*: observed spot occultation amplitudes of HAT-P-11. 95% of the spot occultations have normalized amplitudes ≤ 0.3 below the green dashed line, as one would expect from spots with the mean solar contrast $c = 0.3$. The largest observed spot-occultation amplitude requires a spot contrast $c \geq 0.8$ – similar to the spot contrast of sunspot umbra. Since most other spots are consistent with the mean solar spot contrast $c = 0.3$, we adopt the solar contrast value for the spots of HAT-P-11.

differences $I_{spot} \ll I_{phot}$ are “high contrast” and $c \rightarrow 1$. High-resolution studies of sunspots show that the spot darkness correlates with magnetic field strength in the vertical component (Keppens & Martinez Pillet, 1996; Leonard & Choudhary, 2008).

Sunspots have complicated substructures each with their own contrast, such as the dark umbra and less dark penumbra. We cannot typically resolve such substructure in occultation photometry, so we chose to adopt the area-weighted contrast of the penumbra and umbra as the contrast for the entire spot. We can approximate sunspots as homogeneous circular features if we average over the penumbra and umbra, which have contrasts $c_{umbra} \sim 0.5 - 0.8$ and $c_{penumbra} \sim 0.15 - 0.25$. The mean area encompassed by the penumbra is roughly four times larger than the umbral area (Solanki, 2003). Adopting $c_{umbra} = 0.65$ and $c_{penumbra} = 0.2$, the area-weighted mean spot contrast of sunspots is $c_{total} = 0.3$.

We can compare solar spot contrasts to constraints on the spot contrasts of HAT-P-11 from *Kepler* photometry. Spot contrasts are constrained by the amplitudes of spot occultations events. The difference in flux during a transit with a spot occultation and a transit without a spot occultation is set by the spot contrast, and the projected size of the spot compared to the planet. We derive spot occultation amplitudes as a function of spot radius and contrast in Appendix 5.5.1.

In Figure 10.2 we compare the spot occultation amplitudes normalized by the flux of the unspotted star at each time during the transit, for a variety of spot contrasts and spot sizes with the observed spot amplitudes. As the spot contrast c increases and the spot becomes darker, the amplitude of the spot occultation increases for spots of any radius. For spots larger than the planet, the contrast controls the maximum occultation amplitude. Therefore the maximum observed spot occultation amplitude sets a lower bound for the maximum spot contrast. The spot occultation with the largest normalized amplitude ~ 0.80 requires a spot contrast of $c_{min} \geq 0.8$, which is similar to the contrast of sunspot umbra. 95% of the spot amplitudes could be produced by occultations of spots with the area-weighted mean solar spot contrast $c = 0.3$, so we adopt $c = 0.3$ as our spot contrast in fits with STSP model, since it is consistent with both the spots of the Sun and HAT-P-11.

5.3 Detailed STSP Spot Occultation Model

The STSP model is constructed as follows (see Hebb et al., 2017, for more details). The star is represented by a series of discrete concentric circles with intensities decreasing radially outward to approximate limb darkening. Spots on the star are represented as non-overlapping circles that are darker than the local photosphere, which follow the stellar surface in fixed-body rotation. Each spot is defined by four parameters: radius, latitude, longitude, and intensity contrast relative to the photosphere. The planet is represented by an opaque circle, and the relative flux received by the observer is calculated throughout the orbit of the planet. We marginalize over the spot position and radius parameters.

We fit for spot properties with STSP using the number of spots and initial positions given by the simple model in Section 5.2.3, which narrows the sample to 138 transits with highly significant spot occultations. We approximate stellar limb darkening with 40 concentric circles. We fix the spot contrast to $c = 0.3$, which we justified in Section 10.2.4.

We run the affine-invariant MCMC with 300 chains and no priors for each transit, until the parameter posterior distributions are stationary (Goodman & Weare, 2010). One advantage of the pure C implementation of STSP is that it is naturally portable and scalable for distributed computing. We run STSP for each of the 138 transits independently on the Extreme Science and Engineering Discovery Environment (XSEDE) Open Science Grid (Pordes et al., 2007; Towns et al., 2014).

5.3.1 Model parameter degeneracies

For most transit light curves with spot occultations, there exists a series of spot positions and radii which produce equally good fits to the observations. There are two main degeneracies in our choice of spot model which are critical to understanding the fit results of HAT-P-11; we will call these degeneracies: (1) the transit chord degeneracy and (2) the radius-position degeneracy.

The transit chord degeneracy is a simple consequence of symmetry. For any small spot

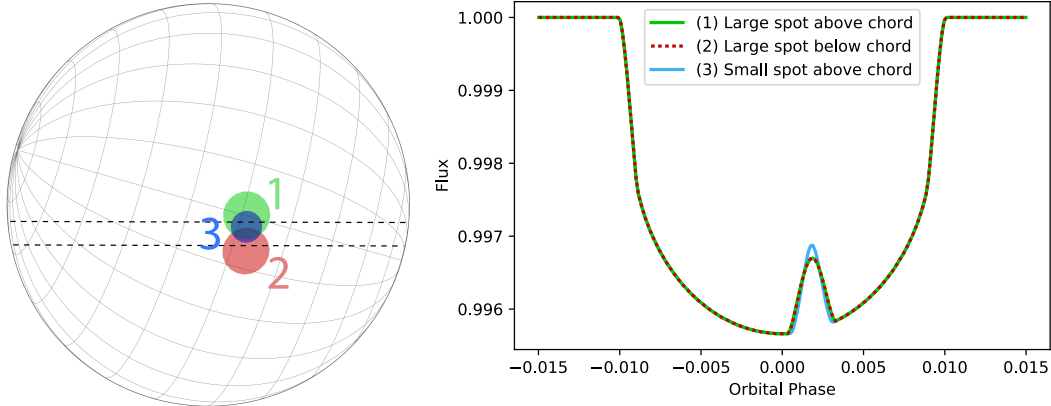


Figure 5.5: *Left*: Map of a few hypothetical spots on HAT-P-11 which would produce similar anomalies in the transit light curve. The transit chord is bounded by the black dashed lines, the red latitudinal grid mark is the stellar equator – the stellar rotational pole is tilted into the page and on the right. In this diagram, the planet transits from left to right, from near opposite the rotational pole to near the rotational pole. The $(R_{spot}/R_{star}, \text{latitude}, \text{longitude})$ parameters for spot 1 (green), 2 (red), and 3 (blue) are: $(0.12, 1.4^\circ, 359.8^\circ)$, $(0.12, 4.3^\circ, 9.8^\circ)$, and $(0.08, 2.3^\circ, 2.9^\circ)$, respectively. *Right*: STSP model transits for each spot in the map above. With *Kepler*'s flux precision for HAT-P-11 (~ 80 ppm), these three models would be indistinguishable.

placed near the transit chord, a spot of the same radius could be placed on the opposite side of the transit chord (at the same distance from the transit chord) to create an identical bump in the light curve. See for example spots 1 and 2 in Figure 5.5.

The transit chord degeneracy may be broken in two scenarios: (1) for some star-planet systems with large impact parameters, the spots would be significantly more foreshortened on one side of the transit chord than the other; or (2) large spots that subtend large angles from the center of the stellar disk to the limb will be more foreshortened near the limb than at disk center, producing asymmetries between spot-crossing ingress and egress. HAT-P-11 has impact parameter $b = 0.141$ so spots projected onto either side of the transit chord will appear roughly symmetric, and therefore the spot position solutions most often come in pairs that are symmetric about the transit chord. However, there are a few exceptionally large spots that give rise to asymmetric spot crossings, which allows the model to select a spot position on only one side of the transit chord.

The radius-position degeneracy arises from trade-off in spot occultation amplitude between spot size and position. A large spot which grazes the edge of the transit chord will produce a bump in the transit light curve similar to a much smaller spot laying within the transit chord. See for example spots 1 and 3 in Figure 5.5.

The radius-position degeneracy can be broken with observations at infinite time resolution and flux precision. In the *Kepler* observations of HAT-P-11, the one minute cadence and the single measurement uncertainty $\sigma_{\Delta F/F} \sim 80$ ppm prevent us from distinguishing between small spots near to the transit chord and somewhat larger spots farther from the transit chord.

More details about STSP model parameter degeneracies are discussed in Hebb et al. (2017). Examples of STSP fits to the HAT-P-11 light curves and the effects of these degeneracies are discussed in detail in the following section.

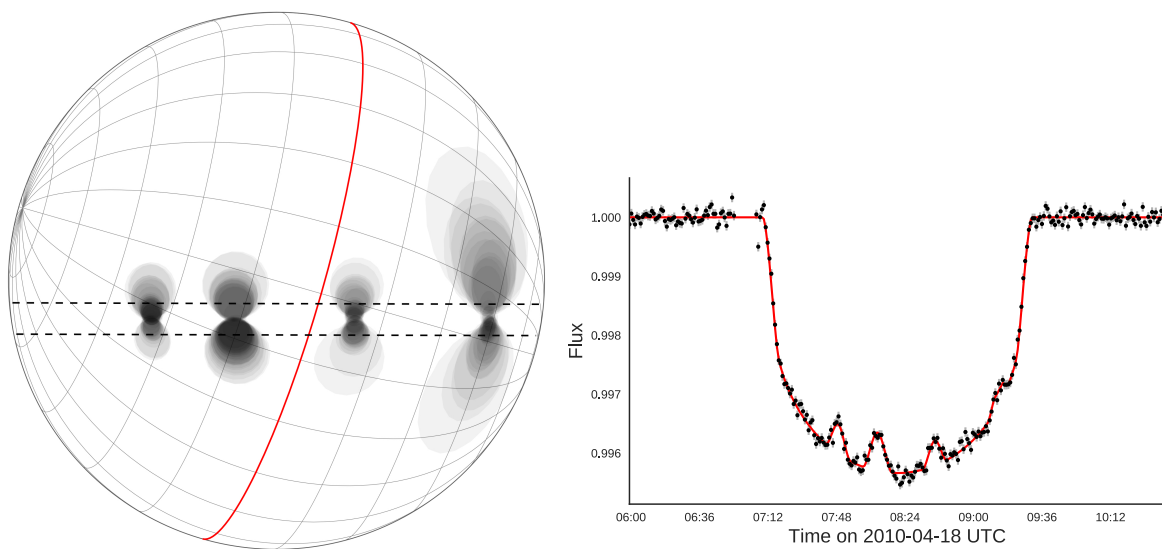


Figure 5.6: *Right:* an example transit light curve of HAT-P-11 b (black points) with the maximum likelihood STSP model (red curve). *Left:* a few random draws from the posterior samples for the spot positions and radii. These four spots are highlighted in blue on the spot map in Figure 5.9.

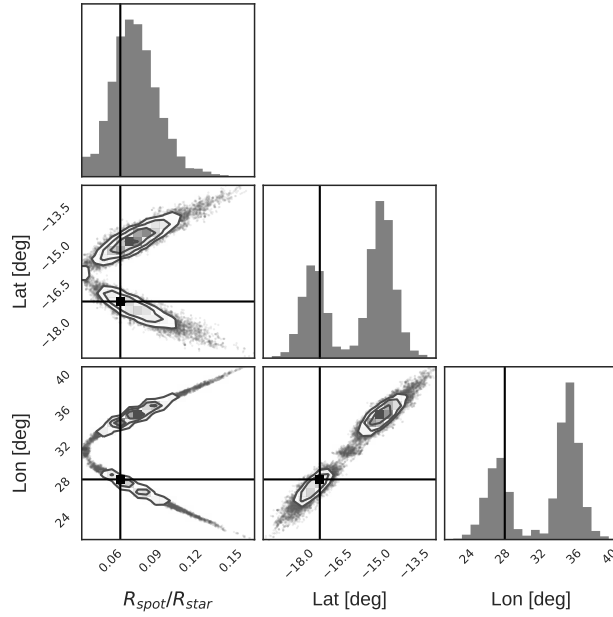


Figure 5.7: Correlations between posterior samples for latitude, longitude and spot radius for the spot second from the left in the graphic in Figure 5.6. The vertical/horizontal black lines mark the maximum likelihood values from the Markov chains. For the analysis of the spot latitude and radius distributions, we use the maximum likelihood values to compute the spotted area in the transit chord, for example, which selects one of the two possible groups of solutions for each spot. Note that the model constrains the minimum spot radius for this spot despite the position-radius degeneracy, which is a result of fixing the spot contrast.

5.3.2 Examples of degeneracies in results

We can begin to understand the spot radius-position degeneracy which affects the radius distribution by inspecting the transit on April 18, 2010; see Figures 5.6 and 5.7. There are four spot occultations visible in the transit light curve, so we seed the STSP model with four spots, and optimize for the latitude, longitude and radius of each spot with fixed flux contrast ($c = 0.3$, as defined in Equation 9.4). The posterior samples for latitude, longitude and radius of each spot cluster into two groups of solutions – one on each side of the transit chord. In some spot occultations, asymmetry in the photometry produces a preferred solution on one side of the transit chord. In the case of the spot posteriors shown in Figure 5.7 (see also the light curve and spot geometry in Figure 5.6), the latitude and longitude have bimodal solutions. Therefore, rather than adopting the mean of these bimodal posteriors as the best solution, we use the parameter values at the maximum likelihood step of the MCMC chains to study spot radii (and latitudes).

For a fixed spot contrast, the radius-position degeneracy biases us towards larger radii. The asymmetry towards large radii can be seen in the bottom left plot of Figure 5.7. If the spot contrast cannot vary, there exists a minimum spot radius which is capable of reproducing the observed occultation amplitude for a direct spot occultation (impact parameter $b = 0$). Any indirect or grazing occultations ($b \neq 0$) would require a larger spot to produce the same occultation amplitude, producing an abundance of possible solutions with large spots, centered farther away from the transit chord. For this reason, we do not assert that any spots on HAT-P-11 are certainly larger than the largest sunspot, though the maximum likelihood solutions suggest such spots exist (more on spot radii in Section 5.4.3).

Figure 5.8 shows an example light curve model and a few draws from the spot parameter posteriors for the transit on December 31, 2009 UTC. The model of the second spot occultation in this transit has a flat top, and an amplitude similar to $\Delta F/\delta \sim c = 0.3$, which implies that the spot was occulted with a small impact parameter, and that the spot radius was larger than the planet radius. The geometry of this eclipse parallels planetary transits

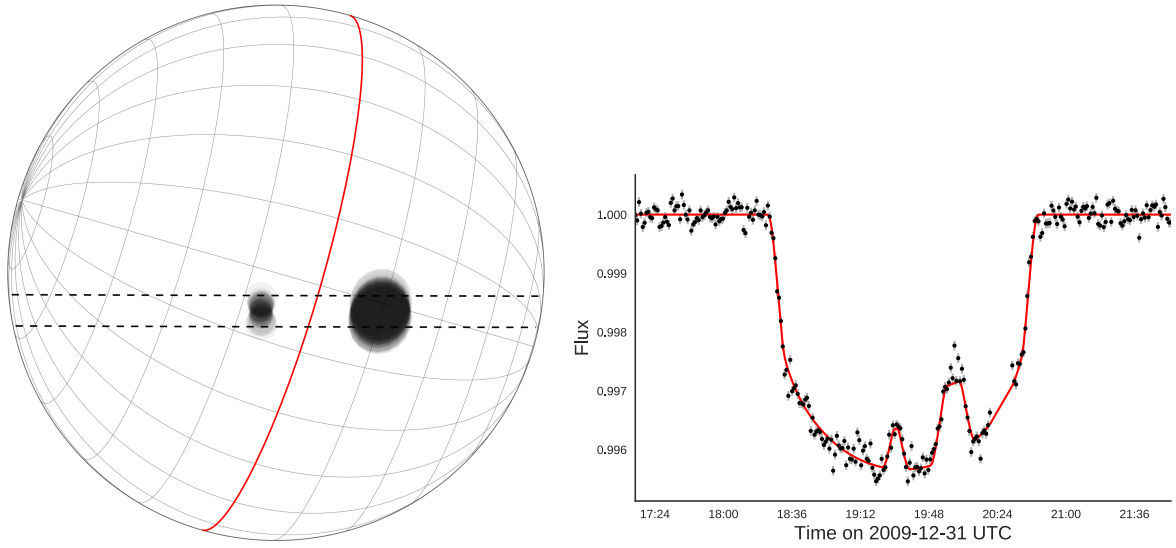


Figure 5.8: *Right:* an example transit light curve of HAT-P-11 b (black points) with the maximum likelihood *STSP* model (red curve). *Left:* a few random draws from the posterior samples for the spot positions and radii. The transit chord is bounded by the black dashed lines, the red latitudinal grid mark is the stellar equator – the stellar rotational pole is tilted into the page and on the right. In this diagram, the planet transits from left to right, from near opposite the rotational pole to near the rotational pole. The grid lines are separated by 15° , so the active latitudes appear near the grid lines on either side of the equator. Note that the flat-topped spot occultation model light curve corresponds to a spot that must appear to be wider than the transit chord – setting a constraint on the minimum radius of the spot. The observed fluxes are higher than the model near the mid-occultation time, which is suggestive of a higher spot contrast near the center of the spot. These two spots are highlighted in red on the spot map in Figure 5.9. In physical units, these spots have radii of 22400^{+4000}_{-300} and 63700^{+3000}_{-200} km.

with negligible limb-darkening, which produce a “u”-shaped eclipse with a flat bottom. We note that the *Kepler* fluxes at the peak of the second spot occultation have a net positive scatter. This could imply that a more extreme spot contrast is justified at the center of the spot ($c < 0.3$), where one might expect the umbra to be. The duration of the flat-topped spot occultation is proportional to the diameter of the spot, so the position and size of this spot are relatively well-constrained by the photometry. This is reflected by the uniformity of the posterior samples of the second spot in Figure 5.8 compared to the earlier grazing spot occultation, which is less constrained. The inverted “v”-shape of the first spot occultation implies that the planet either grazed the spot at high impact parameter – similar to planetary transits or binary eclipses with high impact parameters, which produce “v”-shaped eclipses – or that the spot is similar in size to the size of the planet. As you can see in the samples from the posteriors on the map in Figure 5.8, the model tends towards a spot centered in the transit chord, slightly smaller than the planet.

5.4 STSP Results

5.4.1 Spot Map of HAT-P-11

We map the maximum-likelihood starspot positions for all 138 transits in Figure 5.9. The circles represent the positions and sizes of the spots inferred with STSP. The shading of the map corresponds to the number of times the center of the planet occulted each location on the star, which is a proxy for completeness of the spot map – darker regions were occulted more often. We choose to plot the maximum-likelihood spot positions and radii rather than the means of the posterior samples, because degeneracies between the model parameters can produce bimodal posterior distributions (see Section 5.3 for discussion on model degeneracies).

The spin-orbit misalignment and spin-orbit commensurability of this system lead to highly inhomogeneous sampling in longitude, so an investigation into the true spot longitude distribution is beyond the scope of this work. However, asymmetries in spot latitude

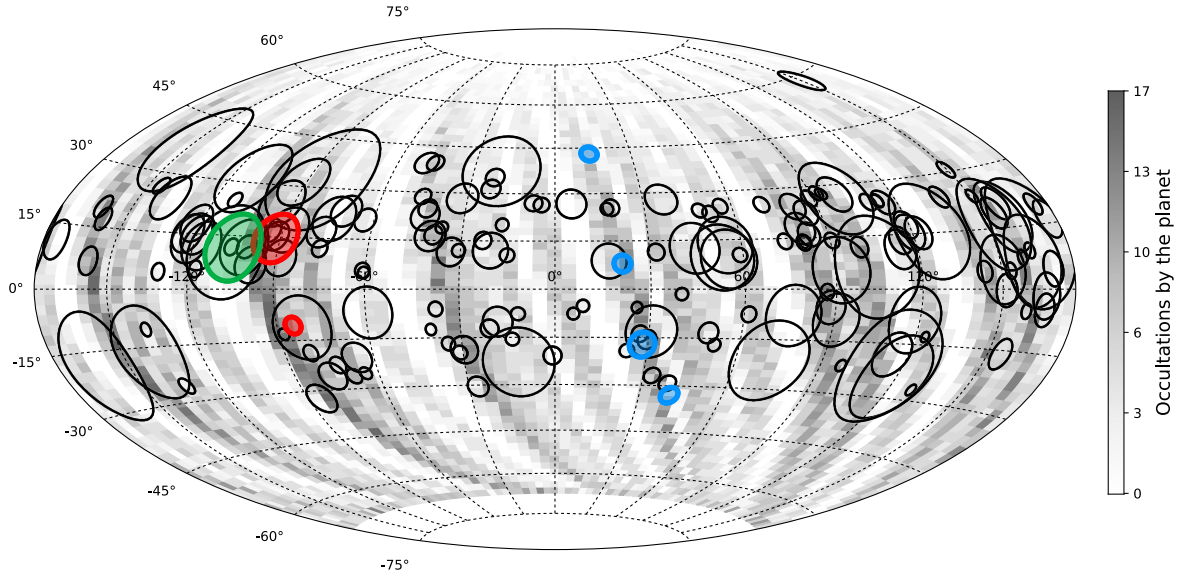


Figure 5.9: Spots detected on HAT-P-11 with STSP (see Section 5.3). The radius of each circle corresponds to the size of the spot. The shading beneath corresponds to the number of times the planet occulted that spatial bin on the stellar surface, which can be used as a proxy for relative completeness. Note that the spots occur preferentially at two active latitudes near $\pm 15^\circ$. The 6:1 period commensurability between the orbital period and stellar rotation period produces the alternating longitudinal stripes in relative occultation number. The two red circles in the western hemisphere near longitude -90° highlight the spots derived from the transit light curve in Figure 5.8, and the four blue circles in the eastern hemisphere near longitude 30° correspond to the spots derived from the transit light curve in Figure 5.6. The green circle near longitude -100° corresponds to the large spot discussed in Figure 5.13.

are detectable and readily visible in the spot map in Figure 5.9. The spots are distributed into two active latitudes near $\pm 16^\circ$ latitude, and the northern hemisphere appears to have more spots than the southern hemisphere. We investigate the latitude distribution of spots in the next section.

The transit chord of HAT-P-11 b is inclined 16° from perpendicular to the stellar equator – refer back to Figure 5.3 for a schematic of the orientation. As a result of this slight misalignment from perpendicular, the planet never occults either pole of the star. It is possible that there are spots at latitudes $\geq 60^\circ$, which have been produced in simulations of highly-active sun-like stars (e.g. Schrijver & Title, 2001). Our spot map from transit photometry is insensitive to polar or high latitude spots.

5.4.2 Latitude Distribution

The mean latitudes of sunspots and the widths of their distributions across each hemisphere undergo an ~ 11 year cycle, which gives rise to the “butterfly diagram” of latitudinal spot density as a function of time (see for example Hathaway, 2011, 2015). Near solar minimum, there are very few sunspots. Spots begin to appear at “high” latitudes $|\ell| \sim 25^\circ$, and the mean spot latitude drifts towards the equator throughout the cycle, with the maximum number of spots occurring near $|\ell| \sim 15^\circ$. The northern and southern hemispheres of the Sun can have asymmetric numbers of spots, flares, and other activity indicators (see for example Carbonell et al., 1993; Li et al., 2002; Newton, 1955; Vizoso & Ballester, 1990).

To compare the activity of HAT-P-11 to solar activity, we characterize the Sun’s spot latitude distribution in the 1917-1985 sunspot catalog from Mt. Wilson Observatory published by Howard et al. (1984). We group the solar spot observations into four-year bins similar to the *Kepler* time series of HAT-P-11. On these timescales, the spot latitude distributions on both stars are often similar to Gaussians (see Figure 5.10), though sometimes the deviations from Gaussians are significant.

We construct a probabilistic model to describe the latitude distributions of spots on HAT-P-11 and on the Sun, following the description of the Gaussian mixture model in

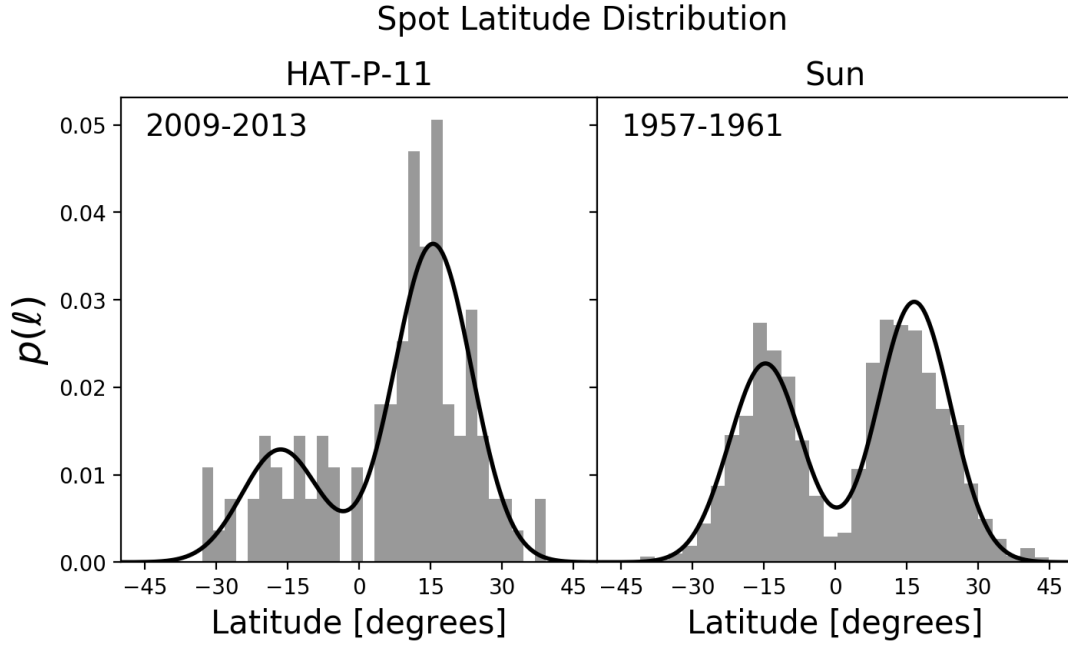


Figure 5.10: Distribution of spot latitudes over four years of observations for both HAT-P-11 and the Sun. The four years of solar observations correspond to the maximum of solar Cycle 19 as observed by Howard et al. (1984). The HAT-P-11 spot latitudes and their uncertainties are taken from the best-fit solutions from the STSP spot occultation model. Both stars have active latitudes centered on $\pm 16^\circ$ with standard deviations of $\sim 8^\circ$. We put these latitude distributions in context throughout the solar activity cycle in Figure 5.11. Though HAT-P-11’s hemispheric spot number asymmetry is greater than the Sun’s in this particular bin of solar observations, we find that the asymmetry on HAT-P-11 is within the range observed on the Sun; see Section 5.4.2 for details.

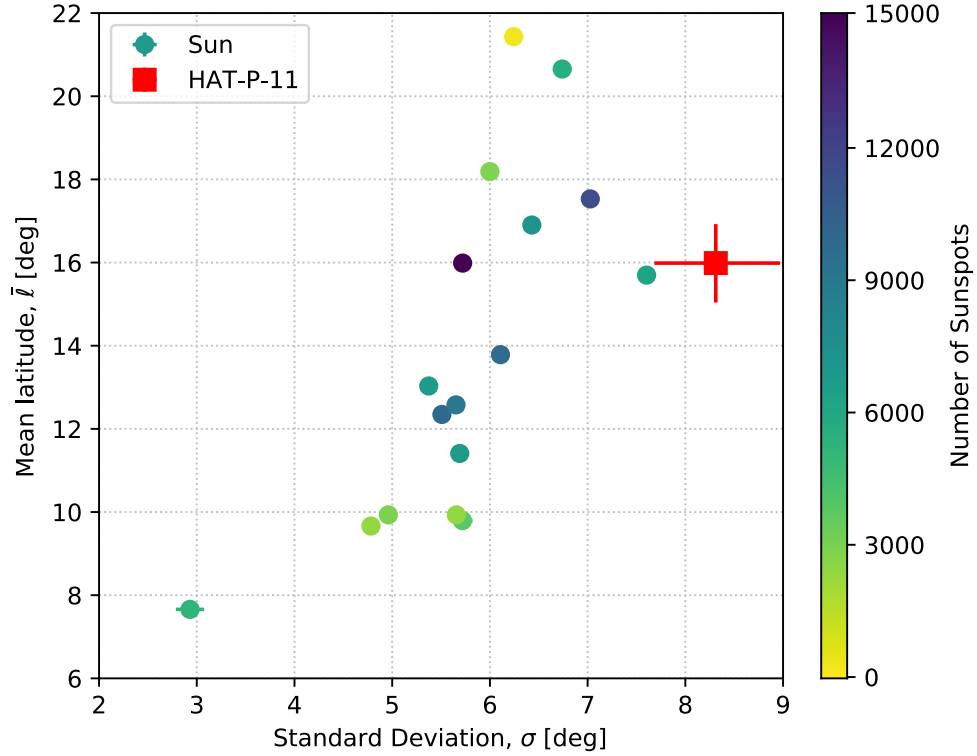


Figure 5.11: Latitude distributions of sunspots and spots on HAT-P-11, parameterized by the mean latitude of spots in each hemisphere and the standard deviation of spot latitudes in each hemisphere. The circles are the best-fit parameters for four-year bins of the Mt. Wilson sunspot catalog (Howard et al., 1984). The squares are fits to the HAT-P-11 latitude distribution over the four years of *Kepler* data. The colors of the solar circles represent the number of sunspots in each bin, which is a good proxy for phase of the solar activity cycle (darker points are nearer to solar maximum). Some of the fits have large uncertainties even with many spots, because the latitude distributions are not always well-approximated by Gaussians. The solar measurement closest to HAT-P-11’s corresponds to the period 1957-1961 during solar Cycle 19, which is plotted in Figure 5.10 for comparison to HAT-P-11.

Section 5.2.4. We fit for the amplitude, mean, and variance of Gaussians representing the latitude distributions of spots in each hemisphere. We focus on fitting the shape of the latitude distribution and do not compare the total number of spots observed on the two stars to each other, since a correction for the sensitivities and biases of the different observing methods is beyond the scope of this paper.

The latitude distribution of spots of HAT-P-11 and four years of solar observations are shown in Figure 5.10. The four-year span of solar observations closely resembles the mean spot latitudes and standard deviation of spot latitudes that we measure for HAT-P-11. The sunspots included in Figure 5.10 span the active maximum of solar Cycle 19, which was the solar maximum with the largest recorded number of spots since telescopic observations began (Solanki et al., 2013).

The properties of the maximum-likelihood Gaussian mixture models for HAT-P-11 and the Sun are shown in Figure 5.11. The circles show the mean latitudes of spots on each hemisphere of the Sun, and the standard deviations of the spot distributions. The pattern of the solar activity cycle is visible — sunspots in the beginning of the cycle appear in small numbers at high latitudes, then large numbers near 15° , before settling back to lower numbers near the equator. The standard deviations of the spot distributions are correlated with the mean latitude — the active latitudes are broadest at the beginning of the activity cycle when spots form at high latitudes, and the active latitudes become narrower as they approach the equator later in the activity cycle. The combined effect of the shrinking standard deviations with declining mean latitudes produces the “wings” in the butterfly diagram.

The distribution of spots on HAT-P-11 sits near the region of $\bar{\ell} - \sigma$ space corresponding to solar maximum. The most similar four-year bin of sunspots, which is roughly consistent with the HAT-P-11 spot distribution in terms of $\bar{\ell}$ and $\bar{\sigma}$, is the bin plotted in Figure 5.10. The mean active latitudes on HAT-P-11, $\ell = 16 \pm 1^\circ$, corresponds to the mean latitudes of sunspots near most solar maxima.

The number of spots observed in each hemisphere is rather asymmetric, but within the range of observed asymmetries on the Sun. Hemispheric asymmetries of the solar spot

distribution are often quantified by $(N - S)/(N + S)$, where N is the spot area in the northern hemisphere and S is the spot area in the southern hemisphere (Carbonell et al., 1993; Waldmeier, 1971). The maximum likelihood STSP spot latitudes and radii from the entire *Kepler* mission give $(N - S)/(N + S) = 0.35$. This asymmetry is within the range observed on the Sun by Howard et al. (1984) when observed in four-year bins, varying from -0.1 to 0.6.

5.4.3 Radius distribution

We compute the physical spot radius distribution using the radius measurement of HAT-P-11 from Bakos et al. (2010), $R = 0.752 \pm 0.021 R_{\odot}$. The spot radius distribution is shown in Figure 5.12, along with sunspot radii near activity maximum and minimum.

The spot radius distribution of HAT-P-11 closely resembles the Sun’s at activity maximum for spots with radii $2 \times 10^4 < R_{spot} < 5 \times 10^4$ km. 85% of the spots on HAT-P-11 are smaller than the largest observed sunspot. The HAT-P-11 radius distribution is incomplete for small spots with $R_{spot} \lesssim 2 \times 10^4$ km, since spot occultation amplitudes of those spots are similar in scale to the noise in *Kepler* photometry. The smallest observed sunspots have radii of order 10^3 km (Solanki, 2003), so it is likely that there are also small spots on HAT-P-11 below our S/N threshold.

HAT-P-11’s spot distribution has a tail of spots larger than those observed on the Sun, with $R_{spot} > 5 \times 10^4$ km. From visually inspecting the individual transits, it is clear that some of the spots are larger than the largest sunspots. The largest published sunspot measurement that we encountered in the literature was recorded in 1947 by Newton (1955) to have area $6132 \mu\text{Hem}$. We can calculate the radius of a circular spot with this area in units of hemispheres (Hem) by normalizing the area of the circular spot $A_{spot} = \pi R_{spot}^2$ by the area of the observer-facing hemisphere of the star $A_{star} = 2\pi R_{star}^2$,

$$A_{\text{Hem}} = \frac{1}{2} \left(\frac{R_{spot}}{R_{star}} \right)^2 \frac{R_{spot}}{R_{star}} = \sqrt{2A_{\text{Hem}}} \quad (5.6)$$

Therefore in the circular approximation, the largest reported sunspot had radius $R_{spot}/R_{\odot} =$

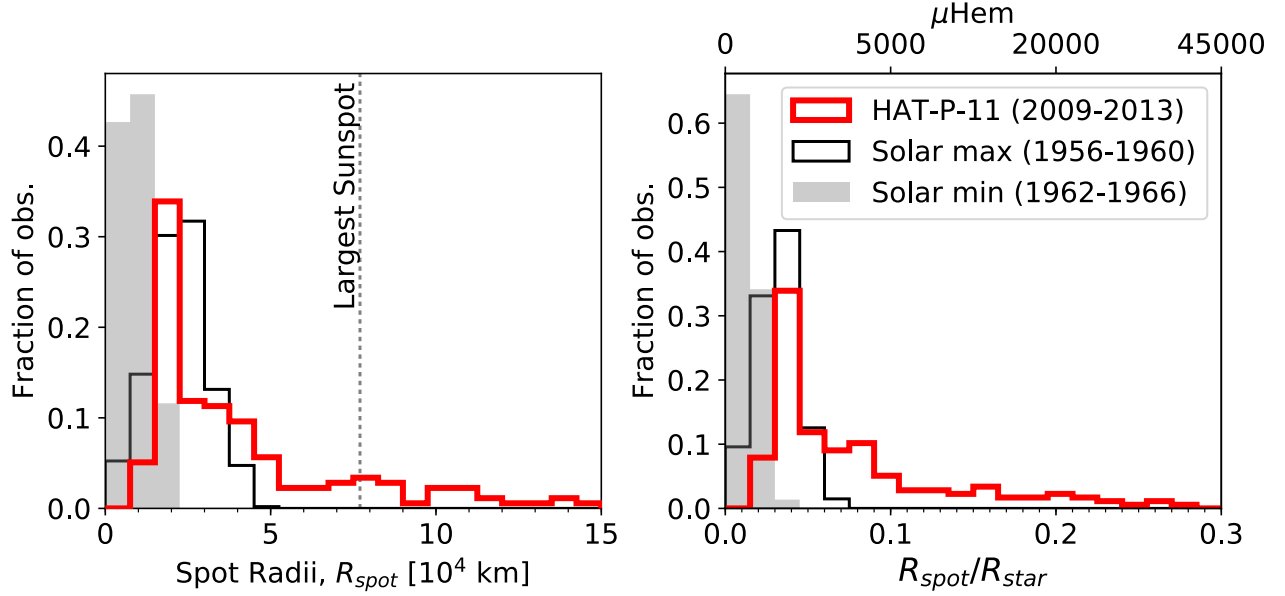


Figure 5.12: Maximum likelihood spot radii for HAT-P-11 from *Kepler* spot occultations, and for the Sun from Mt. Wilson Observatory (Howard et al., 1984). The spot radii are given in physical units on the left panel and in fractions of the stellar radius (R_{spot}/R_{star}) and millionths of the observer-facing hemisphere (μHem) in the right panel. We adopt the radius of HAT-P-11 from Bakos et al. (2010), $R_{star} = 0.752R_{\odot}$. For reference, the largest sunspot measurement we could find in the literature was $6132 \mu\text{Hem} = R_{spot}/R_{\odot} = 7.7 \times 10^4$ km. We suspect that a significant fraction of HAT-P-11’s spots with very large radii are in fact occultations of multiple spots.

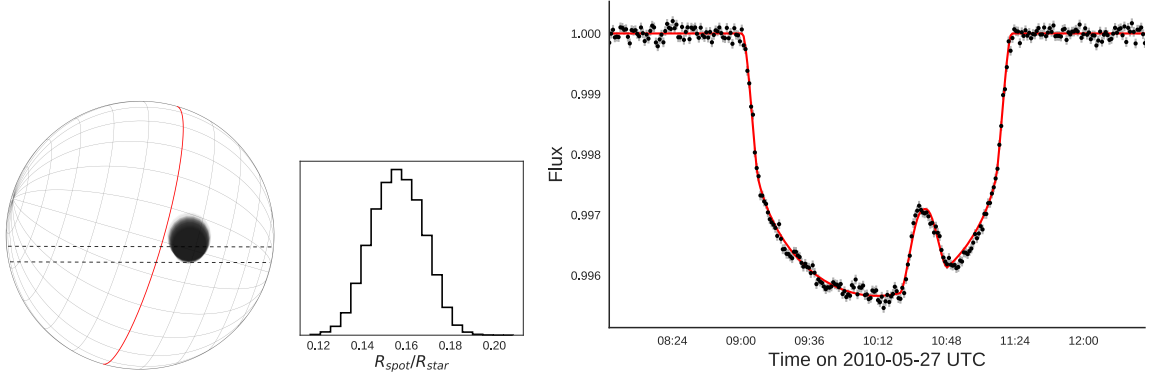


Figure 5.13: An occultation of a particularly large spot. The maximum likelihood spot radius is $R_{spot}/R_{star} = 0.160^{+0.007}_{-0.016}$, or $84000^{+4000}_{-8000} \pm 6000$ km – just larger than the largest recorded sunspot (77000 km, Newton 1955). This spot is highlighted in green on the spot map in Figure 5.9.

0.110 and $R_{spot} \sim 77$ Mm. We can compare that to the spot in Figure 5.13, for example, which has $R_{spot}/R_{star} = 0.160^{+0.007}_{-0.016}$ corresponding to $R_{spot} = 84^{+4}_{-8}$ Mm — consistent with the largest sunspot. The radius posterior distribution shown in Figure 5.13 has a single solution. However, many of these larger spots could be somewhat smaller than the maximum likelihood solution that we are reporting. The spot radius posterior distributions exhibit families of degenerate solutions in which the spot occultation fluxes can be fit equally well by a grazing spot occultation of a large spot or a more direct occultation of a smaller spot (see Section 5.3.1 for discussion of degeneracies). This could produce a systematic bias towards larger maximum-likelihood spot radii in the values that we report.

5.4.4 Spotted area

The spot area coverage of the observable hemisphere of a star, or the spot “filling factor” f_S , has been constrained for several stars with Zeeman-Doppler imaging and molecular band modeling. Since these methods are sensitive to different spot sizes (Solanki & Unruh, 2004), we chose to compare the spots that we detect on HAT-P-11 via photometry with starspots

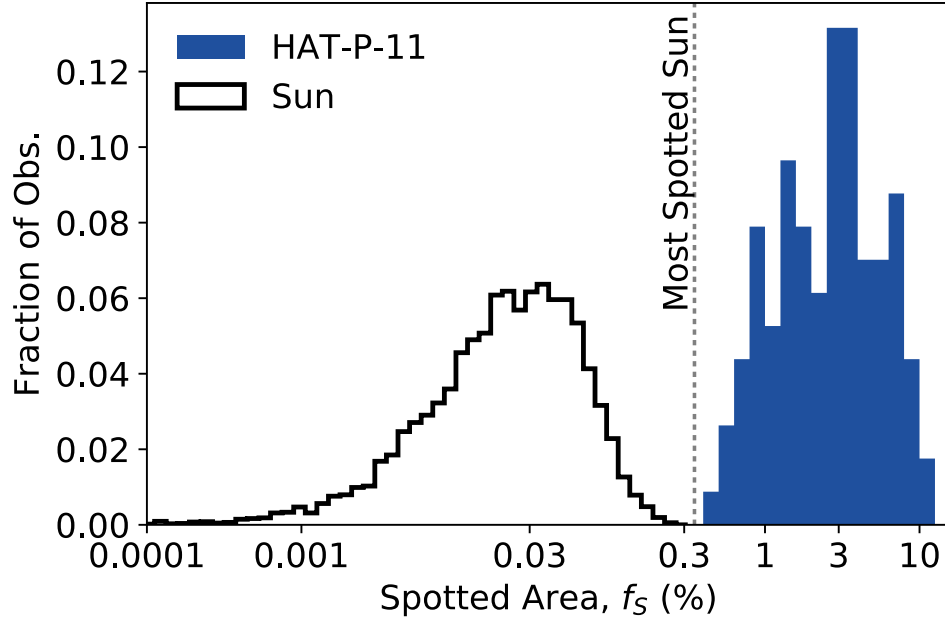


Figure 5.14: Spot coverages of HAT-P-11 and the Sun. The HAT-P-11 spotted area is computed the area of the transit chord occulted by spots in the maximum likelihood STSP fit. The spotted areas of the Sun are gathered from the Mt. Wilson Observatory spot catalog of Howard et al. (1984), scaled up to account for the areas of penumbra and penumbra, assuming an area ratio of $A_{pen}/A_{umb} = 4$. We have excluded spot coverages for transits that had either no significant spot occultations, or where multiple spot occultations were fit with a single unrealistically large spot, narrowing the sample down to 90 of the 205 transits observed by *Kepler*.

Name	Sp. Type	T_{eff} [K]	P_{rot} [d]	T_{spot} [K]	$f_s [A_{*/2}]$	$\langle S \rangle$	Ref.
Sun	G2V	5777	24.47	3900-5500	$0.0003^{+0.0006}_{-0.0001}$	0.17	[1, 2, 3]
HAT-P-11	K4V	4780	29.2	4500 (fixed)	$3^{+0.06}_{-0.01}$	0.6	(This work, [4])
OU Gem	K3V/K5V	4925/4550	6.991848	—	$\leq 0.04 - 0.35$	0.796	[5, 6]
EQ Vir	K5Ve	4380	3.96	3350 ± 115	$0.33 - 0.45$	3.68	[5, 7]
XX Tri	K0 III	4750	23.96924	3425 ± 120	$0.31 - 0.35$	—	[8]
V833 Tau	K4V	4500	1.7955	3175	0.51	2.460	[6, 8]

Table 5.2: Comparison of HAT-P-11, the Sun, and several stars in order of increasing spot coverages (f_S , in units of hemispheres $[A_{*/2}]$). The spot temperature range listed for the Sun includes the typical lower limit of umbral temperatures and typical upper limit of penumbral temperatures. The spot temperature of HAT-P-11 is estimated by selecting the PHOENIX model atmosphere that most closely produces a spot contrast of $c = 0.3$ in the *Kepler* band-pass (Husser et al., 2013), and should be thought of as the approximate area-weighted spot group temperature in both the umbra and penumbra. The typical solar spot temperature range spans from the coolest regions of the umbra to the hottest regions of the penumbra. References: [1] Howard et al. (1984), [2] Solanki (2003), [3] Egeland et al. (2017), [4] Bakos et al. (2010), [5] O’Neal et al. (2001), [6] Pace (2013), [7] Cincunegui et al. (2007), [8] O’Neal et al. (2004),

detected via molecular band modeling only. The molecular absorption band spot temperatures and filling factors from O’Neal et al. (2004, 2001) are enumerated in Table 5.2, with spot areas ranging from a few percent to nearly half of the stellar surface.

We can calculate the spotted area within the transit chord at the maximum-likelihood step in the MCMC chains for each transit. This spotted area measurement is not identical to the spotted area fraction f_S from O’Neal et al. (2004, 2001), which measures the fractional area of spots on the entire observer-facing hemisphere of a star. However, since the transit chord of HAT-P-11 b is nearly perpendicular to the stellar equator, the planet occults most latitudes of the star at one longitude during each transit. Since we expect the distribution of starspots to be azimuthally symmetric – i.e. the spot distribution may change as a function of latitude but not longitude – each transit samples the spotted area of a relatively unbiased slice of the stellar surface. Thus we use the spot coverage within the transit chord as a characteristic spot coverage on the whole star.

In Figure 5.14, we plot the spotted area within the transit chord for the 138 transits with significant spots modeled by STSP, compared with the spotted area on the Sun (including both the umbra and penumbra). During the *Kepler* mission, the spotted area on HAT-P-11 varied with mean area coverage $\langle f_{s,H11} \rangle = 3_{-1}^{+6}\%$, where the upper and lower error bars are the 84th and 16th percentiles, respectively. We have excluded the transits with no significant spot detections from the above reported $\langle f_{s,H11} \rangle$ since the abundance of non-detections is distinct from measurements of zero spotted area; and as we discuss in Section 5.4.5, the star likely always has large spots facing the observer.

The mode of the solar spot coverage from Howard et al. (1984) is $\langle f_{s,\odot} \rangle = 0.0003_{-0.0001}^{+0.0006}$, $\sim 100\times$ smaller than HAT-P-11’s. Upper limits on the maximal recorded spotted area of the Sun vary depending on the observations considered, but are typically $\lesssim 0.6\%$ (Balmaceda et al., 2009).

We note that the completeness of spot detections on the Sun is nearly 100%, whereas on HAT-P-11 we are only sensitive to large spots in the transit chord, which covers about 6% of the observer-facing hemisphere. Therefore the spot coverage that we report for HAT-P-11

is best treated as a lower limit on the actual spot coverage. With that caveat in mind, HAT-P-11’s spot coverage is most similar to the molecular band observations of OU Gem, which varies in the range $f_s \leq 0.04$ to 0.35 (O’Neal et al., 2001).

The high spot coverage of HAT-P-11 compared to the Sun is consistent with its CaII H & K emission. The Sun’s mean S -index during Cycle 23 was $\langle S_\odot \rangle = 0.1701 \pm 0.0005$ (Egeland et al., 2017), compared to $\langle S_{H11} \rangle = 0.61$ for HAT-P-11 (Bakos et al., 2010). The solar S -index directly correlates with the area coverage by sunspots, so naturally it follows from the high S -index that HAT-P-11 should have a higher spot coverage.

Shapiro et al. (2014) fit for the relation between sunspot coverage $f_{s,\odot}$ as a function of the solar S -index and found:

$$f_{s,\odot}(S) = 0.105 - 1.315S + 4.102S^2. \quad (5.7)$$

If we naively substitute our measured spot coverage $f_{s,H11} \sim 0.03$ for HAT-P-11 into Equation 5.7, we predict $\langle S_{H11,pred} \rangle \sim 0.26$. The observed S -index is much larger — evidently the activity of Sun-like stars does not scale quadratically with S -index in the activity regime relevant to HAT-P-11.

We now revisit the assumption made in Section 5.2.1 that the maximum flux during each *Kepler* quarter is approximately the unspotted brightness of the star. The spotted area observed on HAT-P-11 is as high as 10% at times, so the maximum quarterly flux is unlikely to be the unspotted flux of the star. If we are underestimating the unspotted flux of the star, then we will underestimate the transit depth (see Section 5.2.1), and therefore underestimate spot occultation amplitudes. This propagates into underestimates of spot radii and underestimates of the spotted area. This bias acts to oppose the bias towards larger spot radii and larger spotted areas discussed in Section 5.4.3. Visual inspection of the transit light curve residuals shows that the transit depth is generally consistent with the observations, so we deem that our normalization in Section 5.2.1 is sufficient.

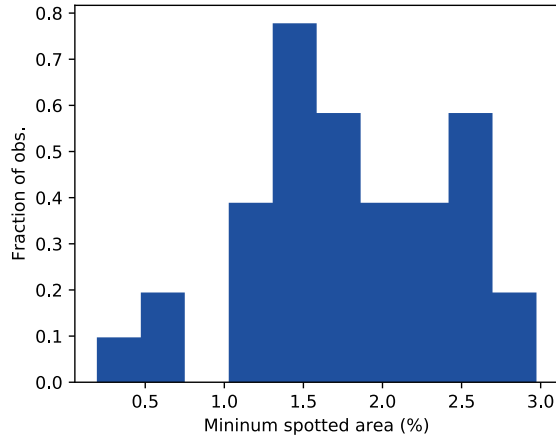


Figure 5.15: Minimum spot coverage of HAT-P-11, independently inferred from the flux deficits in the out-of-transit portions of the *Kepler* light curve. The minimum spot coverage in the range 0.5 to 3% is consistent with the spot coverage inferred from the spotted area in the transit chord in the maximum-likelihood STSP models, $f_S = 3_{-1}^{+6}\%$.

Spotted area via flux deficit

The rotational modulation of the out-of-transit fluxes can independently constrain the spotted area of HAT-P-11 (for an assumed spot contrast). The difference between the brightest and dimmest flux measured in each *Kepler* quarter is equivalent to the product of the fractional projected spotted area and $1 - c$, where c is the spot contrast as defined in Equation 9.4.

In practice, the estimate of the spotted area via the flux deficit is a lower limit on the total spotted area. If there were only a few small spots on the star, the flux deficit would yield the true spot covering fraction. However in the limit of many small spots distributed evenly across the star, each spot that rotates out of view will be replaced by another spot rotating into view, and thus adding more spots would not increase the flux deficit. As we argue in this section and Section 5.4.5, there are a significant number of spots on the star, and it is unclear if the star is in this saturated flux deficit regime. Thus the spotted area inferred by the flux deficit should be treated as a lower limit on the spotted area.

We compute the fractional spotted area for each *Kepler* quarter from the flux deficit as follows. We mask out all transits, and convolve the fluxes with a Gaussian kernel ($\sigma = 50$ fluxes). We normalize each quarter’s fluxes by its smoothed maximum flux. The minimum fractional spotted area during each quarter is given by $f_S = (1 - \min(\text{flux})) / (1 - c)$.

The minimum spotted area inferred by the quarterly flux deficits is shown in Figure 5.15. We see that minimum spotted area ranges from 0.1% to 3% over the different *Kepler* quarters. This is consistent with the 0.5-10% spotted area that we infer from modeling spots in the transit chord (Figure 5.14).

5.4.5 Spot number

During the solar activity cycle, the number of spot groups observed on the Sun at any instant varies from near zero at activity minimum to hundreds at maximum. We measure the number of high-signal spot occultations per transit for HAT-P-11, which we can use to (1) search for evolution in the spot number over time; and (2) to compare to the number of sunspots.

The simplest measurement of the number of starspots that we can obtain from the *Kepler* photometry is the number of spots per transit for all 205 transits. Each transit is short compared to the expected spot evolution timescale (weeks) and the stellar rotation period (29.2 d), so each transit gives an instantaneous measurement of the number of spots within the transit chord. These spot numbers of HAT-P-11 are not directly comparable to sunspot numbers because solar observations can resolve much smaller spots than occultation photometry. It is also likely that what appear to be large spots in occultation photometry might really be groups of smaller spots at higher resolution.

We assume that the observed spot count per transit follows a Poisson distribution, and compute the likelihood of detecting the observed spot numbers for a given Poisson rate parameter λ (with units of spots detected per transit). We allow the spot count rate to vary as a function of time, as it would throughout the solar activity cycle. We model the number of spots observed per transit with a Poisson distribution $P(\lambda)$ with a linearly varying Poisson

rate parameter $\lambda(t) = \lambda_0(t - t_0) + \lambda_1$, where λ_0 is the rate of change of the Poisson rate parameter over time (i.e.: how many more/less spots will be counted per year), and λ_1 is the rate parameter at time t_0 . We marginalize over the hyperparameters with MCMC and find that the rate parameter slope is $\lambda_0 = 0.12 \pm 0.06$ spots per year. Since this slope is consistent with no slope, we fix $\lambda_0 = 0$ and solve only for a constant rate parameter, and find $\lambda = 0.870 \pm 0.066$ spots per transit.

The apparently constant spot number over four years could be observed for a Sun-like star with period ~ 11 years if observed near maximum or minimum, or at any phase if the activity cycle has a long period. Spectroscopic activity index measurements over time may distinguish between these two possible cases.

We can compute a rough estimate of the number of spots on the entire stellar surface by extrapolating from number of spots observed within each transit chord. The occulted fraction of the entire stellar surface area, $A_* = 4\pi R_*^2$, within each transit chord is $\sim 2.9\%$. If we assume there are $\lambda = 0.87$ spots per transit from the analysis above, then there are $\sim 30 \pm 2$ spots like the ones detected in transit on the surface of the entire star at any given time, and about 15 ± 1 on the observer-facing hemisphere of the star.

We refrain from comparing the number of spots on HAT-P-11 to the common solar spot group number because solar observations are not directly analogous to the *Kepler* photometry. Ground-based observations of the Sun can observe sunspots as small as $R_{spot} = 1750$ km – well below the smallest spots detected with high confidence on HAT-P-11 via transit photometry. However, we can compare the number of sunspots with radii as large as HAT-P-11’s. The turnover in spot frequency for small spots on HAT-P-11 suggests that we are insensitive to spots with $R_{spot,min} < 2 \times 10^4$ km (see Figure 5.12). We identify 898 spots larger than 2×10^4 km observed over 10818 days on the Sun (Howard et al., 1984), which is roughly a rate of 0.08 spots on the observer-facing hemisphere of the Sun at any instant. On HAT-P-11 we detect 130 such spots in 205 transits. The transit chord of HAT-P-11 b spans 6% of the observer-facing hemisphere, so we expect roughly 11 spots on HAT-P-11 at any instant with radii $> 2 \times 10^4$ km. Clearly there are more spots on HAT-P-11 of this size

than on the Sun.

In light of the large spot number of HAT-P-11, and the sunspot-like radii of its spots, we can now interpret the spot area determined in Section 5.4.4. The spotted area on HAT-P-11 is 100x greater than solar largely due to the presence of *more* spots, since the spot radii are typically quite similar to large sunspots near solar maximum (see spot radius discussion in Section 5.4.3).

5.5 Conclusions and discussion

We have measured the properties of starspots on the active K4 dwarf HAT-P-11 from *Kepler* photometry of its transiting planet. We take advantage of the planet’s well known orbital orientation to measure starspot positions during occultations by the planet. The highly misaligned orbit of the planet allows us to unambiguously resolve spot latitudes.

The spots of HAT-P-11 are similar to the Sun’s in several ways. The spot contrast is consistent with the area-weighted contrast of typical sunspots, $c = 0.3$ (Eqn. 9.4). The mode of the spot radius distribution is similar to the radii of sunspots at solar maximum. The active latitudes of HAT-P-11 have the same mean latitude and standard deviation as the Sun at solar maximum. The asymmetry in the number of spots in each hemisphere is consistent with the range of values observed on the Sun.

However, the activity of HAT-P-11 is more extreme than the Sun’s. The mean spot coverage from 2009-2013 is $3_{-1}^{+6}\%$, ~ 100 x greater than the Sun’s. The number of large starspots is roughly 100x greater than the number of similarly sized spots on the Sun. The S -index of HAT-P-11 is a factor of two greater than one would expect by extrapolating from the spot coverage– S -index relation observed on the Sun.

The similarities between the spot distributions on the Sun and HAT-P-11 are interesting in the context of dynamo theory (e.g. Charbonneau, 2010). This K4 star is not fully convective, and therefore is expected to have a tachocline like the Sun. Perhaps the $\alpha\Omega$ dynamo is operating within HAT-P-11 as it does in the Sun. It seems that a $0.8M_{\odot}$ star with a near-solar rotation rate produces starspots in strikingly similar active latitudes, with more

large spots. The theoretical prescriptions for magnetic flux emergence developed for the Sun may therefore be applicable out to spectral type K4 (e.g. Cheung & Isobe, 2014).

Precision spot occultation analysis made possible by *Kepler* could potentially be reproduced with photometry from NASA’s TESS mission for HAT-P-11 in particular, and for active planet-host stars in general (Ricker et al., 2014). However, the one-minute cadence photometry was critical for resolving the spot occultation features of HAT-P-11, and time resolution directly translates to latitude resolution for highly misaligned systems. The TESS mission’s planned two-minute cadence is likely sufficient to detect spot occultations in systems like HAT-P-11, though shorter cadence ground-based photometry would be preferred.

5.5.1 Future Work

HAT-P-11 is exceptionally bright ($V = 9.47$), which makes ground-based observations of spot occultations with amplitudes on the order of 0.1% feasible. In particular, we plan to collect transit photometry with the holographic diffuser and the ARCTIC imager on the ARC 3.5 m Telescope at the Apache Point Observatory (APO) (Stefánsson et al. 2017, submitted). If HAT-P-11 exhibits evolution in the spot latitude distribution like the Sun does, we may be able to observe changes in the mean spot position as the activity cycle progresses. Observing spot occultations from the ground is advantageous because the latitude resolution is linked to the time resolution of the photometry, which can be minimized with large aperture telescopes and thus shorter exposure times compared to *Kepler* or TESS.

The phase of the activity cycle of HAT-P-11 can be constrained over several years by analyzing long-term spectroscopy of the S -index. In Morris et al. (2017, in prep), we constrain the period and amplitude of the activity cycle of HAT-P-11 using archival high resolution spectroscopy of the star, in combination with recent high resolution spectra obtained at APO.

The constraints on the spot coverage of HAT-P-11 from the *Kepler* photometry are complementary to spectroscopic constraints from molecular band modeling. The spot coverage reported here could be independently measured by modeling absorption by TiO and OH in

starspots (O’Neal et al., 2004, 2001).

In this work we limited ourselves to studying only the spot occultations in transit to make direct comparisons between spots on HAT-P-11 and sunspots. Simultaneous modeling of the out-of-transit fluxes would provide complementary constraints on the total spot coverage on HAT-P-11.

Spot contrast

We make some simplifying assumptions to derive constraints on the spot contrast from the amplitudes of spot occultations, and we generalize the formalism later. We will at first calculate the flux only for spot-planet orientations where the planet completely occults the spot or the spot completely encompasses the planet. By ignoring grazing spot occultations, we will calculate maximum spot-occultation amplitudes, since grazing spot occultations yield smaller amplitudes than complete occultations. We also ignore stellar limb darkening.

The flux lost during the transit of a planet with radius R_p across an unspotted star with radius $R_\star$ without limb darkening is

$$\delta_{unspotted} = \frac{\Delta F}{F_\star} = \frac{I_\star \pi R_p^2}{I_\star \pi R_\star^2} = \frac{R_p^2}{R_\star^2} \quad (5.8)$$

where $I_\star$ is the mean surface intensity of the stellar disk per unit area.

We measure the amplitude of brightening during a spot occultation A , see Figure 5.16 for a schematic representation. During an occultation of a starspot, the appropriate formula for the observed flux depends on the size of the spot R_{sp} relative to the size of the planet R_p . If the spot with radius larger than or equal to the radius of the planet $R_{sp} \geq R_p$ and the spot has contrast c , the amplitude of the difference in flux between a transit of an unspotted and a spotted star is

$$A = \delta_{unspotted} - \delta_{spotted}|_{R_{sp} > R_p} \quad (5.9)$$

$$= \frac{I_\star \pi R_p^2}{I_\star \pi R_\star^2} - \frac{((1 - c)I_\star) \pi R_p^2}{I_\star \pi R_\star^2} \quad (5.10)$$

$$A/\delta_{unspotted} = c. \quad (5.11)$$

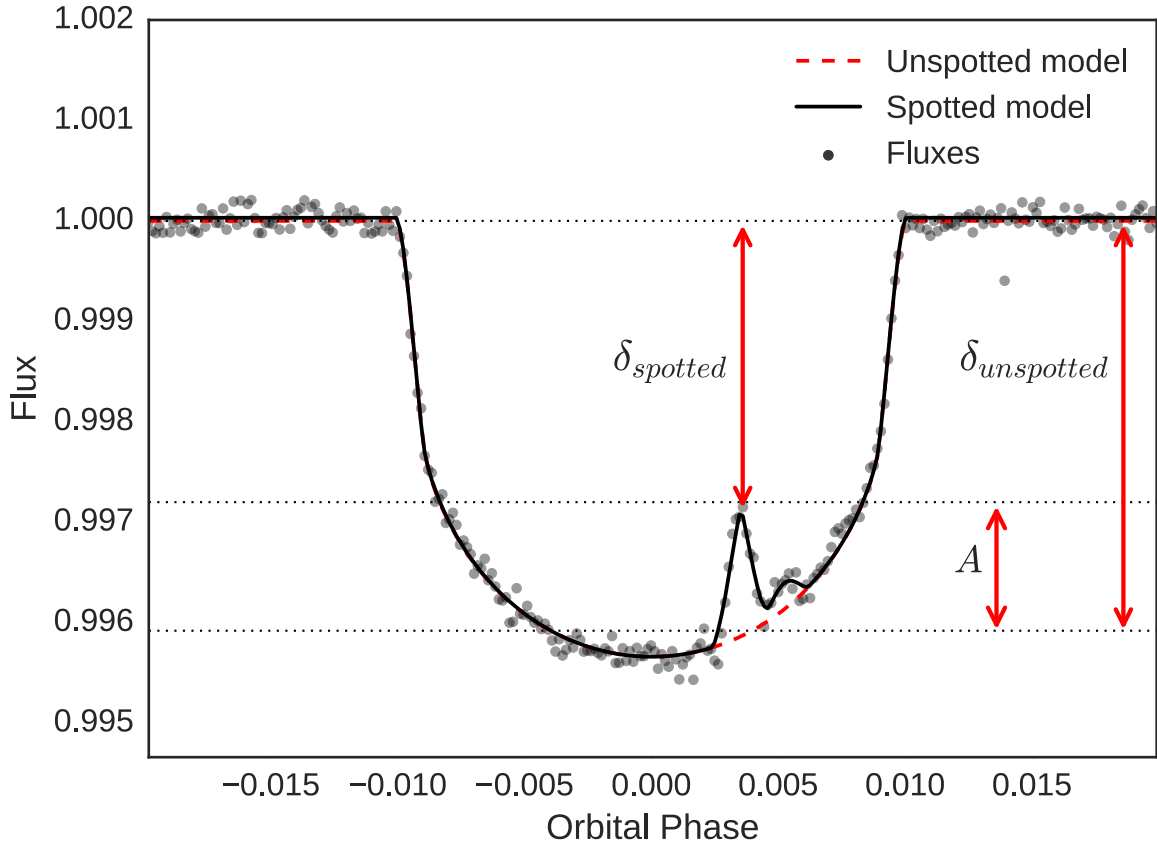


Figure 5.16: Schematic for parameter definitions in Section 10.2.4, plotted on the transit of HAT-P-11 b on August 20, 2011 UT. The spot occultation amplitude A is the difference between the flux lost during a transit with no spot occultations and the flux lost during a transit with spot occultations, $A = \delta_{unspotted} - \delta_{spotted}$. Note that in this terminology the “depth” $\delta(\mu) = \Delta F(\mu)/F$ is a function of the sky-projected distance between the planet and the star μ , or equivalently time or orbital phase, for a star with limb-darkening.

For a spot smaller than the planet, the difference between the spotted and unspotted flux is

$$A = \delta_{unspotted} - \delta_{spotted}|_{R_{sp} < R_p} \quad (5.12)$$

$$= \frac{I_\star \pi R_p^2}{I_\star \pi R_\star^2} - \frac{I_\star \pi R_p^2 - c I_\star \pi R_p^2 R_{sp}^2 / R_p^2}{I_\star \pi R_\star^2} \quad (5.13)$$

$$A / \delta_{unspotted} = c \left(\frac{R_{sp}}{R_p} \right)^2 \quad (5.14)$$

In the small planet limit where $R_p/R_\star \ll 1$, the stellar limb darkening could be defined, for example, with a quadratic law $I(\mu)/I_0 = 1 - u_1(1 - \mu) - u_2(1 - \mu)^2$, and the instantaneous unspotted depth becomes

$$\delta_{unspotted}(\mu) = \frac{R_p^2}{R_\star^2} \left[\frac{1 - u_1(1 - \mu) - u_2(1 - \mu)^2}{1 - \frac{1}{3}u_1 - \frac{1}{6}u_2} \right] \quad (5.15)$$

where μ is the sky-projected distance between the planet and the star. Equations 5.11 and 5.14 above can be generalized for stars with limb-darkening by replacing $\delta_{unspotted} \rightarrow \delta_{unspotted}(\mu)$.

Chapter 6

THE CHROMOSPHERIC ACTIVITY OF HAT-P-11: AN UNUSUALLY ACTIVE, PLANET-HOSTING K DWARF

In Chapter 5, we opened a window into the stellar magnetic activity of the K4 dwarf HAT-P-11 using its transiting exoplanet. We found that HAT-P-11’s starspots are distributed in latitude similar to sunspots, with most spots lying near $\pm 15^\circ$ latitude. We found that the starspots have similar physical sizes to sunspots at solar maximum. Yet there are several questions that were left unanswered in the previous chapter. From the four years of *Kepler* photometry alone, it was not possible to build an analog to the solar butterfly diagram, showing the evolution of spot latitudes as a function of time; so one question that remains is – how long is the full duration of the stellar magnetic activity cycle of HAT-P-11?

Another unanswered question in the previous chapter is whether or not HAT-P-11 is “normal”? In other words, for planet-hosting stars of similar rotation periods and spectral types, is the magnetic activity of HAT-P-11 typical? We showed that the starspots of HAT-P-11 were similar sizes and distributed with latitude in a similar fashion to sunspots, and found that the typical spot coverage on HAT-P-11 was two orders of magnitude greater than the Sun’s. We now ask the question: is that activity level common among similar stars? The answer to this question has important implications for exoplanet astronomy. If HAT-P-11 is typical among similar stars, then the spot distribution discovered in Chapter 5 provides us with valuable prior knowledge about the distribution of starspots on Sun-like stars.

This chapter was first published in the *Astrophysical Journal* (Morris et al., 2017c).

6.1 Introduction

The K4 dwarf HAT-P-11 bears many spots on its surface, despite its 29 day rotation period. Morris et al. (2017a) used *Kepler* photometry to measure spot sizes and positions during transits of its hot Neptune with a nearly polar orbit. They showed that the spots cover $\sim 100\times$ more surface area on HAT-P-11 than sunspots cover on the Sun, and that the spots cluster into active latitudes similar to the solar active latitudes near activity maximum. The analysis by Morris et al. (2017a) was limited in time to the four years of *Kepler* photometry, preventing the detection of activity evolution throughout the stellar activity cycle. The transit photometry also restricted their analysis to spots within the transit chord, which covers only 6% of the observer-facing stellar hemisphere per transit.

High resolution spectroscopy is a complementary means of quantifying the disk-integrated activity of HAT-P-11 on long timescales. Emission in the cores of the CaII H & K features is generated in the chromosphere over active regions. CaII H & K emission is typically measured as the flux in the emission features normalized by two pseudocontinuum regions on either side of the absorption features, called the S -index. The S and related R'_{HK} indices of solar-like stars has been studied over many years and across spectral types and ages (Baliunas et al., 1995; Duncan et al., 1991; Noyes et al., 1984; Wilson, 1978). CaII emission generally declines with age (Skumanich, 1972) – with a large intrinsic variance driven by the rotation of active regions into and out of view, and stellar activity cycles (see review by Hall, 2008).

Here we measure the S -index of HAT-P-11, and put the activity of HAT-P-11 into context among stars of similar spectral type and age by calculating R'_{HK} . In Section 6.2 we present spectroscopy from Keck/HIRES and Apache Point Observatory (APO) ARC 3.5 m Telescope from 2008-2017 and find evidence for an activity cycle. We compare the activity cycle observed in spectroscopy with the total stellar brightness in the *Kepler* band from full-frame image photometry in Section 6.3. In Section 6.4 we investigate whether or not the abundant activity of HAT-P-11 is “normal” among stars of similar age and spectral type.

6.2 Observations of the *S*-index

We can search for the activity cycle of HAT-P-11 if we combine observations from Keck/HIRES and recent observations from the Astrophysical Research Consortium (ARC) 3.5 m Telescope at APO. However, the definition of the *S*-index has the unfortunate property that its value varies from one instrument to the next for the same intrinsic flux. Therefore *S*-index measurements must be calibrated against the stars observed in the Mount Wilson Observatory (MWO) sample before spectra from different observatories can be compared. In Section 6.2.1 we calibrate the linear correction for the *S*-index measured by the ARC Echelle Spectrograph (ARCES) at APO, and in Section 6.2.2 we combine the recent APO spectra with archival Keck/HIRES spectra to span nine years of observations.

6.2.1 Calibrating the *S*-index for APO

We reduce the raw ARCES spectra with IRAF methods to subtract biases, remove cosmic rays, normalize by the flat field, and do the wavelength calibration with exposures of a thorium-argon lamp¹. We fit the spectrum of an early-type star with a high-order polynomial to measure the blaze function, and we divide the spectra of HAT-P-11 and the MWO stars by the polynomial fit to normalize each spectral order.

Next the normalized spectra must be shifted in wavelength into the rest-frame by removing their radial velocities. We remove the radial velocity by maximizing the cross-correlation of the ARCES spectra with PHOENIX model atmosphere spectra (Husser et al., 2013).

To calibrate the ARCES spectra, we follow the calibration procedure developed in Isaacson & Fischer (2010) for HIRES. We collect 51 spectra of 30 stars in the Duncan et al. (1991) MWO sample with the ARC 3.5 m Telescope at APO and the ARCES spectrograph, including 22 K stars, 7 G stars and one M star – see Figure 6.1 for example spectra.

We measure the *S*-index for these stars by taking the sum of the flux in the cores of the

¹ An ARCES data reduction manual by J. Thorburn is available at http://astronomy.nmsu.edu:8000/apo-wiki/attachment/wiki/ARCES/Thorburn_ARCES_manual.pdf

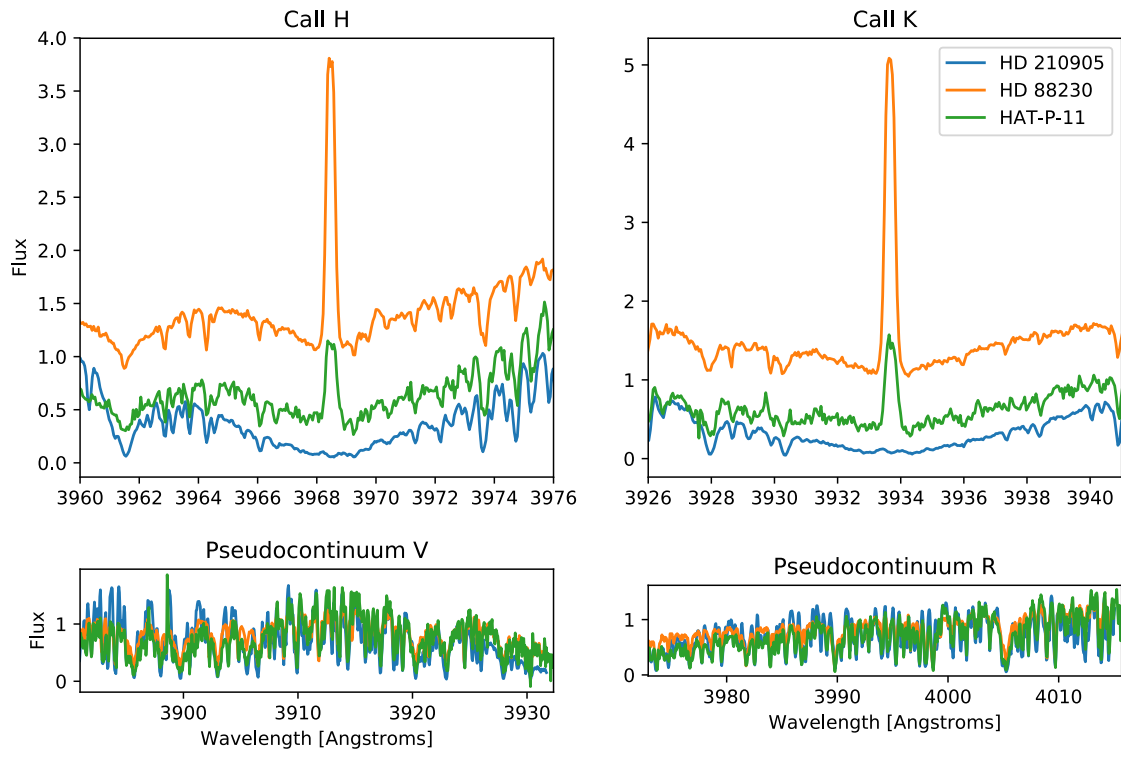


Figure 6.1: Spectra of two CaII H & K calibration targets on the high and low activity ends, and HAT-P-11 in the middle.

H and K features at 3968.47 Å and 3933.66 Å, weighted with a triangular weighting function with FWHM=1.09Å. We normalize the weighted emission by the flux in pseudocontinuum regions R and V , which are 20 Å-wide bands centered on 3900 and 4000 Å, respectively. Then S on the MWO-calibrated scale is

$$S_{APO} = \frac{a H + b K}{c R + d V} \quad (6.1)$$

$$S_{MWO} = C_1 S_{APO} + C_2, \quad (6.2)$$

where a , b , c , d , C_1 and C_2 are parameters that can be tuned to make ARCES S -indices match the scale of S_{MWO} (Duncan et al., 1991). Following the example of Isaacson & Fischer (2010), we chose values of a, b, c, d so that S has roughly equal flux contributions from the H and K emission lines, and roughly equal flux from the R and V pseudocontinuum regions in the APO spectra. Thus we set $a = c = 1$, and we choose $b = 2$ and $d = 1$, so that $H \sim b K$ and $K \sim d V$.

Since S varies over time for each star in the sample, the linear correlation between the S_{APO} and S_{MWO} will have some intrinsic spread. To incorporate this into our model, we adopt the $\langle S \rangle$ and the standard deviation of S from Duncan et al. (1991) as the measurement and uncertainty of the MWO values. We solve for the constants C_1 and C_2 and their uncertainties with Markov Chain Monte Carlo (MCMC) (Foreman-Mackey et al., 2013; Goodman & Weare, 2010); the results are shown in Figure 6.2.1. We find $C_1 = 21.26^{+0.99}_{-0.83}$ and $C_2 = 0.009^{+0.011}_{-0.009}$. The S -indices for each target are enumerated in Table 6.1. The software tools used to calculate calibrated S -indices with spectra from ARCES are publicly available².

6.2.2 The S -index of HAT-P-11

With the transformation computed in the previous section, we can compare the APO S -index measurements with those from the archival Keck/HIRES spectra. HAT-P-11 was the target

² <https://doi.org/10.5281/zenodo.886629>

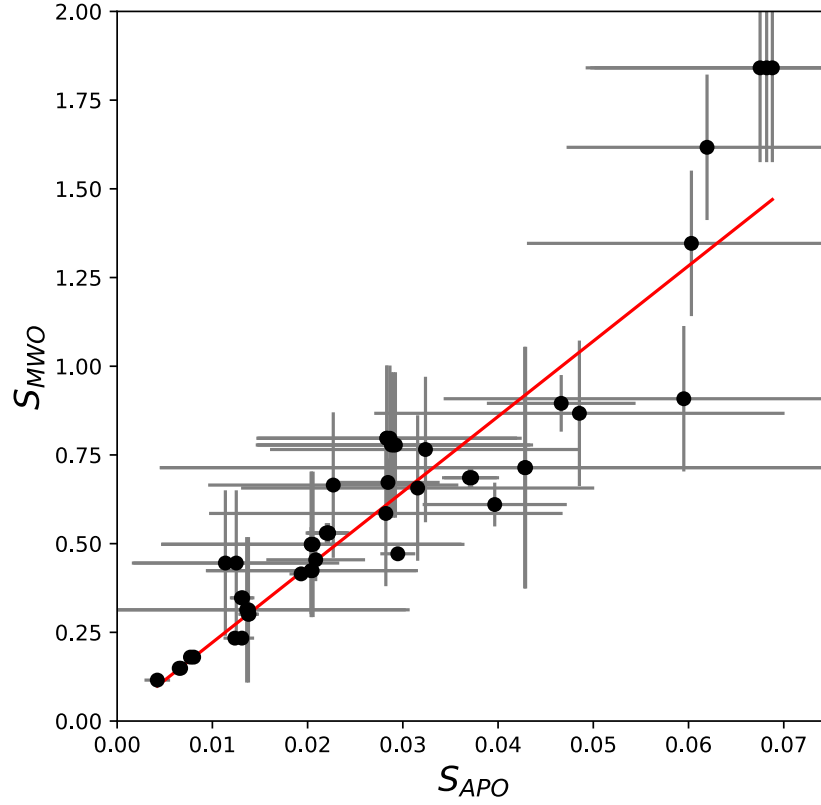


Figure 6.2: We calibrate the S -index measured with the APO echelle spectra against previous measurements from Mount Wilson Observatory (MWO) (Duncan et al., 1991). The large uncertainties in the MWO measurements are a result of the intrinsic activity variation of each star, and the uncertainties of the APO observations correspond to the measurement uncertainties.

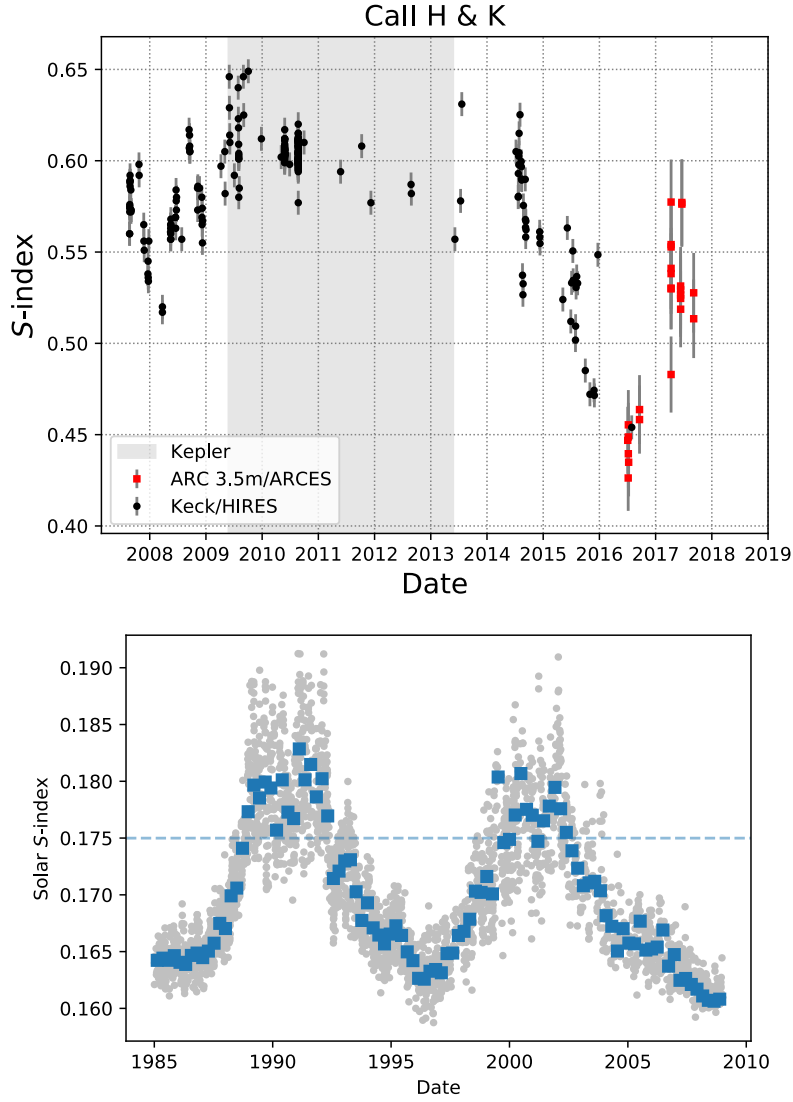


Figure 6.3: *Upper:* S -index of HAT-P-11 over time with archival Keck/HIRES spectra and calibrated APO spectra from this work. We see evidence for an activity cycle with period ~ 10 years or more. *Lower:* the S -index of the Sun, from the National Solar Observatory (NSO) Integrated Sunlight Spectrometer (ISS) on the Synoptic Optical Long-term Investigations of the Sun (SOLIS) telescope. We convert the ISS CaII K line fluxes to S -indices with Eqns. 5 and 12 of Egeland et al. (2017). If we have observed nearly one complete activity cycle of HAT-P-11, it appears that HAT-P-11 spends a longer fraction of the cycle near activity maximum than the Sun does.

of several Keck/HIRES programs since the planet’s discovery, with the aims of measuring the Rossiter-McLaughlin effect and searching for a third body³. We measure S -indices from these observations with the HIRES activity pipeline described in Isaacson & Fischer (2010). A complete description of the HIRES pipeline developed for these measurements is beyond the scope of this paper; we refer the reader to Isaacson & Fischer (2010) for the full description. The result is an unevenly-sampled series of 239 S measurements spanning 2007-2016, with typical $S/N \sim 20$.

Figure 6.3 shows the S -index of HAT-P-11 between 2008-2017, including both the APO and Keck spectra. The APO S -indices are enumerated in Table 6.2. The black circles are measurements from Keck/HIRES, and the red circles are measurements from APO. The chromospheric activity of HAT-P-11 appears to ramp up in the years preceding the *Kepler* mission, stabilize near a maximum throughout the *Kepler* years from 2009-2014, and then decline rapidly from 2014-2016 before rising at a similar rate through the present.

Activity indices like S vary on two timescales – one driven by the rotation period of the star (29.2 d) as active regions rotate into and out of view, and the longer timescale throughout the activity cycle. It appears from this limited time series that HAT-P-11 may have entered activity maximum near the beginning of the *Kepler* observations. It is interesting to note that Morris et al. (2017a) found that the starspots of HAT-P-11 are distributed in active latitudes centered on $\bar{\ell} = 16 \pm 1^\circ$, similar to the distribution of sunspots near solar activity maximum. The S -index appears to corroborate that if HAT-P-11’s activity cycle is similar to the Sun’s, it was at active maximum during the *Kepler* years.

Further spectroscopic monitoring will be required to determine the period of the activity cycle of HAT-P-11. During the summer of 2017, we measure $\langle S \rangle_{2017} = 0.54 \pm 0.04$, still less than the earliest available measurements from the summer of 2007 $\langle S \rangle_{2007} = 0.569 \pm 0.006$ – it appears that one complete activity cycle has not yet elapsed. This gives a lower limit on

³ We use archival spectra from program PIs: Bakos, D. Bayliss, Beichman, Borucki, P. Butler, D. Fischer, Ford, Fortney, J. Fuller, Gaidos, Hillenbrand, Howard, J. Johnson, Knutson, Mandushev, Marcy, Rogers, Sanchis-Ojeda, S. Vogt

the activity cycle period of ~ 10 years. The solar activity cycle is not perfectly periodic; the mean cycle duration and standard deviation are 10.9 ± 1.2 years (Hathaway et al., 2002). This lower limit on the activity cycle of HAT-P-11 observed thus far is longer than some solar activity cycles, but not longer than the mean. In principle one could attempt to measure the period of HAT-P-11's cycle by invoking empirical models of S inspired by the solar activity cycle. However, as we will discuss below, HAT-P-11's S -index distribution with time departs from the typical S distribution of the Sun – HAT-P-11 spends more time near active maximum than minimum. Therefore we can only constrain a lower limit on the period with the observations thus far, and refrain from attempting to fit for the cycle period.

The activity minimum of HAT-P-11 was short compared to its maximum. We note the marked difference between HAT-P-11 and the Sun in this respect in Figure 6.3. Since we have not yet measured a full activity cycle of HAT-P-11 and the time sampling is very uneven, it is difficult to make concrete statements about the true duration of its maximum or minimum. One quantity that might be robust against these biases is the fraction of the activity cycle spent above or below the mean of S_{min} and S_{max} , assuming the minimum and maximum observed S are close to the true minimum and maximum of S throughout the cycle. The Sun spends 25% of the cycle above $0.5(S_{min} + S_{max}) = 0.174$. The same quantity for HAT-P-11 is $0.5(S_{min} + S_{max}) = 0.53$, and its S was above that value from around or before 2008 until mid-2015, and stayed below that value until mid-2017. It appears that HAT-P-11 spent 63% of its cycle above the mean of S_{min} and S_{max} , assuming an ~ 11 year cycle.

If HAT-P-11 has an ~ 11 year activity cycle, it falls in a sparse region of rotation period-cycle period parameter space. Böhm-Vitense (2007) showed that stars typically fall into one of two categories: the young, active A -sequence, and old, inactive I -sequence (see Böhm-Vitense 2007 Fig. 1). A -sequence stars typically have ratios of cycle periods to rotation periods $P_{cyc}/P_{rot} \sim 360$, and I -sequence stars have $P_{cyc}/P_{rot} \sim 80$. The Sun is a notable outlier residing in between the sequences with $P_{cyc}/P_{rot} \sim 160$. If HAT-P-11's activity cycle is roughly ~ 11 years, it is interesting to note that it has $P_{cyc}/P_{rot} \sim 139$, and it falls between the A and I sequences, like the Sun.

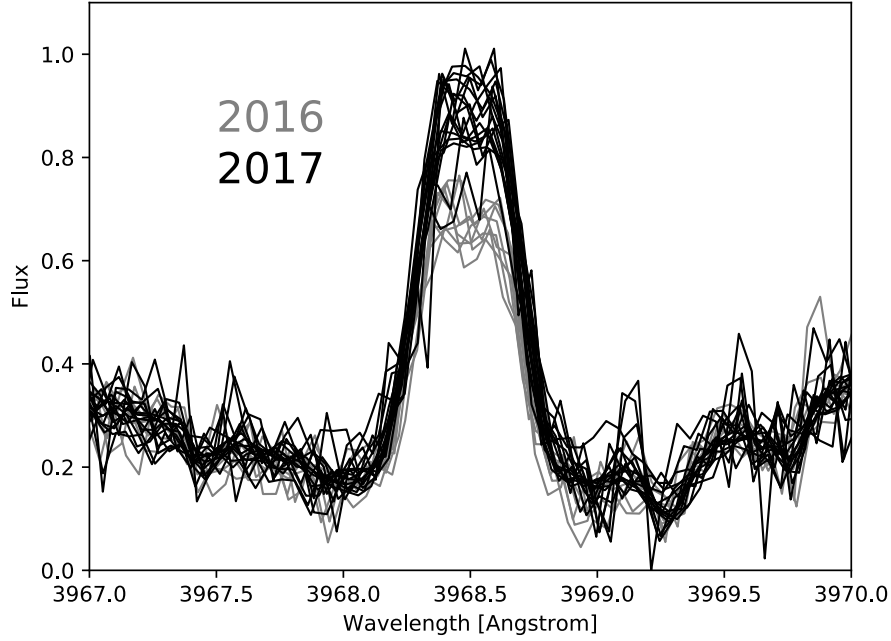


Figure 6.4: The CaII H feature of HAT-P-11 shows clear evolution towards more activity from 2016 to 2017 in the APO spectra. It appears that the activity may be approaching its maximal level as of mid-2017.

The APO spectra in Figure 6.4 demonstrate that the activity has increased significantly in just the last two years. If we assume the cycle has a period of ~ 11 years, we expect the next maximum to begin near 2019-2020. We predict that TESS photometry of HAT-P-11 will show spot occultations similar to those observed during the *Kepler* mission.

6.3 *Kepler Full-frame image photometry*

Montet et al. (2017) searched for long term variability of *Kepler* targets in photometry from the full-frame images (FFIs). These were special exposures where the entire *Kepler* detector was read-out, whereas the short and long cadence photometry from *Kepler* was only telemetered for a small subset of the pixels. There were eight FFIs in 2009 during

commissioning, and then approximately one per month for the remainder of the mission.

We use HAT-P-11 as a test-case for the reliability of long-term trends in FFI photometry, see Figure 6.5. The FFI photometry shows that the flux of HAT-P-11 varied by $\sim 2\%$ from 2009-2013 without a significant secular trend. The scatter in the FFI photometry is consistent with the scatter in the short-cadence SAP fluxes due to rotational variability of the star. Note that one should only compare the global scatter of the FFI and SAP fluxes to one another, and one should not expect the SAP light curve to perfectly intersect with the SAP measurements, since the SAP fluxes shown in Figure 6.5 are normalized by the median flux of each quarter, and the FFI fluxes are normalized by the median flux over all FFIs.

The S -index in Figure 6.3 indicates that HAT-P-11 had nearly uniform chromospheric emission throughout the years of the *Kepler* mission. Both the *Kepler* photometry and S -index are consistent with an active maximum period from 2009-2013.

The long term photometric variability of most Sun-like stars with rotation periods of 29 d is dominated by bright faculae (Montet et al., 2017). Future space-based photometry missions could therefore expect to measure a small dimming of the star during its short activity minimum.

6.4 HAT-P-11 in context

6.4.1 Comparison to stars of similar color

Is the chromospheric activity of HAT-P-11 typical for K4 dwarfs? The photometric analysis by Morris et al. (2017a) can't be reproduced for many other *Kepler* stars. HAT-P-11 is exceptionally bright ($V = 9.59$), and the highly inclined orbit of its planet reveals the latitude distribution of spots during transit events. Since very few similar targets are available for comparison in the *Kepler* sample, we seek to compare the spectrum of HAT-P-11 to spectra of other stars.

The S -index varies with stellar effective temperature, so the large S of HAT-P-11 compared to the Sun does not imply that HAT-P-11 has more chromospheric activity than the

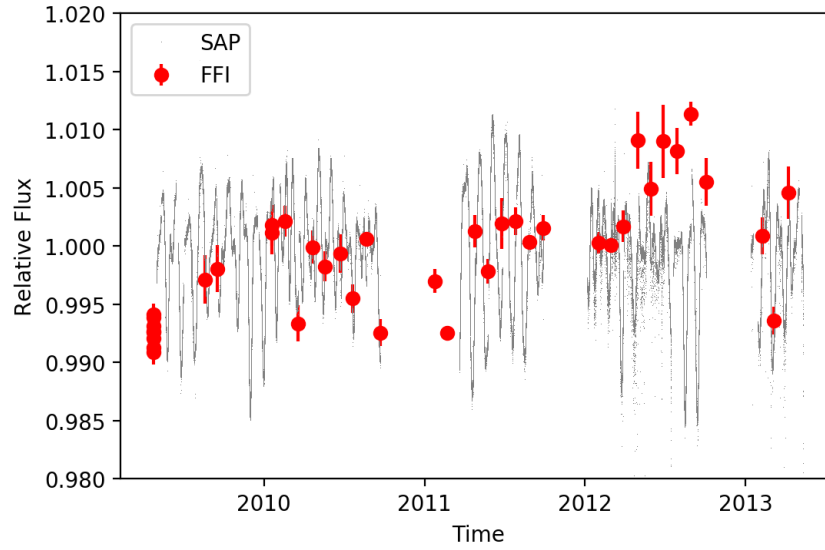


Figure 6.5: Full-frame image photometry of HAT-P-11 (red circles) and *Kepler* SAP one minute cadence fluxes (gray). Montet et al. (2017) searched for evidence of stellar activity cycles in the full-frame image (FFI) photometry. The S -index was near maximum throughout the *Kepler* mission, so we expect the FFI photometry to show scatter consistent with the 2% rotational modulation in the *Kepler* short-cadence light curve. The FFI photometry indeed show scatter consistent with the rotational variability, without a significant secular trend.

Sun. The R'_{HK} index is often used instead to compare activity levels across the main sequence, by normalizing the flux in the CaII H & K emission features by the basal flux from the photosphere (Noyes et al., 1984). For stars of any effective temperature, R'_{HK} increases with chromospheric activity.

We compute the R'_{HK} index for a large sample of main sequence stars, following the procedure of Mittag et al. (2013). We gathered published S -indices from Duncan et al. (1991), Wright et al. (2004) and Isaacson & Fischer (2010). As in Mittag et al. (2013), we select only main sequence stars with color and absolute magnitude cuts using Hipparcos parallaxes (Perryman et al., 1997), yielding a sample of 4677 main sequence stars with measured S -indices. We then solve for R'_{HK} for each star. We also compute R'_{HK} for HAT-P-11 using its mean $\langle S \rangle = 0.58 \pm 0.04$.

The R'_{HK} index for each star in the literature is shown in Figure 6.6. The characteristic rise in chromospheric activity for later type stars is visible in the right half of the figure. HAT-P-11 is the red square with $B - V = 1.19$ and $\log R'_{HK} = -4.35$ (evaluated for $\langle S \rangle$). The Sun is represented with the $\odot$ symbol and resides in the inactive sequence, blueward of HAT-P-11.

HAT-P-11 has typical chromospheric activity among field stars of similar color. It lies near the lower envelope of R'_{HK} at $B - V \sim 1.2$, which one might expect given its rotation period $P_{rot} = 29.2$ d since R'_{HK} declines with increasing age and rotation period (Noyes et al., 1984). HAT-P-11 also hosts a close-in planet which one might speculate could affect its activity, and in general we don't know the planet occurrence frequency in this sample of stars. As a result, it is perhaps more interesting to compare the chromospheric activity of HAT-P-11 to planet-hosting stars of similar color *and* age.

6.4.2 Comparison to planet hosts of similar color and age

Is the chromospheric activity of HAT-P-11 typical for planet-hosting K stars with long rotation periods? We build a sample of stars with similar effective temperatures to HAT-P-11 from the California-Kepler Survey (CKS), in which Petigura et al. (2017) published Keck-

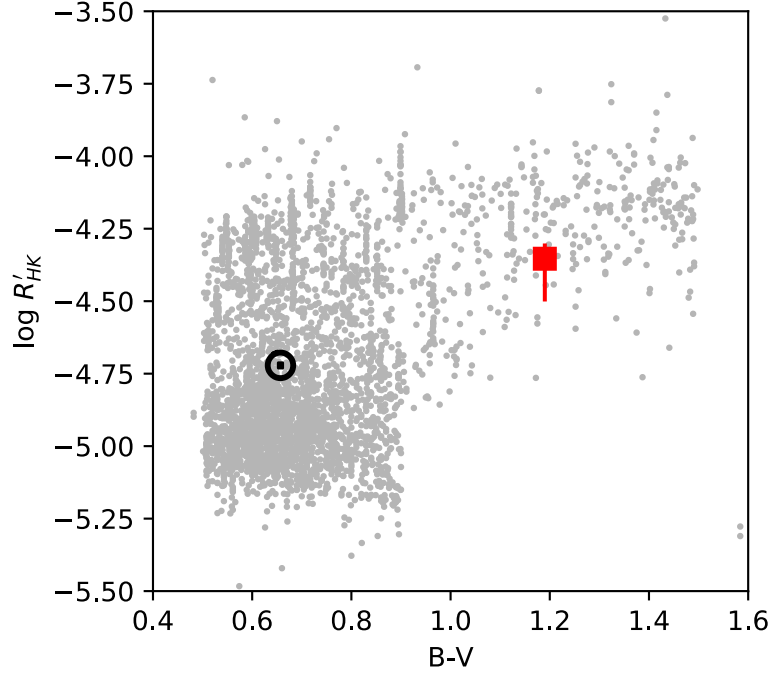


Figure 6.6: The R'_{HK} index of HAT-P-11 (red square) among other main sequence stars (circles). The Sun is represented by the black “ $\odot$ ” symbol, and resides on the the inactive branch of bluer stars. The distribution of R'_{HK} at a given $B - V$ color is dominated by variation with age. Dwarfs with $B - V > 1$ typically have more active chromospheres than dwarfs with $B - V < 1$. The errorbars on the square representing HAT-P-11 denote the minimum and maximum R'_{HK} given the complete range of observed S values throughout the activity cycle.

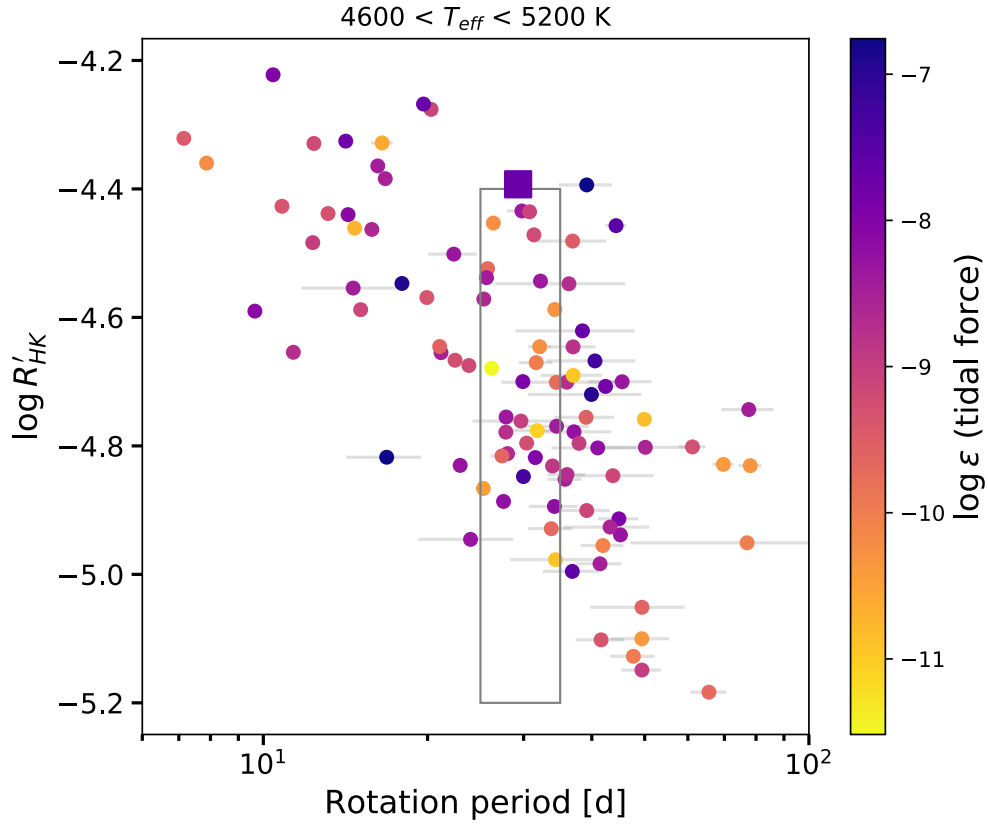


Figure 6.7: The R'_{HK} index of HAT-P-11 (big square) among other main sequence planet-hosting stars (circles). HAT-P-11 is among the most active planet-hosting K stars with rotation periods near 30 d – its R'_{HK} is similar to the median R'_{HK} for stars with rotation periods near ~ 15 days.

/HIRES spectra and Johnson et al. (2017) published precise stellar parameters for 1305 planet-hosting *Kepler* stars. We gather the CKS spectra of 107 planet-hosting stars which meet the following criteria: they have (1) effective temperatures in the range $4600 < T_{eff} < 5200$ K Petigura et al. (2017), bracketing HAT-P-11 at $T_{eff} = 4780 \pm 50$ K (Bakos et al., 2010); (2) innermost planets with orbital periods < 20 days; and (3) $S/N > 50$, where we approximate S/N by dividing the median flux in the blue spectrum by the median uncertainty in the public CKS spectra.

We replicate the procedure in Section 6.2.1 to calculate S -indices for the CKS stars using the HIRES correction coefficients from Isaacson & Fischer (2010), and use the relations of Mittag et al. (2013) to compute R'_{HK} indices for each star as in Section 6.4.1. We also gather rotation periods for each star from Mazeh et al. (2015), and we compute the Rossby number for each star with convective turnover times computed from the relations of Wright et al. (2011).

We are particularly interested in whether or not HAT-P-11 experiences unusual planet-induced tides, which could provide a coupling between the planet’s orbit and stellar activity. To quantify the relative tidal force on each star at the seat of stellar activity, the base of the convective zone, we use the simple dimensionless parameter ϵ ,

$$\epsilon = \frac{M_p}{M_\star} \left(\frac{R_c}{a} \right)^3 \quad (6.3)$$

where M_p and $M_\star$ are the masses of the planet and star, R_c is the radius of the convective zone, and a is planet’s orbital semi-major axis (Ogilvie, 2014). The above equation is the ratio of the tidal force of the planet at the base of the convective zone $F_{tide} \propto M_p R_c / a^3$ to the local force of gravity within the star $F_g \propto M_\star / R_c^2$. This simple ratio does not take into account other likely important factors like the stellar obliquity. However, in the vast majority of cases the stellar obliquity is not known, so we continue to investigate tides with the imperfect index ϵ , and discuss the implications of this caveat below.

We evaluate the tidal ϵ for the innermost planet in each system. We adopt the stellar radii and semi-major axes from the isochrone fits of Johnson et al. (2017). We estimate the radius

of the convective zone for each star by interpolating between the convective zone radii of model stars by van Saders & Pinsonneault (2012) of solar metallicity with $4600 < T_{eff} < 5200$ K. Finally, we adopt the mass measurement for HAT-P-11 b, $M_p = 0.081 M_J$ from Bakos et al. (2010), and estimate the most probable mass for all other planets using the **forecaster** tool by Chen & Kipping (2017), given the measured planetary radii from Johnson et al. (2017).

We recover the canonical result that R'_{HK} generally decreases with rotation rate (or age) in Figure 6.7. It appears that HAT-P-11 (large square) has more chromospheric activity than other planet-hosting stars of similar rotation periods and effective temperatures. The gray box in Figure 6.7 circumscribes 31 stars with rotation periods $25 < P_{rot} < 35$ d. The median activity level within the box is only 40% of HAT-P-11's, $\log R'_{HK} = -4.75$.

6.4.3 *The possible role of tides*

Could the relatively high level of chromospheric activity on HAT-P-11 (for stars with its age and color) be related to the tides raised by the close-in planet? We show the ϵ - R'_{HK} distribution of stars with $25 < P_{rot} < 35$ d in Figure 6.8. We note that in this range of rotation periods, HAT-P-11 (red square) has the most chromospheric activity and the second-greatest ϵ . However, the lack of correlation between R'_{HK} and ϵ suggests: (1) the tidal force isn't the only important factor in setting the level of chromospheric activity; and (2) the simple parameterization of ϵ does not capture all of the relevant physics.

Significant tides are raised by HAT-P-11 b, even when compared to solar system objects. We can compare it's $\log_{10} \epsilon = -7.7$ with more familiar systems. ϵ at the base of the solar convective zone due to tides raised by Mercury gives $\log_{10} \epsilon = -13$, much less than any of the systems in Figure 6.8. The Earth-Moon system experiences more similar tides with $\log_{10} \epsilon = -7.3$, and the dimensionless tidal force on HAT-P-11 is significantly less than the Jupiter-Io tides, $\log_{10} \epsilon = -6.6$. The tides raised by HAT-P-11 b are significant, and may have non-negligible effects on the interior dynamics of the star.

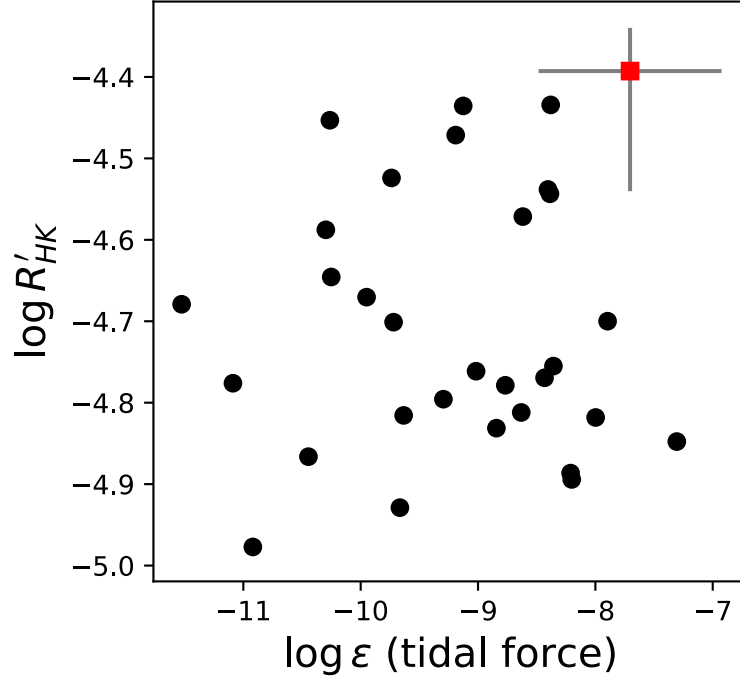


Figure 6.8: The R'_{HK} index for stars within the gray box in Figure 6.7, with rotation periods $25 < P_{rot} < 35$ d and effective temperatures $4600 < T_{eff} < 5200$ K. HAT-P-11 (red square) has the most activity in this bin, and the second-greatest tidal force on the base of its convective zone. The uncertainty in R'_{HK} on HAT-P-11 represent its variation throughout its activity cycle. The uncertainty in ϵ on HAT-P-11 represents the characteristic uncertainty for all systems, which is dominated by uncertainty in the planet mass-radius relation of Chen & Kipping (2017).

6.4.4 The possible role of stellar obliquity

Why is there no correlation between tidal force and chromospheric activity in this sample? We investigate the system with the greatest ϵ in more detail. That system is KOI-1050 with $\log_{10} \epsilon = -7.2$. Its star has mass $M_\star = 0.83M_\odot$, effective temperature $T_{eff} = 5068$ K and rotation period $P_{rot} = 29.9$ d. It is orbited by planet with radius $R_p = 1.85R_\oplus$, orbital period 1.27 d and forecasted mass $M_p = 4.4M_\oplus$. R'_{HK} of KOI-1050 is less than half of HAT-P-11's despite its larger ϵ .

The dimensionless tidal force ϵ does not account for the transfer of energy due to obliquity tides – the result of additional torques in star-planet systems with planetary orbits that are highly misaligned with respect to the stellar spin. The amplitude of energy transfer due to obliquity tides is proportional to $\sin^2 \psi$, where ψ is the angle between the orbital angular momentum vector and the stellar spin axis (Wisdom, 2004). The high obliquity of HAT-P-11 $\psi = 106^{+15}_{-11}$ suggests that obliquity tides on HAT-P-11 will contribute additional dissipation of orbital energy, which is not reflected by ϵ . Lacking measurements of the obliquity of the other systems in Figure 6.8 such as KOI-1050, the observations presented here are insufficient to comment on whether or not the high obliquity of HAT-P-11 is responsible for its greater R'_{HK} activity index compared to KOI-1050, for example. Future measurements of spin-orbit misalignment of close-in planets with active host stars may allow us to link stellar activity to the tides raised by planets.

It is also possible that a weak correlation between ϵ and R'_{HK} is obscured by the large uncertainties in the forecasted planet masses. The parameter with the largest uncertainty in the calculation for ϵ is the planet mass. The forecasted mass estimates from Chen & Kipping (2017) have large uncertainties which reflect both measurement uncertainty and intrinsic spread in the observed planetary mass-radius relation. For the planets in the sample considered here, the median uncertainty in the forecasted planet mass is 78%, which contributes to uncertainty on the order of 1 dex in epsilon. Thus the typical uncertainty in our estimates of ϵ is significant compared to the range observed. Follow-up radial velocity

or transit timing variation measurements are needed to better constrain planet masses, and thus their tidal influence on their host stars.

Alternative activity indicators have been used to search for evidence that tidal interactions stoke stellar activity (see reviews by Poppenhaeger, 2017; Wright & Miller, 2015). For example, Poppenhaeger & Wolk (2014) and Miller et al. (2015) found enhanced stellar coronal X-ray emission from host stars that are expected to have strong tidal interactions with their hot Jupiters. Saar & Cuntz (2001) measured the chromospheric emission in the CaII infrared-triplet over time for stars with hot Jupiters, and found that the emission did not fluctuate on the orbital period of the planet.

In addition to tidal interactions, close-in planets can also interact magnetically with their host stars. Cohen et al. (2010); Lanza (2010) showed that star-planet magnetic interactions can affect the angular momentum evolution of host stars. These studies examined planets with orbit normals that were aligned or anti-aligned with the stellar spin. The magnetic interactions between the star and planet in the HAT-P-11 system – with its planet in a polar orbit – are worthy of further study, and beyond the scope of this paper.

6.5 Conclusion

We present S -indices for HAT-P-11 from 2008-2017, which show evidence of an activity cycle of duration $\gtrsim 10$ years. We detail the calibration procedure for measuring S -indices with the echelle spectrograph on the ARC 3.5 m Telescope at APO. If the activity cycle is ~ 11 years, we expect the star to remain highly active from the present until ~ 2023 , thus TESS will be able to observe spot occultations throughout the active maximum.

If we interpret the local minimum in S near mid-2016 to be the true activity minimum, it seems that HAT-P-11 spends a greater fraction of time at maximum ($\sim 63\%$) than the Sun does ($\sim 25\%$). The brightness of HAT-P-11 throughout the maximum lasting from 2009-2014 is consistent with under-sampled rotational variability, and does not show a significant secular trend.

Among all K dwarfs, the strength of HAT-P-11’s chromospheric activity measured by

R'_{HK} is unremarkable. However, among planet-hosting dwarfs with similar rotation periods and effective temperatures, the chromosphere of HAT-P-11 is exceptionally active. We speculate that tides raised by the planet on the star may play a role in the atypical activity.

Appendix

Table 6.1: Stars observed to calibrate the S -index. Star

Sp. Type	S_{MWO}	S_{APO}	N	
HD 210905	K0III	0.092 ± 0.013	0.004 ± 0.000027	1
HD34411	G1V	0.145 ± 0.022	0.007 ± 0.000069	2
HD68017	G3V	0.174 ± 0.024	0.008 ± 0.00011	2
HD98230	G2V	0.266 ± 0.031	0.012 ± 0.000052	2
HD 217906	M2.5II-IIIe	0.284 ± 0.033	0.013 ± 0.00017	2
HD 201251	K4Ib-IIa	0.292 ± 0.034	0.013 ± 0.000085	2
HD110833	K3V	0.306 ± 0.035	0.014 ± 0.0001	2
HD39587	G0VCH+M	0.308 ± 0.035	0.014 ± 0.000091	2
HD134319	G5V:	0.432 ± 0.033	0.019 ± 0.000069	1
HD41593	K0V	0.457 ± 0.049	0.020 ± 0.00012	2
HD87884	K0Ve	0.458 ± 0.06	0.020 ± 0.00018	3
HD 220182	G9V	0.467 ± 0.035	0.021 ± 0.000051	1
HD47752	K3.5V	0.495 ± 0.074	0.022 ± 0.00022	4
HD127506	K3.5V	0.508 ± 0.038	0.023 ± 0.00014	1
HD 122120	K5V	0.633 ± 0.046	0.028 ± 0.00014	1
HD200560	K2.5V	0.638 ± 0.049	0.028 ± 0.00045	1
HD 82106	K3V	0.638 ± 0.08	0.028 ± 0.00017	3
HD 79555	K4V	0.651 ± 0.082	0.029 ± 0.00024	3
HD 129333	G1.5V	0.661 ± 0.048	0.029 ± 0.000066	1
HD149957	K5V	0.708 ± 0.057	0.032 ± 0.0007	1

HD148467	K6V	0.727 ± 0.057	0.032 ± 0.00062	1
HD 218356	K1IV(e)+DA1	0.834 ± 0.085	0.037 ± 0.00022	2
GJ702B	K4V	0.891 ± 0.065	0.040 ± 0.00042	1
HD45088	K3Vk	0.963 ± 0.097	0.043 ± 0.00028	2
GJ 9781A	K7	1.048 ± 0.075	0.047 ± 0.00016	1
HD 113827	K4V	1.091 ± 0.078	0.049 ± 0.00019	1
HD175742	K0V	1.339 ± 0.095	0.060 ± 0.00034	1
HD151288	K7V	1.357 ± 0.098	0.060 ± 0.00057	1
HD 88230	K8V	1.394 ± 0.099	0.062 ± 0.00021	1
HD 266611	K5V	1.534 ± 0.19	0.068 ± 0.00085	3

Table 6.2: S -index measurements of HAT-P-11 from the ARC 3.5 m Telescope Echelle Spectrograph (ARCES) at the Apache Point Observatory (APO), calibrated against the Mount Wilson Observatory S -index.

JD	S	Uncertainty
2457572.9442	0.45	0.04
2457575.9589	0.43	0.04
2457576.8890	0.44	0.04
2457576.8978	0.45	0.04
2457576.9065	0.45	0.04
2457578.9182	0.43	0.04
2457649.6839	0.46	0.04
2457649.6964	0.46	0.04
2457854.8691	0.48	0.04
2457854.8899	0.53	0.04
2457854.9056	0.55	0.05
2457854.9212	0.53	0.04
2457854.9369	0.54	0.04
2457854.9527	0.54	0.04
2457854.9684	0.55	0.04
2457854.9840	0.58	0.05
2457916.8112	0.53	0.04
2457916.8338	0.53	0.04
2457916.8937	0.52	0.04
2457916.9163	0.53	0.04
2457916.9372	0.52	0.04
2457924.8090	0.58	0.05
2457924.8260	0.58	0.05
2458001.6552	0.53	0.04
2458001.6778	0.51	0.04

Chapter 7

ARE STARSPOTS AND PLAGES CO-LOCATED ON ACTIVE G AND K STARS?

In Chapter 5 we discovered that the latitude and radius distributions of starspots on HAT-P-11 are similar to the Sun’s, and in Chapter 6 we found that the chromospheric activity of HAT-P-11 is somewhat elevated compared to stars of similar rotation periods and spectral types. We focused on the dark starspots in Chapter 5 rather than the bright faculae which are probably present on the star for two reasons: (1) typical faculae have smaller flux contrast in the *Kepler* band compared to the mean photosphere than a typical starspot; and (2) our light curve inversion software **STSP** assumes circular active regions with fixed contrast, which is a better approximation for starspots than it is for regions of faculae, which are often extended and increase in contrast towards the limb of the star.

In this chapter, we attempt to measure the presence of faculae *and* starspots with observations of the Ca II H & K emission features and with simultaneous photometric monitoring in a red-optical bandpass. The Ca II H & K emission should be brightest when faculae are facing the observer, whereas the photosphere will appear darkest in the red-optical when the most spotted hemisphere of the star faces the observer. Simultaneously understanding the starspot and faculae distributions of active stars is important in the context of exoplanet transmission spectroscopy, where we often assume that the stellar surface beneath the transit chord of the exoplanet emits a similar spectrum to the rest of the stellar surface. If starspots or plagues occupy the observer-facing hemisphere but not the transit chord of the exoplanet, for example, these unocculted stellar surface features will introduce chromatic variations to the transit depth of the exoplanet which can be mistaken for spectral features of the exoplanet’s atmosphere (see e.g. Rackham et al., 2018). Therefore it is critical that

we understand the distribution of not only starspots but plages as well, and the relationship between their positions on stellar surfaces.

This chapter was first published in the *Astronomical Journal* (Morris et al., 2018f).

7.1 Introduction

Sunspots are regions of the solar photosphere where convection is suppressed by strong magnetic fields (Solanki, 2003; Spruit, 1977). These spots typically account for a small portion of the photosphere, covering only a fraction of a percent of the solar hemisphere (Howard et al., 1984). Approximately a thousand kilometers above the photosphere lies the chromosphere. Observing the chromosphere in the cores of the Ca II H or K lines reveals regions of bright emission known as plages. Plages show a latitude dependence similar to sunspots, and the largest solar plages are typically spatially associated with dark sunspots. However, smaller plages often appear without cospatial sunspots, although at scales larger than 4 arcsec darker photospheric features, due to flux emergence, are observed to be cospatial with Ca II enhanced sites (Guglielmino et al., 2010; Hall, 2008; Mandal et al., 2017).

For distant stars, we are not privy to the same spatially resolved view. However, we can probe the connection between plages and starspots with time resolved spectroscopy and precision photometry. Plages are bright in the cores of the Ca II H & K features, while the broadband *Kepler* flux of a star, for example, is diminished when starspots face the observer (Douglas et al., 2016, 2017, 2014; McQuillan et al., 2013, 2014; Walkowicz & Basri, 2013). In this work, we present a study of chromospheric Ca II H & K emission and photospheric starspot absorption on the rotation period timescale for three stars to address the question: *are plages and starspots co-located on active G and K stars?*

Synoptic observations of chromospheric emission in Ca II H & K among many stars suggest that the emission variations of older, Sun-like stars increase with the stellar photometric variation; whereas young stars tend to become fainter overall as emission from plages increases (Radick et al., 2018, 1998). These observations are based on long-term monitoring

campaigns of many stars with multi-epoch photometry and spectroscopy spread over years, and represent the effect of the activity cycle on the total irradiance and chromospheric emission of each star.

We collected simultaneous ground-based photometry and spectroscopy of young G star KIC 9652680 over the course of several rotations. This star is remarkable for having 8% amplitude flux variations in the *Kepler* band – see Figure 7.1 – and for producing a “super-flare” (Notsu et al., 2015a). The largest observed flare of KIC 9652680 reached 10^{34} erg, or roughly $100\times$ more energy than the Carrington event (Carrington, 1859; Neuhäuser & Hambaryan, 2014; Notsu et al., 2015b). We present a similar analysis of the chromospheric and photospheric activity on this possible proxy for the young Sun.

We also present simultaneous *K2* photometry and spectroscopy of two mid-K dwarfs in the young (650 Myr), nearby Praesepe cluster (M44). Confined to the ecliptic, the K2 mission provided precision photometry of Praesepe members in Campaigns 5 and 16 (Howell et al., 2014). Campaign 16 was remarkable for being a “forward-looking” campaign, meaning that simultaneous observations were possible from ground-based observatories. We took advantage of that opportunity and collected more than 30 hours of high resolution spectra of EPIC 211928486 and EPIC 211966629 throughout the campaign, allowing us to study the connection between chromospheric and photospheric activity. These two Praesepe members may be young proxies for the well-studied mid-K dwarf HAT-P-11 (Deming et al., 2011; Morris et al., 2018g, 2017b,c; Sanchis-Ojeda & Winn, 2011).

We describe our spectroscopy of all targets in Section 7.2. We measure the rotation periods and flux-activity correlation of the young G star in Section 7.3, and do the same for two K-dwarfs in Section 7.4. We discuss the results in Section 11.6 and conclude with Section 11.7.

7.2 APO/ARCES Spectroscopy

The ARC Echelle Spectrograph (ARCES) on the ARC 3.5 m Telescope at Apache Point Observatory is an $R \approx 31,000$ cross-dispersed spectrograph. This analysis closely follows the

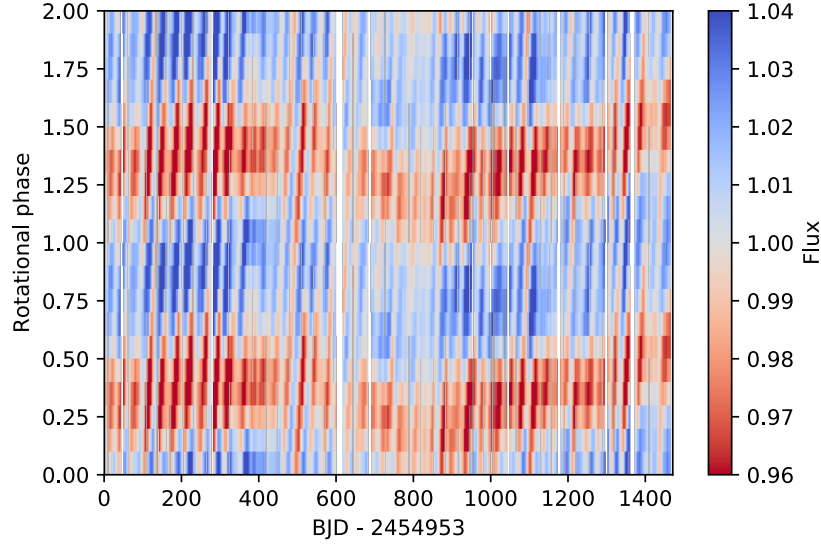


Figure 7.1: Rotational map of KIC 9652680. Each column shows one rotation (repeated twice for clarity, as in (Davenport et al., 2015)) of the star, where color corresponds to relative flux of the star as a function of rotational phase. Each row is therefore a time-series of fluxes at one longitude, averaged over all latitudes, spanning the duration of the *Kepler* mission. The map shows one predominantly bright hemisphere, and the other darker, which remains roughly stable over the four year *Kepler* mission.

	KIC 9652680	EPIC 211928486	EPIC 211966629
T_{eff} [K]	5900 ± 100	4408 ± 100	4484 ± 100
$\log g$	4.47	4.66	4.66
[Fe/H]	+0.21	+0.12	+0.12
$v \sin i$ [km s ⁻¹]	39	2 ± 2	3 ± 2
P_{rot} [d]	1.41 ± 0.01	11.8 ± 0.1	11.6 ± 0.2
$\log R'_{\text{HK}}$	-3.92 ± 0.03	-4.16 ± 0.03	-4.11 ± 0.02
$f_{S,\text{min}}$	0.26	0.041–0.046	0.061–0.083

Table 7.1: Stellar parameters

procedure of Morris et al. (2017c) and makes use of its software (Morris & Dorn-Wallenstein, 2018). After stacking all exposures on a given night, we reduce the raw ARCES spectra with IRAF methods to subtract biases, remove cosmic rays, normalize by the flat field, and do the wavelength calibration with exposures of a thorium-argon lamp.¹ We fit the spectrum of an early-type star with a high-order polynomial to measure the blaze function, and we divide the spectra of each star by the polynomial fit to normalize each spectral order.

Next, the normalized spectra must be shifted in wavelength into the rest-frame by removing their radial velocities (RVs). We remove the radial velocity by maximizing the cross-correlation of the ARCES spectra with PHOENIX model atmosphere spectra (Husser et al., 2013).

7.3 Young G Star: KIC 9652680

7.3.1 Stellar Properties

KIC 9652680 is a rapidly-rotating, chromospherically active, G-type star. Rapid rotation is often interpreted as a sign of youth, but can also be caused by a tidally-interacting companion (e.g., a RS CVn type binary, Eaton & Hall 1979) or as a result of blue straggler formation (e.g., mass accretion Bailyn 1995), though these scenarios require the presence of a stellar companion. According to the second data release of the European Space Agency’s *Gaia* Mission (DR2 Gaia Collaboration et al., 2018a), this star has RV error 3.42 km s^{-1} from 12 observations (Katz et al., 2018; Soubiran et al., 2018); we measured RVs from our 13 ARCES observations and found a standard deviation of $\approx 1 \text{ km s}^{-1}$. These low RV values are consistent with KIC 9652680 being a single, rapidly rotating star, which is suggestive of youth.

Its age is further corroborated by the presence of strong Li absorption at $6707.8 \text{ \AA}$, where $A(\text{Li}) = 3.39 \text{ dex}$ (Honda et al., 2015), which is unexpected in the alternative scenarios.

¹ An ARCES data reduction manual by J. Thorburn is available at http://astronomy.nmsu.edu:8000/apo-wiki/attachment/wiki/ARCES/Thorburn_ARCES_manual.pdf

Considering its rotation and activity via the gyrochronology and activity–age relations and cluster activity data presented in Mamajek & Hillenbrand (2008), together with the lithium data for the Pleiades provided by Bouvier et al. (2018), KIC 9652680 appears to be at least as young as the Pleiades, or $\lesssim 110\text{--}125$ Myr (Gaia Collaboration et al., 2018c; Stauffer et al., 1998).

Its rapid rotation, and resulting $v \sin i \approx 39 \text{ km s}^{-1}$, complicates our spectroscopic characterization of KIC 9652680. However, if it is in fact a young star on or near the zero-age main-sequence, then its absolute magnitude or luminosity is actually a powerful indicator of metallicity. We therefore compare KIC 9652680 to other young stars from *Gaia* DR2 in order to constrain its metallicity.

Figure 7.2 shows the *Gaia* DR2 color–magnitude diagram (CMD; $G_{\text{BP}} - R_{\text{RP}}$ vs M_G) for chromospherically active (i.e., relatively young stars, with $\log R'_{\text{HK}} < -4.7$ dex corresponding to ages under 2 Gyr), solar-type stars observed with Keck/HIRES by the California Planet Survey (CPS) and characterized with Spectroscopy Made Easy (SME; Piskunov & Valenti, 2017; Valenti & Fischer, 2005; Valenti & Piskunov, 1996) by Brewer et al. (2016) with the procedures outlined in Brewer et al. (2015).

We excluded stars with $\log g < 4.3$ dex to ensure that we are focusing on un-evolved dwarf stars, and included stars with HIRES spectra with $S/N > 70$ per pixel to select those with precise spectroscopic properties, and focused on stars with precise DR2 photometry ($\sigma < 0.05$ mag) with parallax-inverted distances within 200 pc to minimize the effect of interstellar reddening and extinction on the CMD. The majority of these stars are presumably single, and on or near the main-sequence. The stars in Figure 7.2 are color-coded according to their spectroscopic metallicities; as expected, metallicity explains the majority of the apparent scatter in this CMD, and the higher metallicity stars follow a more luminous track in the CMD. KIC 9652680 is found at the top of the main-sequence envelope among a string of 8 stars with the following properties (median $\pm$ standard deviation): $[\text{Fe}/\text{H}] = +0.205 \pm 0.024$ dex, $\log g = 4.475 \pm 0.023$ dex, and $T_{\text{eff}} = 5844 \pm 90$ K. Fitting a quadratic function to $(G_{\text{BP}} - G_{\text{RP}})$ vs. T_{eff} for this sequence, KIC 9652680 has $T_{\text{eff}} = 5900 \pm 20$ K, where the

uncertainty is calculated as the rms of the spectroscopic values about our quadratic color- T_{eff} relation.

The two stars with $(G_{\text{BP}} - G_{\text{RP}})$ closest to KIC 9652680 (marked as cyan-colored squares in Figure 7.2), and which happen to bracket it, have the following spectroscopic properties: HD 222986 has $T_{\text{eff}} = 5858$ K, $\log g = 4.47$ dex, $[\text{Fe}/\text{H}] = +0.26$ dex, $v \sin i = 5.8$ km s $^{-1}$, and $\log R'_{\text{HK}} = -4.35$ dex; HD 101847 has $T_{\text{eff}} = 5948$ K, $\log g = 4.47$ dex, $[\text{Fe}/\text{H}] = +0.23$ dex, $v \sin i = 5.6$ km s $^{-1}$, and $\log R'_{\text{HK}} = -4.43$ dex; The $v \sin i$ values are much lower than KIC 9652680, which allowed Brewer et al. (2016) to measure precise stellar properties from the HIRES spectra. According to the Mamajek & Hillenbrand (2008) activity-rotation-age relation, their chromospheric emission indices imply ages of 105 and 227 Myr, which is young enough to assume negligible main-sequence evolution through the CMD for these stars. From this analysis, we find the following properties for KIC 9652680 from our *Gaia*-CPS analysis: $T_{\text{eff}} = 5900$ K (based on the color- T_{eff} relation), $\log g = 4.47$ dex (based on these two stars), and $[\text{Fe}/\text{H}] = +0.21$ dex (based on the median for the 8 star sequence).

Next, we analyzed our 13 ARCES observations of KIC 9652680 with SME version 522 using the Valenti & Fischer (2005) strategy, which focuses on the 5164–5190 Å region centered on the pressure-sensitive Mg1 b triplet and seven additional segments spanning 6000–6180 Å. We ran SME with T_{eff} , $\log g$, the global metallicity parameter $[\text{M}/\text{H}]$, and $v \sin i$ as free parameters; this yielded $T_{\text{eff}} = 6022 \pm 99$ K, $\log g = 4.40 \pm 0.1$ dex, $[\text{M}/\text{H}] = +0.17 \pm 0.08$ dex, and $v \sin i = 39 \pm 0.5$ km s $^{-1}$.

The T_{eff} from our ARCES spectra is warmer than our *Gaia*-CPS value by 122 K (1.2 σ using the spectroscopic T_{eff} dispersion for the uncertainty), and this discrepancy and the high dispersion in fitted parameters is likely due to the challenges of analyzing spectra of rapidly rotating stars, especially with such a restricted wavelength range compared to the full optical spectrum observed with ARCES. For this work, we will take the results from our *Gaia*-CPS analysis as our final adopted stellar properties for KIC 9652680, and assign an uncertainty to T_{eff} of 100 K to reflect the discrepancy with the SME result. The final values are listed in Table 7.1.

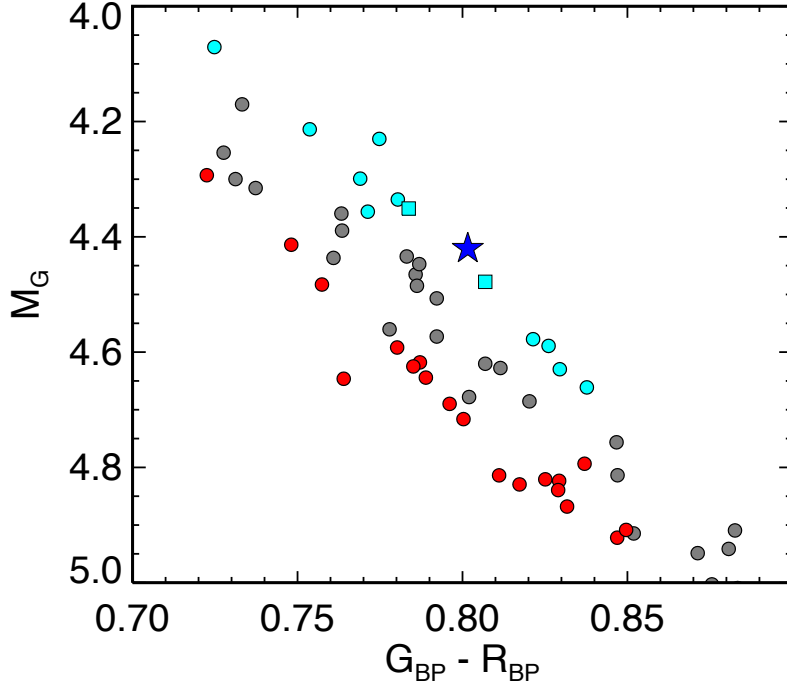


Figure 7.2: *Gaia* DR2 CMD of KIC 9652680 (blue star) and chromospherically active (i.e., young, with $\log R'_{\text{HK}} < -4.7$ dex) stars observed with Keck/HIRES by the California Planet Survey and characterized with SME by Brewer et al. (2016). Stars are color-coded according to their metallicity, where red points have $[\text{Fe}/\text{H}] < 0.0$ dex, cyan points have $[\text{Fe}/\text{H}] > +0.16$ dex, and gray points have intermediate metallicities. Assuming all stars shown are photometrically single and have evolved in isolation as single stars, then the placement of KIC 9652680 in this CMD is indicative of its metallicity, as any such star with $\log R'_{\text{HK}} \approx -4.0$ dex must be very young and on or near the zero-age main-sequence. The stars HD 222986 and HD 101847, marked with cyan-shaded squares, bracket KIC 9652680 in this diagram, indicating that it likely has properties intermediate to their values of $T_{\text{eff}} = 5858$ and 5948 K and $[\text{Fe}/\text{H}] = +0.26$ and $+0.23$ dex, respectively, with $\log g = 4.47$ dex.

7.3.2 Rotational modulation

The *Kepler* PDCSAP light curve of the G1V star KIC 9652680 shows rotational modulation consistent with a bright hemisphere followed by a relatively dark hemisphere, generating photometric variability with semi-amplitude 4%, see Figure 7.1. We compute the rotation period and its uncertainty from the *Kepler* observations by taking the mean and difference between the Lomb-Scargle periodogram and the first peak in the autocorrelation function, finding $P_{\text{rot}} = 1.41 \pm 0.01$ d.

We observed KIC 9652680 over five nights in the SDSS *u* and *g* bands with FlareCam on the ARCSAT 0.5 m telescope at Apache Point Observatory; see Figure 7.3. We computed differential photometry with three neighboring comparison stars – our ARCSAT photometry pipeline is open source and available online².

We model the flux variations in both bands simultaneously with the multiband Lomb-Scargle (MLS) technique of VanderPlas & Ivezić (2015) with two sinusoidal terms (red curves). MLS estimates the relative flux of the star in each band assuming the periodic signals have the same phase but different amplitudes in each band. The flux variations that we observed with ARCSAT show similar rotational modulation amplitude in the SDSS *g* band compared to the *Kepler* semi-amplitude of 4%. The MLS prediction allows us to interpolate between observed fluxes to estimate the flux of the star at the epochs of each ARCES spectrum, to search for correlations between the *S*-index and broadband flux of the host star.

7.3.3 Minimum spot covering fractions via flux deficit

We can compute the minimum spot covering fractions required to produce the observed rotational modulation from the flux deficit, via

$$f_{\text{S,min}} = \frac{1 - \min \mathcal{F}}{1 - c} \quad (7.1)$$

² https://github.com/bmorris3/arcsat_monitoring

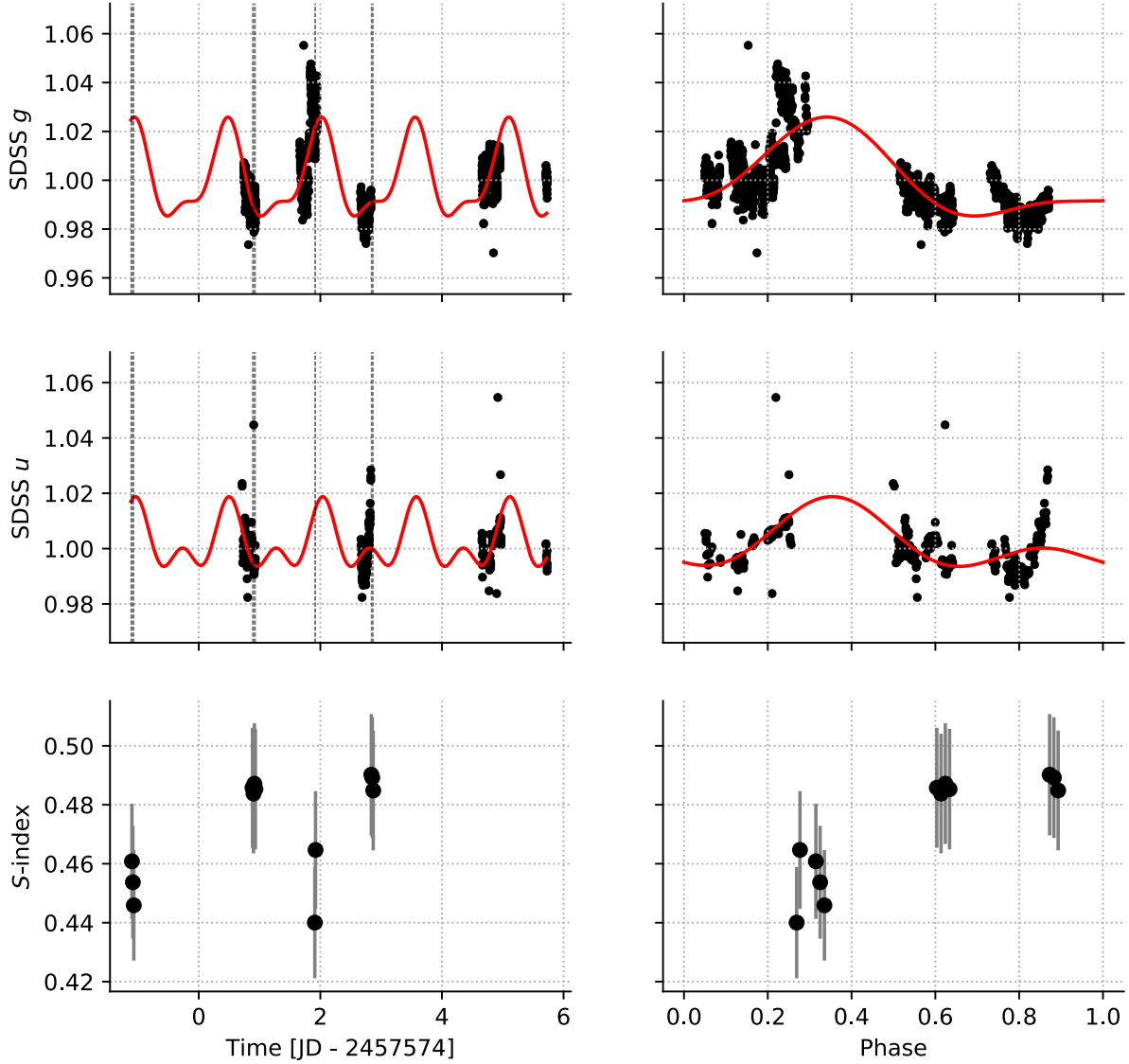


Figure 7.3: ARCSAT and ARCES monitoring campaign of KIC 9652680 to constrain the rotational phase at each spectroscopic measurement. The left column shows the time-series photometry in SDSS g and u bands, along with the Ca II H & K S -index measured as a function of time. The red curve shows the best-fit multiband Lomb-Scargle periodic model to the photometry; the vertical dotted lines mark the times of the spectroscopic observations. The right column shows the same information phased to the rotation period of the star.

where $\mathcal{F}$ is the stellar flux, and c is the spot contrast (where $c = 0$ is a spot with the same intensity as the photosphere and $c = 1$ is a spot that is perfectly dark). Assuming the same average contrast as sunspots, $c = 0.3$ (see e.g. Morris et al., 2017b), we compute spot covering fraction from the *Kepler* light curve, and find $f_{S,\min} \gtrsim 0.17$. This large spot covering fraction is roughly consistent with observations of young G stars like EK Draconis, for example, which has $f_S = 0.25 - 0.40$ according to TiO molecular band absorption measurements by O’Neal et al. (2004).

7.3.4 Flux- S -index correlation

Figure 7.4 shows an anti-correlation between the photosphere flux in SDSS g and the chromospheric emission from KIC 9652680. We interpret this anti-correlation as evidence for spatial association between regions of chromospheric activity and the starspots in the photosphere below, as is observed on the Sun. As the spots and their associated plages rotate into view, the S -index increases and SDSS g flux decreases in sync.

We note that the minimum in KIC 9652680’s observed S -index does not correspond to the minimum possible S -index for a star of KIC 9652680’s color ($S \gtrsim 0.15$, Isaacson & Fischer see e.g. 2010). We still observe significant chromospheric emission when the dark spot which dominates the rotational modulation is out of view – thus the network of plages must extend around all rotational phases of the star, while a significant component of the chromospheric emission is associated with the dark spot.

7.4 Mid-K Dwarfs: *EPIC 211928486* and *EPIC 211966629*

7.4.1 Stellar Properties

EPIC 211928486 and EPIC 211966629 are members of the benchmark open cluster Praesepe (M44, NGC 2632)³ which has an age of 620-790 Myr (Brandt & Huang, 2015; Choi et al.,

³ According to *Gaia* DR2, each star is co-moving with Praesepe. EPIC 211966629 (*Gaia* DR2 661335288963844736) actually has a discrepant parallax that places it 20 pc beyond the cluster center,

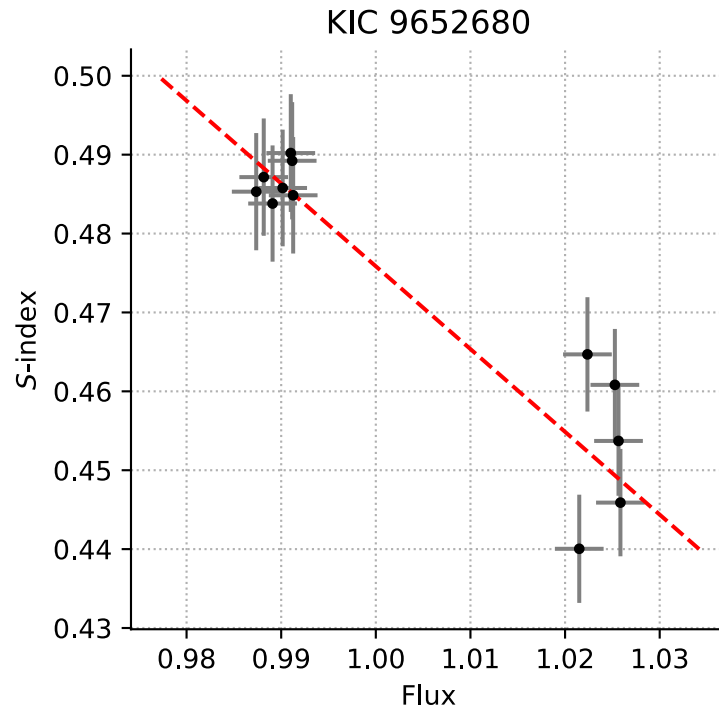


Figure 7.4: S -index of KIC 9652680 as a function of the stellar flux in the SDSS g band. The anti-correlation may suggest that a portion of the chromospherically active region, which produces bright emission in Ca II H & K, is co-located with the photospheric dark starspot, which decreases the stellar flux.

2016; Cummings et al., 2017; Gaia Collaboration et al., 2018c; Gossage et al., 2018), a metallicity of $[\text{Fe}/\text{H}] = +0.12\text{-}0.16$ dex (although various results in the literature range from $+0.038$ to $+0.27$ dex; see Table 4 in Cummings et al., 2017), and suffers little if any interstellar reddening and extinction ($E(B - V) = 0.027$, Taylor, 2006). Allen & Strom (1995) classified these stars with low-resolution optical spectra as K5V and K4V, respectively.

More recently, each star was observed with the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; Luo et al., 2015) and stellar properties and RVs were measured and provided in the third data release. EPIC 211928486 and EPIC 211966629 were both classified as K5 dwarfs with the following properties: $T_{\text{eff}} = 4413$ K and 4487 K, $\log g = 4.69$ dex and 4.49 dex, and $[\text{Fe}/\text{H}] = +0.08$ dex and -0.03 dex.

Each star appears to be effectively single. First, their *Gaia* DR2 RVs have small errors ($\sigma \lesssim 1 \text{ km s}^{-1}$) and are consistent with the cluster’s bulk velocity. We also measured relative RVs between the two stars on seven separate nights (six in Dec 2017, one in Feb 2018), and found that they are constant to within 0.5 km s^{-1} . Second, EPIC 211928486 is within 0.02 mag of, and EPIC 211966629 is 0.10 mag brighter than, the Praesepe single-star main-sequence, according to the *Gaia* DR2 CMD for Praesepe using the membership from Gaia Collaboration et al. (2018c). We attribute this modest apparent magnitude enhancement to the cluster’s depth (at 186 pc, a cluster with an angular size of 2.5 degrees has a physical radius of ~ 8 pc; this translates to a ± 0.09 mag distance modulus effect); alternatively, there could be a $\sim \text{M3V}$ companion, but it would likely be non-interacting due to the observed low RV dispersion.

While Andrae et al. (2018) provided T_{eff} values inferred from the *Gaia* DR2 photometry, we opted to re-calibrate the DR2 T_{eff} scale using the benchmark sample of K and M dwarfs characterized with interferometry and bolometric fluxes by Boyajian et al. (2012) by fitting a quadratic function between the DR2 color ($G_{\text{BP}} - G_{\text{RP}}$) and T_{eff} for these stars. We adopted

which we assume is why it was not classified as a member by Gaia Collaboration et al. (2018c); however, we note that this might be due to its non-zero astrometric noise excess, and we will consider it a real member of Praesepe based on its consistent 3D kinematics, rotation, and chromospheric activity.

the Taylor (2006) value of $E(B - V) = 0.027$ and used it to de-redden the DR2 photometry for EPIC 211928486 and EPIC 211966629, then infer $T_{\text{eff}} = 4408$ K and 4484 K, respectively, whereas the DR2 catalog listed values of 4683 K and 4922 K. Our values are much closer to the LAMOST DR3 values, being only 5 and 3 K cooler, whereas the DR2 catalog values are 275 K and 438 K warmer than our values. Combining our results with LAMOST, we conclude that EPIC 211966629 is only 75 K warmer than EPIC 211928486.

We also fit the APO/ARCES spectra for these stars with SME, despite the fact that the Valenti & Fischer (2005) strategy we followed is optimized for late-F to early-K dwarfs. According to Gaia Collaboration et al. (2018c), Praesepe’s DR2 CMD can be approximately described with a PARSEC isochrone (Bressan et al., 2012a; Marigo et al., 2017) with an age of 700 Myr and $[\text{Fe}/\text{H}] = +0.12$ dex. We decided to ignore the Mg1 b order (5164-5190 Å) which is challenging to accurately normalize for mid-K dwarfs, then fixed the metallicity to $[\text{Fe}/\text{H}] = +0.12$ dex, and fixed $\log g$ to 4.65 dex based on this isochrone. We fit the spectrum for T_{eff} and $v \sin i$, then combined the results from the multiple observations as the median and standard deviation, and report the following properties: for EPIC 211928486, $T_{\text{eff}} = 4510 \pm 28$ K and $v \sin i = 2 \pm 2$ km s $^{-1}$; for EPIC 211966629, $T_{\text{eff}} = 4592 \pm 19$ K, and $v \sin i = 3 \pm 2$ km s $^{-1}$, where the $v \sin i$ error is primarily due to the uncertain spectral resolution at each epoch, as well as the macroturbulent broadening. Here, we found that EPIC 211966629 is 82 K warmer than EPIC 211928486, which is nearly identical to the relative T_{eff} we found from our photometric calibration and the LAMOST DR3 value, although the spectroscopic T_{eff} values are systematically warmer than these other results by ~ 100 K. We set this offset as our T_{eff} uncertainty, and adopt the photometric results as our final values. For metallicity, we adopt $[\text{Fe}/\text{H}] = +0.12 \pm 0.05$ dex (a value commonly cited for the cluster, with uncertainty estimated to encompass most modern estimates of the cluster’s metallicity). For surface gravity, we set $\log g = 4.66$ dex, taken from the 700 Myr PARSEC isochrone with this metallicity at these temperatures. These final values are listed in Table 7.1.

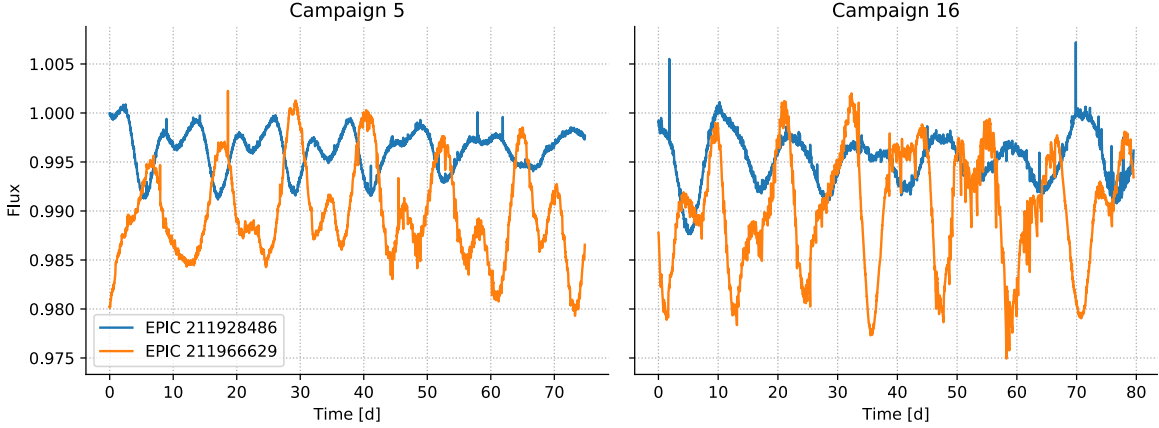


Figure 7.5: *K2* PDCSAP light curves for each target from Campaign 5 (left) and Campaign 16 (right).

7.4.2 Rotation Periods

We use *K2* photometry processed with PDCSAP pipeline for Campaigns 5 and 16, see Figure 7.5. Both stars show rotational modulation consistent with 1-2 starspots. We measure the rotation periods for each star by taking the autocorrelation function and Lomb-Scargle periodogram for each target and each campaign; see Figure 7.6. We take the mean and standard deviation of the four rotation period measurements (one LS and one ACF period for each campaign) and find $P_{\text{rot}} = 11.80 \pm 0.11$ days for EPIC 211928486, and $P_{\text{rot}} = 11.68 \pm 0.22$ days for EPIC 211966629.

The rotation periods of EPIC 211966629 measured in Campaigns 5 and 16 appear to be slightly different, though within the observational uncertainties. It is possible that the differing period measurement is astrophysical, and not an artifact of noise. If it is astrophysical, we may be measuring slightly different periods as starspots emerge at different latitudes on the star throughout the stellar activity cycle, giving a hint at differential rotation on this star. We refrain from making such a claim as previous work has made it clear that differential rotation is exceptionally hard to determine from rotational modulation (Aigrain et al.,

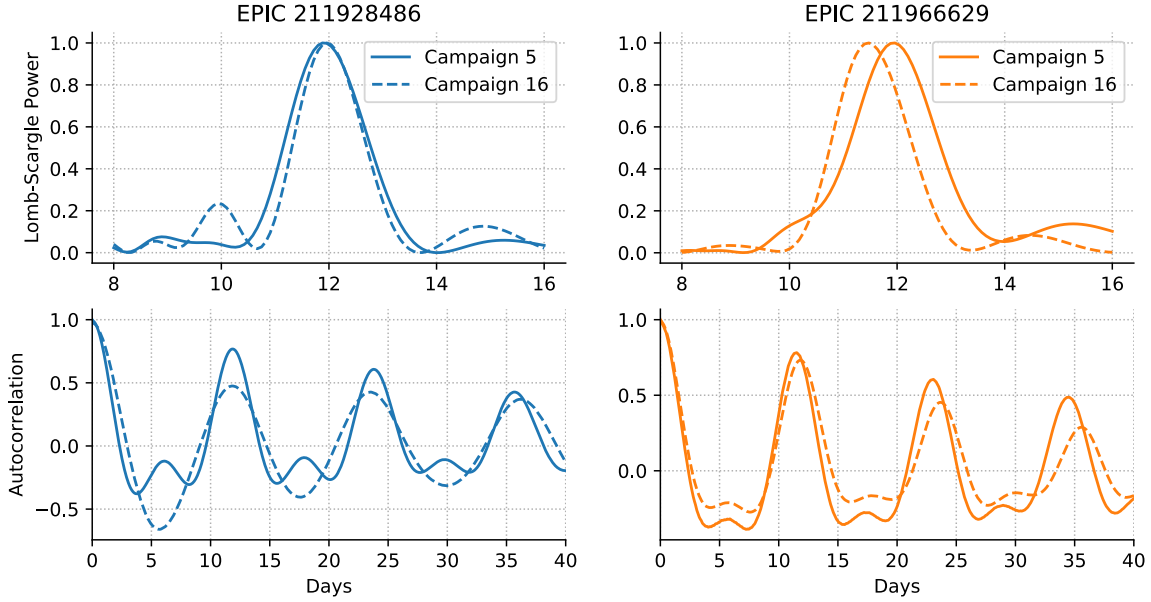


Figure 7.6: Lomb-Scargle periodogram and autocorrelation functions for the K2 photometry in Campaigns 5 and 16.

2015).

7.4.3 Minimum spot covering fractions via flux deficit

We compute the flux deficit as in the previous section. The flux deficit indicates that both stars have similar spot covering fractions, between 1 and 4%. Both stars are 100x more spotted than the Sun, and they appear to be similar to the K4 dwarf HAT-P-11 ($0 \leq f_s \leq 0.14$), which has a longer rotation period $P_{\text{rot}} = 29$ d (Morris et al., 2018g, 2017b). If we assume that these stars are young proxies for HAT-P-11, it's interesting to note that while they have more chromospheric activity, their spot coverage is similar to their slower rotating counterpart HAT-P-11.

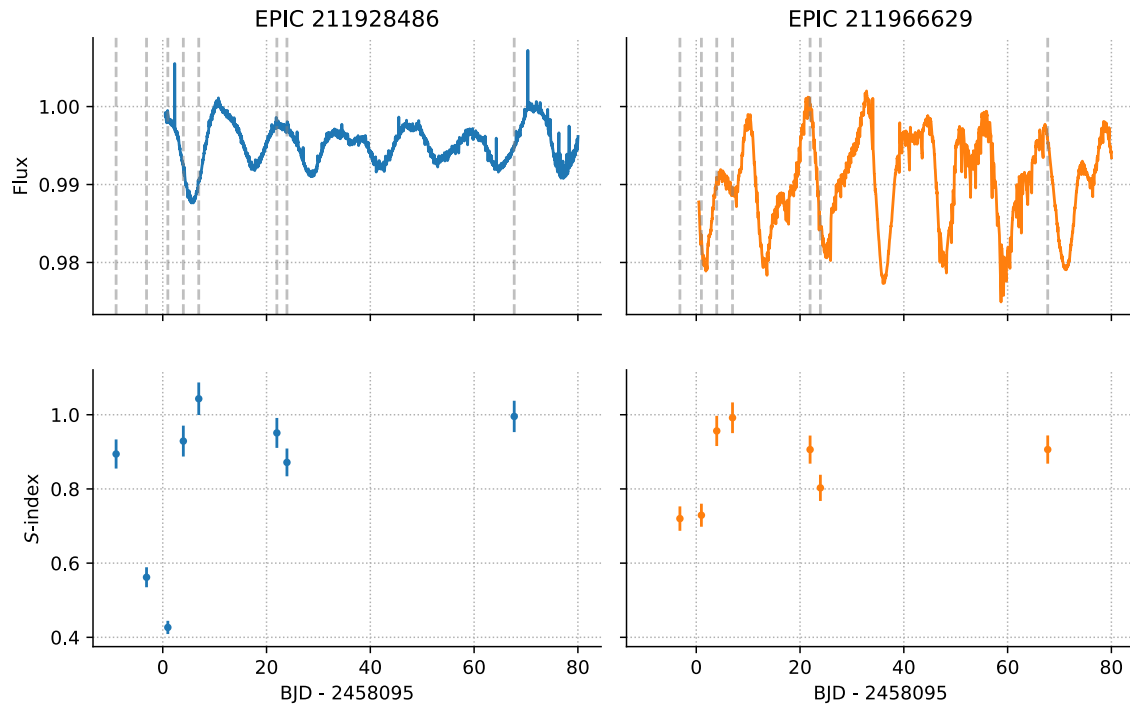


Figure 7.7: *K2* photometry with simultaneous ground-based Ca II H & K *S*-index monitoring with ARCES spectrograph on the ARC 3.5 m Telescope at APO. Vertical dashed lines on the upper row correspond to the times of spectra.

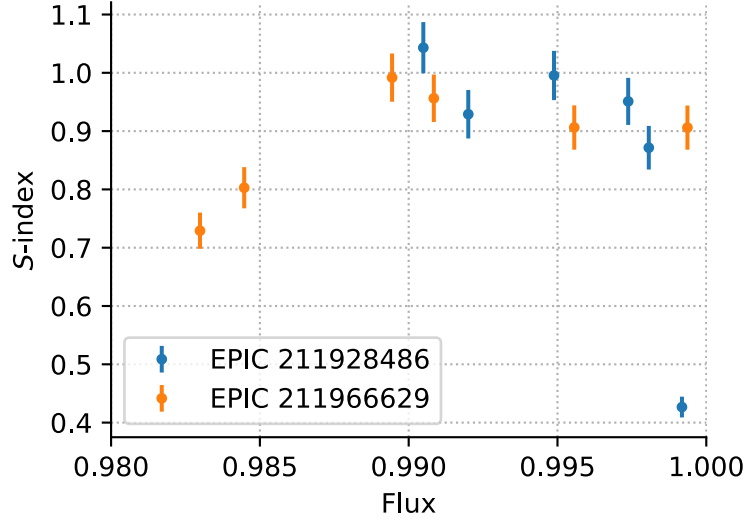


Figure 7.8: Comparing the S -index with the instantaneous stellar flux. EPIC 211928486 shows a weak anticorrelation between the chromospheric activity and the stellar flux, perhaps indicating that the dominant dark starspots are co-located with chromospherically active regions on the stellar surface. EPIC 211966629 shows no significant correlation between the flux and chromospheric activity, perhaps indicating that the chromospherically active regions are decoupled from the dominant starspots.

7.4.4 Lack of Flux- S -index correlation

Figure 7.7 shows the K2 photometry of each target (top panels), along with the S -indices that we measured with ARCES (bottom panels). Excluding the two spectra of EPIC 211928486 near BJD=2458095, the other 13 S -index measurements are more or less consistent with constant $S \approx 0.9$ for both stars, at all rotational phases. The lack of correlation between the observed stellar flux in the *Kepler* band and the S -index is demonstrated in Figure 7.8. This lack of correlation is interesting given that the corresponding $\log R'_{\text{HK}} \sim -4.1$ is generally considered “very active” (Wright et al., 2004), though the minimum spot coverage inferred from rotational modulation is only a few percent.

One could interpret of the high S -index and small minimum spot coverage to imply that there are many plages without accompanying starspots, generating significant Ca II H & K emission at all rotational phases, but not contributing significantly to the rotational modulation in the *Kepler* band. This is frequently the case on the Sun. An alternative scenario is that the star is blanketed in spots which all generate Ca II emission and photospheric absorption, and as each spot rotates into view, another rotates out of view, causing the relatively small changes in the observed *Kepler* flux ($\lesssim 2\%$).

7.4.5 Precipitous decline in S -index of EPIC 211928486

The S -indices of both stars are relatively constant with a significant exception. There is a 50% decline in the emission in the cores of the Ca II H & K lines during two consecutive epochs; see Figures 7.7 and 7.9. We have simultaneous K2 photometry for the second low- S observation, but not the first (see Figure 7.7). We have inspected the spectra to verify that there were no additional sources of continuum emission, due to interloping nearby stars or solar contamination (reflected off of clouds or the sky, though these observations were not collected near twilight), which may appear to suppress the S -index. A flare could increase the continuum relative to the Ca II emission (Kowalski et al., 2013), which would make the emission core appear weaker. If a flare was responsible, however, we would also expect to see significant H α emission; we have verified that the H α line does not show any change during these epochs.

As a result, it appears that one hemisphere had significantly less plages for a duration of about one rotation, and that the plages had recovered to their near-axisymmetric distribution by the next rotation. We are unaware of any observations in the solar literature that show a similar precipitous decline in chromospheric activity without an accompanying signature in the number of sunspots, indicating perhaps that this surprising phenomenon may be relevant to cooler or younger stars than the Sun. Continued observations of this star, preferably at higher cadence, would be valuable to constrain whether or not this phenomenon occurs regularly.

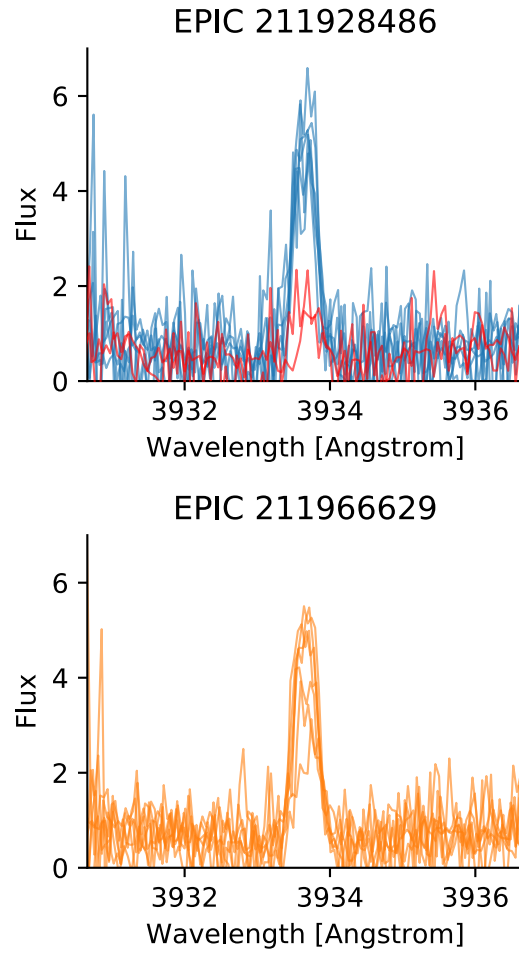


Figure 7.9: Close-in look at the Ca II K line emission from each star, highlighting the anomalously low emission from two spectra near BJD=2458095 in red (see Figure 7.8).

7.5 Discussion

A large sunspot in the solar photosphere is almost always spatially associated with a bright active region plages in co-temporal Ca II K images of the chromosphere (Mandal et al., 2017; Stix, 1989). Thus we expected to find some degree of anti-correlation between the chromospheric emission and broadband flux for Sun-like stars with large spots/plages. We observed such an anti-correlation on the young G star KIC 9652680, perhaps indicative of large plages that accompany its most-spotted hemisphere.

Similar association between plages and starspots has been observed many stars, including: 12 Oph (K1V) and 61 Cyg A (K5V) (Dorren & Guinan, 1982), several stars in the famous sample of Olin Wilson’s (Radick et al., 1983), several Hyades members (Lockwood et al., 1984), and the RS CVn variable UX Ari (K0IV) (Gu, 2005).

We do not find a correlation between the broadband flux and chromospheric emission for the two mid-K stars EPIC 211928486 and EPIC 211966629. This may indicate that the plages are distributed axisymmetrically about the stellar surface, or that the spots that contribute to rotational modulation are too small to generate substantial chromospheric emission. From spot occultations during planetary transits of HAT-P-11 b, we know that the spots on mid-K stars can be as large as the largest spots on the Sun at solar maximum (Morris et al., 2018g, 2017b), and therefore one might expect plages to accompany those large spots. Thus we posit that the near-constant significant chromospheric emission of EPIC 211928486 and EPIC 211966629 is more likely due to an axisymmetric distribution of plages (and perhaps spots as well).

The sudden decrease and recovery in the S -index of EPIC 211928486 may indicate that the evolution timescale of plages on these mid-K dwarfs is of order the rotation period. Large active regions on the Sun can last from days up to several rotations (Solanki, 2003). What we are observing is a curious *lack* of activity lasting only a rotation, without an accompanying brightening of the star, as one might expect if the spots vanished, or dimming of the star, as one might expect if a planet or companion eclipsed the active regions. We invite observers

to monitor the Ca II emission of this star, for want of an explanation. We note that solar plages are observed at highest contrast with at the solar limb, and therefore their rotational signal on other stars will be slightly more complicated than the simplistic anticorrelation with total flux that we outline in this work. However, the brightening effect of faculae is small compared to the dimming due to starspots over the course of a full solar rotation. In broad optical bandpasses, the majority of the rotational modulation signal is produced by sunspots rather than faculae (Shapiro et al., 2016).

We also note that the observations presented here do not represent complete phase coverage for all stars. The photometric and spectroscopic observations are expensive and require large telescopes with dedicated observing programs, such as the one we have provided in this work. There are no other proxies for activity indices that we can draw upon for further analysis, other than the rotational modulation of the flux recorded by Kepler/FlareCam.

In future work, it would be interesting to measure the full-disk S -index of the Sun as if it were a star, to determine: (1) whether or not the simple anticorrelation between broadband flux and S indeed holds up for the Sun; and (2) whether or not the Sun exhibits dips significant dips in S like EPIC 211928486.

7.6 Conclusions

We have observed a young G star and two mid-K dwarfs with simultaneous photometry and spectroscopy to probe the connection between the distribution of plages and starspots on their surfaces as they rotate. We find that the young G star KIC 9652680 exhibits Sun-like behavior: when its most spotted hemisphere is facing us and its broadband *Kepler* flux is minimal, we observe enhanced chromospheric emission.

The same is not true for the pair of K dwarfs EPIC 211928486 and EPIC 211966629 in Praesepe. Their chromospheric emission remains relatively constant as a function of rotational phase. There is one exceptional rotation of EPIC 211928486 where the S -index declined by 50%, without the expected corresponding increase in broadband stellar flux, for which we have few good explanations. Future simultaneous observations will be possible with

NASA's TESS mission, which may allow us to determine whether the uncorrelated S -index dipping phenomenon occurs regularly for this star or mid K dwarfs like it.

Chapter 8

STELLAR PROPERTIES OF ACTIVE G AND K STARS: EXPLORING THE CONNECTION BETWEEN STARSPOTS AND CHROMOSPHERIC ACTIVITY

In the previous three chapters (5-7), we studied the magnetic activity of a few stars in detail, using spot occultations and rotational modulation to resolve individual starspots and to study the spatial correlation between faculae and starspots on Sun-like stars. In this chapter, we broaden our scope to study the magnetic activity of 55 nearby stars, including HAT-P-11 and the Sun. We collected high resolution spectroscopy of each star using the echelle spectrograph on the Astrophysical Research Consortium (ARC) 3.5 m Telescope at Apache Point Observatory to measure: the effective temperatures, surface gravities and metallicities of each star; chromospheric emission from each star using Ca II H & K; and absorption due to TiO in starspots. TiO is a molecule that forms at temperatures $\lesssim 4000$ K, thus for stars with temperatures > 4000 K, the presence of TiO features indicates the presence of cooler starspots.

This technique for measuring starspot coverage on magnetically active stars is an attractive means of stellar surface characterization for exoplanet host stars. As we explained in the introduction to Chapter 7, the presence of unocculted starspots during transmission spectroscopy observations can generate apparent trends in the transit depth as a function of wavelength, which should actually be attributed to the spectroscopic differences between the stellar surface beneath the transit chord when compared with the rest of the star. It is common practice to collect high resolution spectroscopy of exoplanet host stars upon the discovery of their exoplanets to measure the star's effective temperature and surface gravity (see e.g. Johnson et al., 2017; Petigura et al., 2017), so it may be possible to do this spec-

troscopic search for TiO absorption to constrain starspot coverages while simultaneously characterizing the host star with the same high resolution spectrum. In this Chapter, we will assess whether $R \approx 31,000$ spectra are sufficient for this task.

This chapter has been submitted for publication in the *Astronomical Journal*.

8.1 Introduction

One of the many remarkable data products produced by the ESA *Gaia* mission is a catalog of stellar effective temperatures (Gaia Collaboration et al., 2018a). The *Gaia* Apsis pipeline uses two-color photometry and parallaxes to measure effective temperatures for a broad range of stars and other objects, totalling more than 10^8 sources (Andrae et al., 2018; Bailer-Jones et al., 2013a). This indispensable resource will be a touchstone catalog for years to come, and as such, it is important to validate its results on bright, nearby stars for which the effective temperatures may be unambiguously determined using other means. In this work, we use high resolution spectroscopy analyzed with two independent methods to measure effective temperatures, and compare results to the ESA *Gaia* effective temperatures.

We also used our spectroscopy to investigate stellar activity. In a high resolution spectrum, starspots change a star's flux as a function of *wavelength*, as well as time. Magnetic starspots are cooler than the surrounding photosphere, and to a first approximation, they emit the spectrum of a cooler star. These starspots are the observable, outer manifestations of the stellar dynamos operating near and below the surface (Berdyugina, 2005).

Magnetically active regions on stellar surfaces play an increasingly important role in understanding exoplanets, both with radial-velocity measurements and transit-transmission spectroscopy (Cameron, 2017; Zellem et al., 2017, and references therein). Uncorrected variations in the stellar flux in time and wavelength can cause degeneracies when inferring the atmospheric properties of a transiting exoplanet, which can lead to, for example, false positive detections of Rayleigh scattering (see McCullough et al. 2014; Oshagh et al. 2014; Sing et al. 2011), or transparent atmospheres in blue spectral regions (Morris et al., 2018b; Rackham et al., 2018). Direct measurement of starspot covering fractions are thus important

inputs for models of photometry and spectra of active stars, which will be used to measure the transmission spectra of exoplanet atmospheres (Wakeford et al., 2018), exoplanet transit timing variations, and host star radial velocities.

The full covering fraction of starspots can be difficult to infer from their rotational variability. Only the time-varying, low-order spherical harmonics contribute to the total flux variability; stationary spots or odd harmonics yield zero net variability, while time-variable high-order even harmonics are strongly suppressed. Thus, longitudinally- or symmetrically distributed spots or slowly evolving spots on stars with long rotational periods can yield an underestimate of the total spot covering fraction. Hence, spectroscopy may be a preferable approach for measuring the total covering fraction of starspots.

One effort towards direct measurements of spot temperatures and covering fractions outside of the Solar System was led by Neff et al. (1995) (see also O’Neal et al., 1998, 2004, 2001, 1996). The authors modeled echelle spectra of active stars with a linear combination of model stellar atmospheres from a G dwarf and an M giant. In particular, they found that titanium oxide (TiO) absorption at 7054 and 8859 Å due to starspots yielded constraints on the spot temperatures and spot covering fractions. The TiO molecule is a useful tracer for starspots as it forms below temperatures of 4000 K—cool starspots near or below this temperature will produce some TiO absorption, while the rest of the photosphere of a G or K star ($T_{\text{eff}} > 4000$ K) will not.

We present a library of stellar template spectra of more than 50 stars taken with the Astrophysical Research Consortium Echelle Spectrograph (ARCES) on the ARC 3.5 m Telescope at Apache Point Observatory in Section 8.2. For each star we compute effective temperatures with a variety of techniques, and measure the activity indices S and $\log R'_{\text{HK}}$. In Section 8.3 we model the spectra of a subset of the active stars with linear combinations of the inactive stellar template spectra to infer the spot area coverage on the active stars. We discuss the results and conclusions in Sections 8.4 and 11.7.

8.2 *Stellar Parameters*

8.2.1 *Sample Selection*

We selected bright, northern targets observable from Apache Point Observatory for inclusion in this work. We chose only stars with previously measured S -indices, a measurement of chromospheric emission indicative of magnetic activity (Wilson, 1968), then divided the sample into two classes: stars that are chromospherically active or inactive.

The stellar sample of 55 stars is comprised of 29 active stars and 26 inactive stars, for a total of one F, 18 G, 34 K, and two M stars. The stellar sample is listed in Table 8.1, and detailed descriptions of each target when available are given in Appendix 8.A.

We selected a set of stars with low-value S -indices to use as templates assuming stars are essentially spotless. We also selected a set of active stars spanning the full dynamic range of the S -index. In the next section, we will fit the spectra of the active stars as a linear combinations of spectra of inactive stars (with small S -indices).

8.2.2 *Raw spectrum reduction*

We reduced the raw ARCES spectra with IRAF methods to subtract biases, removed cosmic rays, normalized by the flat field, and carried out the wavelength calibration with exposures of a thorium-argon lamp.¹ We fit each order of the spectrum of an early-type star with a high-order polynomial to measure the blaze function, and divided the spectra of the target stars by that polynomial to normalize each spectral order.

Next, the normalized spectra must be shifted in wavelength into the rest-frame by removing their radial velocities. We removed the radial velocity by maximizing the cross-correlation of the ARCES spectra with PHOENIX model atmosphere spectra (Husser et al., 2013). We fit a second-order polynomial with robust least-squares (with a Cauchy loss function) to the continuum in each order, before stitching together neighboring orders, taking the mean

¹ An ARCES data reduction manual by J. Thorburn is available at http://astronomy.nmsu.edu:8000/apo-wiki/attachment/wiki/ARCES/Thorburn_ARCES_manual.pdf

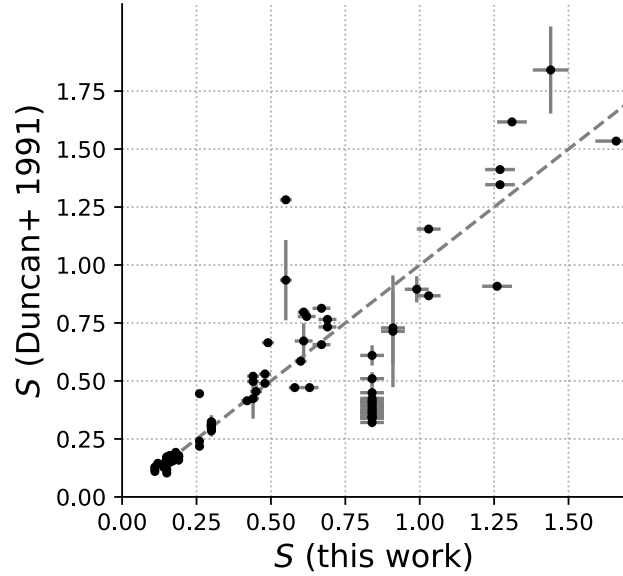


Figure 8.1: S -index measured in this work, compared with previous Mount Wilson Observatory (MWO) observations by Duncan et al. (1991).

flux in regions of overlapping wavelength coverage. The source code for the pipeline used for wavelength corrections and continuum normalization is available online (Morris & Dorn-Wallenstein, 2018).

8.2.3 Activity classification

We calculated the chromospheric Ca2 H & K activity S and $\log R'_{\text{HK}}$ indices by following the algorithm outlined in Morris et al. (2017c). In summary, we computed the flux within triangular-weighted windows centered on the Ca2 H & K features, normalized by pseudo-continuum to the red and blue of the H and K features. We then translated the instrument-native S_{APO} index into the S_{MWO} index for comparison with data collected from other instruments. Figure 8.1 compares our S -indices with measurements for a subset of stars from the Mount Wilson Observatory HK Project (Duncan et al., 1991), and we find good agreement. With these S indices, we follow the procedure outlined in Mittag et al. (2013)

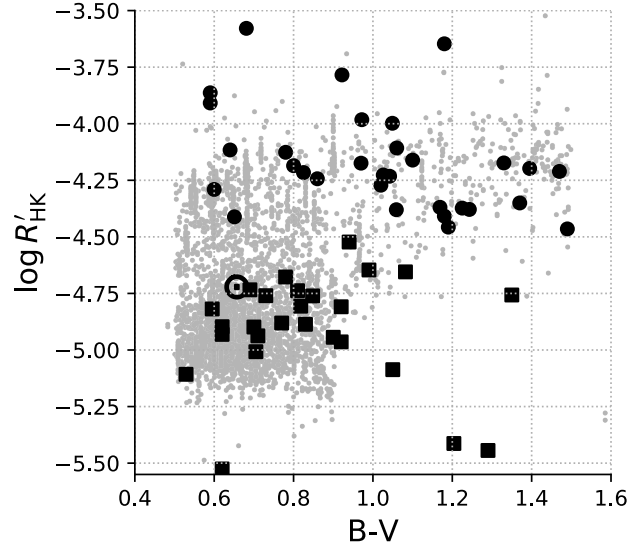


Figure 8.2: Chromospheric activity $\log R'_{\text{HK}}$ index as a function of $B - V$ color for our template stars (black), compared with the large field samples of Duncan et al. (1991), Wright et al. (2004) and Isaacson & Fischer (2010), (gray) computed with the procedure outlined in Mittag et al. (2013). Stars classified as “inactive” are marked with black squares, stars classified as “active” are marked with black circles. The outliers at low activity are giants, including G giant HD 5857, and the K giants Gl 705, HD 6497 and HD 145742 (see Table 8.1 for stellar properties).

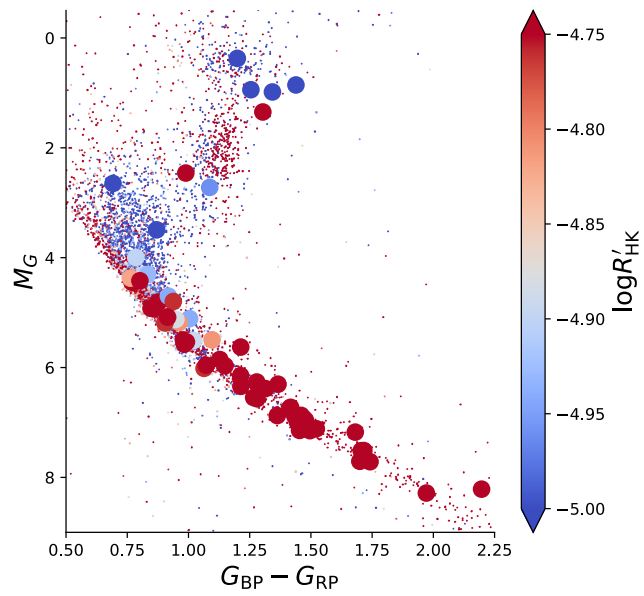


Figure 8.3: Color–magnitude diagram from Gaia Collaboration et al. (2018a), colored by $\log R'_{HK}$, for stars in Duncan et al. (1991), Wright et al. (2004) and Isaacson & Fischer (2010) (small points). The larger circles are the stars observed in this work.

for computing $\log R'_{\text{HK}}$. The results are shown in Figure 8.2 as a function of stellar $(B - V)$ color, and in Figure 8.3 on the *Gaia* DR2 color–magnitude diagram (CMD), and are listed in Table 8.1.

8.2.4 *Stellar parameters*

In this section we measure the effective temperatures of the stars with three techniques: using the ARCES high resolution spectroscopy independently with SME and M00G, and using *Gaia* DR2 broadband photometry (Andrae et al., 2018). We estimated the effective temperatures with three techniques so that we could determine if activity was affecting the T_{eff} estimates. In the following sections we will outline the effective temperature measurement with each technique, and compare the results to one another in Section 8.2.5.

Stellar parameters with SME

We used Spectroscopy Made Easy (SME; Piskunov & Valenti, 2017; Valenti & Fischer, 2005; Valenti & Piskunov, 1996) version 522 to compute the effective temperatures (T_{eff}), surface gravities ($\log g$), metallicities ($[\text{Fe}/\text{H}]$), and projected rotational velocities ($v \sin i$) of all stars in our sample. The SME algorithm fits selected spectral regions with synthetic spectra generated with a particular atmospheric model (ATLAS12; Kurucz 2013) and line list. We followed the basic procedure and adopted the wavelength range and line list from Valenti & Fischer (2005), and analyzed the 5164-5190 Å interval covering the pressure-sensitive Mg1 *b* triplet, and the 6000-6070 and 6100-6180 Å intervals split into 7 segments.

We normalized the Mg1 *b* segment by comparing a solar spectrum (observed with ARCES, reflected off the Moon) to the Wallace et al. (2011) solar atlas, where we matched the velocity offset and instrumental broadening between spectra, then fit a polynomial to the ratio of the two spectra to derive a blaze model for this order. For the other spectral segments, this procedure also works, but the absorption lines in the regions are sparse enough that polynomials fit directly to the spectra are also effective. All spectra were cross-correlated

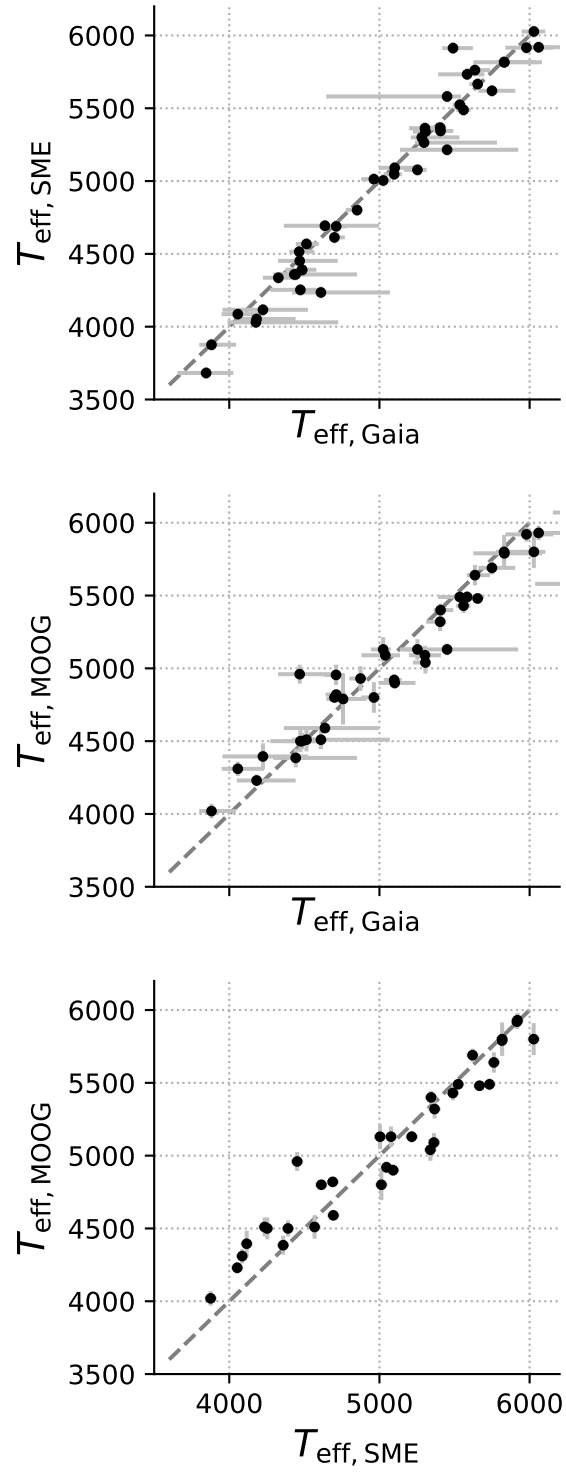


Figure 8.4: Comparisons between effective temperatures [K] computed with SME, MOOG and from the *Gaia* DR2 catalog.

against the solar atlas during normalization. SME also fits for small radial velocity offsets and residual linear trends across spectral segments.

We initialized SME with properties taken from the literature; when spectroscopic results were not available, we used *Gaia* DR2 T_{eff} values; when other parameters were unavailable, we adopted $\log g = 4.6$ dex, $[\text{Fe}/\text{H}] = 0.0$ dex, and $v \sin i = 2 \text{ km s}^{-1}$. Following Valenti & Fischer (2005), microturbulence was fixed to 0.85 km s^{-1} and we adopted their macroturbulence relation. We did not solve for any additional abundances besides the metallicity parameter for this work, which therefore assumes a scaled-solar composition. After running the initial fit, we perturbed the resulting T_{eff} by $\pm 200 \text{ K}$ and refit the spectra. Fits typically converged to within 10 K of the first solution for stars warmer than $T_{\text{eff}} > 4600 \text{ K}$.

The spectra of cooler stars are more complicated, particularly in the Mg1 *b* order. For stars cooler than $T_{\text{eff}} < 4600 \text{ K}$, we removed this order from our analysis, then fixed $\log g$ to a value drawn from a 3 Gyr (i.e., middle-aged) Dartmouth isochrone with $[\text{Fe}/\text{H}] = +0.10$ dex (this choice was arbitrary and made purely for our convenience) at the initial T_{eff} , and iterated the fit once. We verified convergence by varying the initial T_{eff} by $\pm 500 \text{ K}$, and resetting values each time to $[\text{Fe}/\text{H}] = 0.0$ dex and $\log g = 4.6$ dex.

Ryabchikova et al. (2016) assessed the stellar parameter accuracies attainable with SME for FGK dwarfs with high-quality spectra (e.g., $S/N = 200$, $R = 40,000\text{--}110,000$), and found uncertainties on T_{eff} of 50–70 K, on $\log g$ of 0.1 dex, and on metallicity of 0.05–0.06 dex (see also Brewer et al., 2016; Piskunov & Valenti, 2017). While their spectroscopy methodology (including wavelength regions analyzed) differs from ours, these values provide error floors that are consistent with our results. Results for stars with multiple observations and results from varying the initial conditions typically yielded dispersions much lower than this error floor. For now, we will assume that our uncertainties for T_{eff} are 50 K, and will later compare our values to the photometric *Gaia* DR2 and literature values to assign final uncertainties. The results are shown in Figure 8.4.

Stellar parameters with MOOG

For most of the stars, T_{eff} , $\log g$, microturbulent velocity (ξ , in km s^{-1}), and $[\text{Fe}/\text{H}]$ were also determined with a standard model atmospheres approach. Equivalent width (EWs) of Fe1 and Fe2 lines were first measured in the normalized spectra using the Gaussian profile fitting code DAOSPEC (Stetson & Pancino, 2008). DAOSPEC has difficulty measuring lines with $\text{EW} > 100 \text{ m}\text{\AA}$; as a result, those lines were remeasured by hand. The lines from Fulbright et al. (2006) and McWilliam et al. (2013) were utilized. Lines blueward of $5000 \text{ \AA}$ were not included to avoid issues with continuum normalization. Strong lines (with reduced EWs² $\text{REW} > -4.8$) were not included, to minimize uncertainties due to, e.g., damping constants (McWilliam et al., 1995).

The EWs were then input into the 2017 version of the Local Thermodynamic Equilibrium (LTE) line analysis code MOOG (Snedden, 1973). ATLAS model atmospheres were adopted (Castelli & Kurucz, 2004), using an interpolation scheme for temperatures and surface gravities that lie between the grid points. For each Fe line, $[\text{Fe}/\text{H}]$ was calculated relative to the solar abundance for that line (using the solar EWs from Fulbright et al. 2006 and McWilliam et al. 2013). The appropriate T_{eff} and ξ were determined by minimizing trends in $[\text{Fe1}/\text{H}]$ with excitation potential (EP, in eV) and REW, respectively. The appropriate $\log g$ was determined with the BaSTI isochrones (Pietrinferni et al., 2004), utilizing the spectroscopic T_{eff} . This means that the surface gravity could be mildly dependent on the adopted age and metallicity; however, the effect on main sequence stars is small. The $[\text{Fe1}/\text{H}]$ and $[\text{Fe2}/\text{H}]$ ratios are averages from the individual lines. The surface gravities were *not* determined by requiring ionization equilibrium (i.e., by requiring that the Fe1 and Fe2 abundances be equal), both due to larger uncertainties in the Fe2 abundances and possible non-LTE effects (Kraft & Ivans, 2003). While there are $\sim 10 - 120$ acceptable Fe1 lines per star (depending on metallicity, T_{eff} , and S/N), there are many fewer Fe2 lines; as a result, the random errors in $[\text{Fe2}/\text{H}]$ are much larger than those in $[\text{Fe1}/\text{H}]$.

² $\text{REW} = \log(\text{EW}/\lambda)$, where λ is the wavelength of the transition

Note that none of these parameters are independent; the adopted temperatures are therefore dependent upon the other parameters, particularly the microturbulent velocity. The errors in T_{eff} were determined by assuming errors in ξ of $\pm 0.3 \text{ km s}^{-1}$ (errors in $\log g$ and $[\text{Fe}/\text{H}]$ have a negligible effect on the temperatures).

The MOOG effective temperatures are listed alongside the others in Table 8.1; the rest of the MOOG results ($\log g$, $[\text{Fe1}/\text{H}]$, $[\text{Fe2}/\text{H}]$, and microturbulence) are enumerated in Appendix 8.C. The temperatures generally agree with the *Gaia* values, though they may be slightly higher in the coolest stars; see Figure 8.4. The cooler stars have fewer suitable Fe1 lines for an EW analysis; as a result, the temperatures are likely to be more sensitive to line-to-line variations as a result of, e.g., continuum placement or atomic data.

Stellar temperatures with ESA/Gaia DR2

The European Space Agency’s *Gaia* mission recently delivered astrometric, photometric, and radial velocity data for a large number of stars (Gaia Collaboration et al., 2018a). The second data release (DR2) included an analysis of the three-band photometry (G_{BP} , G_{RP} , G), with the Apsis pipeline (Bailer-Jones et al., 2013b), and derived effective temperatures for 161 million sources brighter than $G < 17$ with $3000 < T_{\text{eff}} < 10000 \text{ K}$ (Andrae et al., 2018). The Apsis pipeline consists of a machine learning algorithm trained on large T_{eff} data sets from the literature (e.g., LAMOST, RAVE, the *Kepler* Input Catalog), and was validated using data from GALAH, nearby solar twin stars, and other sources.

We performed additional tests to assess the accuracy and precision of the DR2 catalog effective temperatures by comparing results for well-characterized nearby stars, including the FGK stars observed by CPS with Keck/HIRES and characterized with SME by Brewer et al. (2016), the K and M dwarfs characterized with interferometry and bolometric fluxes by Boyajian et al. (2012), and the M dwarfs characterized with optical and NIR spectroscopy by Mann et al. (2015). The *Gaia* DR2 T_{eff} values are consistent with this joint benchmark sample for $T_{\text{eff}} > 4100 \text{ K}$, but diverge at cooler temperatures. The warmer stars show remarkable agreement, having an rms of only 70 K, which is much lower than the typical

T_{eff} accuracy of 324 K quoted by Andrae et al. (2018). This is due to the fact that these stars are all nearby and likely appear unreddened. We fit a polynomial to the DR2 color ($G_{\text{BP}} - G_{\text{RP}}$) versus the benchmark sample T_{eff} values to re-calibrate the DR2 photometric temperatures and place the cool stars on the benchmark sample’s temperature scale. We will use this re-calibration later in the next subsection. Table 8.1 reports the DR2/Apsis values (Andrae et al., 2018).

8.2.5 Comparison of stellar temperatures

Figure 8.4 compares the effective temperatures we derived with SME and MOOG with the *Gaia* DR2 effective temperatures. The SME and MOOG temperatures have significantly better precision than the *Gaia* temperatures; however, in many cases, it is possible that Andrae et al. (2018) overestimated the uncertainties—we reiterate that remarkable agreement is found when comparing T_{eff} values for benchmark FGKM dwarfs from Brewer et al. (2016), Boyajian et al. (2012), and Mann et al. (2015) with DR2, with an rms of only 70 K. In fact, many of the stars in our sample are drawn from those three catalogs.

Of the 55 stars in our sample, 19 are also in Brewer et al. (2016), five are in SPOCS (Valenti & Fischer, 2005), one is in Boyajian et al. (2012), and two are in Mann et al. (2015). The SB2 spectrum of HD 45088 was characterized by Glazunova et al. (2014), and 61 Cyg A and B are *Gaia* FGK benchmark stars Heiter et al. (2015). This means that 30 of 55 stars, over half of our sample, have been precisely characterized by these other studies. The median and standard deviation of the difference between our SME values and the benchmark values is 6 ± 74 K, where our stars are negligibly cooler, systematically. This rms drops to 43 K when considering the 22 stars with benchmark $T_{\text{eff}} > 4800$ K, and increases to 85 K when considering only the 7 cooler stars (the SB2 is not included in this analysis). Based on this consistency, we set the SME uncertainties to 40 K for stars warmer than $T_{\text{eff}} = 4800$ K, and 100 K for stars cooler than $T_{\text{eff}} = 4800$ K. Unless otherwise noted below, we choose to use the SME effective temperatures because: (1) they show better agreement with the *Gaia* effective temperatures was achieved, and (2) the SME analysis converged on effective

temperatures for the largest number of the stars in the sample, compared to our MOOG analysis.

Target	Sp.T.	$G_{BP} - G_{RP}$	$T_{\text{eff,Gaia}}$	$T_{\text{eff,SME}}$	$T_{\text{eff,MOOG}}$	$\log g$	[Fe/H]	$v \sin i$	S	$\log R'_{\text{HK}}$
Active										
HD 151288	K7.5Ve	1.7053	4224^{+300}_{-270}	4337 ± 100	4395 ± 90	4.68	-0.117	3.64	1.27 ± 0.05	-3.58 ± 0.02
Gl 702 B	K4V	1.4774	4442^{+408}_{-150}	4359 ± 100	4385 ± 65	4.65	-0.144	2.06	0.84 ± 0.04	-3.61 ± 0.02
EQ Vir*	K5Ve	1.496	4433^{+82}_{-106}	4359 ± 100		4.65	-0.144	2.06	3.00 ± 0.12	-3.65 ± 0.02
HD 175742 [‡]	K0V	1.213	4874^{+43}_{-74}	4980 ± 40	4930 ± 85	4.4	-0.09	14.7	1.26 ± 0.05	-3.78 ± 0.02
EK Dra	G1.5V	0.875	5584^{+115}_{-193}						0.58 ± 0.02	-3.91 ± 0.02
Kepler-63	G2V	0.9149	5450^{+92}_{-805}	5581 ± 40		4.69	0.129	5.43	0.45 ± 0.02	-3.95 ± 0.03
HD 45088*	K2Ve	1.2134	4786^{+39}_{-36}	5025 ± 40					0.91 ± 0.04	-3.98 ± 0.02
HD 113827	K4V	1.4537	4610^{+459}_{-191}	4235 ± 100	4510 ± 65	4.66	-0.381	2.59	1.03 ± 0.04	-4.00 ± 0.02
HD 134319*	G5V	0.8469	5636^{+100}_{-54}	5762 ± 40	5640 ± 70	4.59	-0.01	10.9	0.42 ± 0.02	-4.12 ± 0.02
HD 127506	K3.5V	1.2794	4711^{+55}_{-83}	4651 ± 100	4955 ± 70	4.78	-0.265	3.32	0.49 ± 0.02	-4.13 ± 0.02
HD 200560	K2.5V	1.1492	4963^{+42}_{-85}	5013 ± 40	4800 ± 105	4.66	0.09	3.6	0.61 ± 0.03	-4.17 ± 0.02
HD 88230	K6VeFe-1	1.7162	4057^{+174}_{-107}	4086 ± 100	4310 ± 50	4.68	-0.167	0.1	1.31 ± 0.05	-4.17 ± 0.02
HD 220182*	G9V	0.9794	5303^{+106}_{-106}	5363 ± 40	5090 ± 65	4.66	0.0	4.6	0.45 ± 0.02	-4.19 ± 0.02
HD 266611	K5V	1.7415	4182^{+260}_{-132}	4053 ± 100	4230 ± 40	4.69	-0.296	0.1	1.44 ± 0.06	-4.20 ± 0.02
HD 209290	M0.5V	1.9714	3882^{+163}_{-82}	3876 ± 100	4020 ± 50	4.72	-0.321	2.68	1.66 ± 0.07	-4.21 ± 0.02
HD 41593*	K0V	0.9916	5306^{+28}_{-83}	5339 ± 40	5040 ± 75	4.64	-0.01	2.4	0.44 ± 0.02	-4.22 ± 0.02
HD 82106	K3V	1.214	4749^{+71}_{-40}	4726 ± 100		4.45	-0.06	0.4	0.61 ± 0.02	-4.23 ± 0.02
HD 79555 [†]	K4V	1.3148	4861^{+149}_{-251}	4744 ± 100		4.74	-0.19	0.1	0.62 ± 0.03	-4.23 ± 0.02
HD 87884 [†]	K0Ve	1.0725	5098^{+50}_{-69}	5047 ± 40	4920 ± 40	4.63	-0.25	2.5	0.44 ± 0.02	-4.24 ± 0.02
HD 222107 [‡]	G8IVk	1.3037	4637^{+360}_{-274}	4693 ± 100	4590 ± 30	3.08	-0.41	7.8	0.55 ± 0.02	-4.27 ± 0.02
HD 39587 [‡]	G0V	0.7691	6028^{+76}_{-81}	6027 ± 40	5800 ± 110	4.58	-0.01	8.8	0.30 ± 0.01	-4.29 ± 0.03
61 Cyg B [†]	K7V	1.6997	4177^{+548}_{-189}	4030 ± 100		4.69	-0.413	0.1	0.97 ± 0.04	-4.35 ± 0.02
HD 149957	K5V	1.4601	4485^{+37}_{-89}	4389 ± 100		4.65	-0.007	4.54	0.67 ± 0.03	-4.37 ± 0.02
HD 122120	K5V	1.4146	4469^{+253}_{-144}	4452 ± 100	4960 ± 65	4.64	-0.132	1.19	0.60 ± 0.02	-4.37 ± 0.02
HD 47752	K3.5V	1.2662	4700^{+69}_{-22}	4613 ± 100	4800 ± 30	4.63	-0.306	0.1	0.48 ± 0.02	-4.38 ± 0.02
HD 148467	K6V	1.5221	4474^{+153}_{-201}	4253 ± 100	4500 ± 75	4.66	-0.321	0.1	0.69 ± 0.03	-4.38 ± 0.02
61 Cyg A [†]	K5V	1.445	4327^{+101}_{-103}	4336 ± 100		4.65	-0.493	0.65	0.57 ± 0.02	-4.41 ± 0.02
HAT-P-11	K4V	1.2787	4757^{+154}_{-111}	4800 ± 100	4790 ± 175				0.53 ± 0.02	-4.46 ± 0.02
GJ 9781 A [†]	K7	1.4343	4484^{+95}_{-110}	4391 ± 100	4500 ± 55	4.65	-0.239	0.1	0.99 ± 0.04	-4.46 ± 0.02
Inactive										
HD 110833 [†]	K3V	1.128	5025^{+50}_{-82}	5004 ± 40	5130 ± 85	4.64	0.06	0.5	0.30 ± 0.01	-4.52 ± 0.02
HR 8832	K3V	1.2078	4787^{+92}_{-73}	4828 ± 40		4.63	0.03	0.2	0.26 ± 0.01	-4.65 ± 0.03
GJ 4099	M2.0Ve	2.1969	3846^{+181}_{-190}	3682 ± 100		4.77	-0.494	5.68	0.87 ± 0.05	-4.67 ± 0.02
σ Draconis	K0V	0.983	5450^{+474}_{-314}	5215 ± 40	5130 ± 40	4.58	-0.28	0.1	0.20 ± 0.01	-4.68 ± 0.03
HD 68017 [†]	G3V	0.8587	5749^{+155}_{-90}	5620 ± 40	5690 ± 45	4.76	-0.37	0.1	0.18 ± 0.01	-4.73 ± 0.04
HD 67767	G7V	0.9891	5297^{+486}_{-61}	5264 ± 40		3.81	-0.1	0.1	0.19 ± 0.01	-4.74 ± 0.03
HD 73667	K2V	1.0636	5039^{+98}_{-159}	4800 ± 100	5090 ± 30	4.38	-0.68	0.1	0.19 ± 0.01	-4.76 ± 0.03
Kepler-17	G2V	0.9381	5490^{+132}_{-72}	5913 ± 40		4.72	0.381	5.05	0.40 ± 0.02	-4.76 ± 0.03
HD 62613	G8V	0.9037	5560^{+47}_{-49}	5489 ± 40	5430 ± 50	4.53	-0.12	0.1	0.18 ± 0.01	-4.76 ± 0.04
HD 14039	K1V	1.0963	5072^{+98}_{-73}						0.19 ± 0.01	-4.81 ± 0.03
HD 182488	K0V	0.9621	5404^{+41}_{-93}	5367 ± 40	5320 ± 65	4.51	0.14	0.1	0.17 ± 0.01	-4.81 ± 0.04
HD 50692	G0V	0.7631	6060^{+235}_{-118}	5919 ± 40	5930 ± 50	4.46	-0.16	0.1	0.16 ± 0.01	-4.82 ± 0.05
HD 42250	G9V	0.9487	5407^{+85}_{-46}	5344 ± 40	5400 ± 45	4.48	-0.05	0.1	0.16 ± 0.01	-4.88 ± 0.04
HD 38230	K0V	1.0214	5253^{+61}_{-89}	5077 ± 40	5130 ± 70	4.39	-0.16	0.1	0.16 ± 0.01	-4.89 ± 0.04
51 Peg	G2IV	0.817	5830^{+214}_{-55}	5817 ± 40	5800 ± 115	4.42	0.24	1.8	0.15 ± 0.01	-4.90 ± 0.05
HD 34411	G1.5IV-VFe-1	0.785	5979^{+178}_{-140}	5916 ± 40	5920 ± 50	4.33	0.12	0.1	0.15 ± 0.01	-4.90 ± 0.06
HD 86728	G3VaHdel1	0.8329	5832^{+251}_{-207}	5816 ± 40	5790 ± 50	4.45	0.25	0.2	0.15 ± 0.01	-4.93 ± 0.06
HD 145675	K0V	1.0049	5282^{+251}_{-73}	5300 ± 40		4.46	0.37	0.1	0.16 ± 0.01	-4.94 ± 0.04
HD 210277	G8V	0.918	5535^{+42}_{-48}	5524 ± 40	5490 ± 30	4.47	0.22	0.3	0.15 ± 0.01	-4.94 ± 0.05
HD 221639	K1V	1.0866	5102^{+139}_{-106}	5091 ± 40	4900 ± 40	3.75	0.14	0.1	0.15 ± 0.01	-4.96 ± 0.04

HD 10697	G3Va	0.8701	5654^{+36}_{-56}	5666 ± 40	5480 ± 35	4.13	0.14	1.1	0.14 ± 0.01	-5.01 ± 0.06
HD 145742	K0	1.1996	4851^{+13}_{-75}	4801 ± 100		2.85	-0.05	3.6	0.15 ± 0.01	-5.09 ± 0.06
HD 89744	F7V	0.6919	6239^{+23}_{-84}	6254 ± 40	6070 ± 110	4.04	0.26	9.3	0.14 ± 0.01	-5.11 ± 0.10
HD 6497	K2III-IV	1.3428	4514^{+82}_{-71}	4568 ± 100	4510 ± 80	2.92	0.02	3.0	0.11 ± 0.01	-5.41 ± 0.04
Gl 705	K2	1.4388	4465^{+102}_{-66}	4377 ± 100		2.85	0.06	3.5	0.12 ± 0.01	-5.44 ± 0.04
HD 5857	G5	1.2549	4712^{+67}_{-71}	4689 ± 100	4820 ± 30	2.92	-0.2	3.1	0.11 ± 0.01	-5.53 ± 0.21

Table 8.1: Spectral types, Stellar colors, effective temperatures, SME properties ($\log g$, $[\text{Fe}/\text{H}]$, $v \sin i$), S -indices and $\log R'_{\text{HK}}$ indices. Stars with names marked with * are listed as BY Dra variables; † denotes long-period binary stars; ‡ denotes RS CVn binaries.

A Note on GJ 4099

Jódar et al. (2013) identified a companion to GJ 4099 with high-angular-resolution optical imaging and measured a contrast of $\Delta i = 0.27$ mag (Sloan), a proper motion indicating that the stars are co-moving, and an angular separation of 300-400 mas, which *Gaia* DR2 would not resolve (see Figure 1 from Ziegler et al., 2018).

Blended photometry will bias the photometric estimation of T_{eff} . Instead, we model the photometry as a binary system. First, we assembled the K and M dwarf sample from Mann et al. (2015), which provides T_{eff} and metallicity measurements derived from optical and NIR spectroscopy as well as synthetic J, H, K_S magnitudes computed by integrating the absolutely flux-calibrated optical spectra over each filter. Next, we cross-matched this catalog with DR2, which provided parallax and the DR2 photometric magnitudes. To model the binary, we randomly drew primary and secondary stars with replacement from the sample, combined the absolute magnitudes, and assembled the 6-band SEDs (*Gaia* DR2 $G, G_{\text{BP}}, G_{\text{RP}}$, 2MASS J, H, K_S), then minimized χ^2 between the empirical binary SEDs and the observed SED for GJ 4099. This procedure yielded temperatures for the primary and secondary of $T_{\text{eff}} = 3743$ K and 3668 K, respectively. HD 209290 has a DR2 T_{eff} similar to GJ 4099—we performed a similar fit assuming it is single and found $T_{\text{eff}} = 3875$ K (only 7 K cooler than its DR2 value). Whereas DR2 listed this star as only 36 K warmer than GJ 4099, we find it to be 132 K warmer than the primary and 207 K warmer than the secondary. This is consistent with the SME analysis that found $T_{\text{eff}} = 3876$ K for HD 209290, $T_{\text{eff}} = 3682$ K for GJ 4099, and a difference of 194 K. Our photometric analysis of GJ 4099 indicates that the primary

is 75 K warmer than the secondary, which is consistent with the Δi measurement from Jódar et al. (2013). Given this small difference in T_{eff} , and the fact that the components are well-separated and non-interacting, we will assume that our spectrum for GJ 4099 is representative of a quiescent 3700 K photosphere.

8.3 *TiO Molecular Band Modeling*

The spectrum of a spotted star can be approximated as the linear combination of the spectrum of an unspotted star with the effective temperature of the stellar photosphere, and the spectrum of a cooler star with the effective temperature of the starspots. In principle, there is also a hot component from plages, but the small temperature contrast of plages compared to the mean photosphere makes it difficult to detect in practice.

Figure 8.5 shows four segments of stellar spectra centered on TiO absorption features. These regions have been selected for their strong absorption band intensities computed by Valenti et al. (1998). By construction, the only star with significant TiO absorption is the M star, since obvious TiO absorption is the defining characteristic of that spectral class. However, there may be a small component of TiO absorption in the spectrum of a spotted star like HAT-P-11 when compared with the inactive star HD 73667, for example, which is a star of similar effective temperature but much less chromospheric activity. The goal of this work is to model the spectrum of stars like HAT-P-11 as a linear combination of the other two spectra—one spectrum of a star without TiO absorption, and another with some TiO absorption—in order to infer the spot covering fraction.

The total flux as a function of wavelength, F_{total} , that we observe for a given star is a combination of the flux from the photosphere and spot components. In practice, each spectrum is normalized such that the pseudocontinuum is unity, so the linear combination of (hot) photospheric and (cool) spot components is defined by Equation 1 of Neff et al. (1995):

$$F_{\text{total}} = \frac{f_S R_\lambda F_S + (1 - f_S) F_Q}{f_S R_\lambda + (1 - f_S)} \quad (8.1)$$

where f_S is the spot filling factor, F_Q is the spectrum representing the quiescent stellar

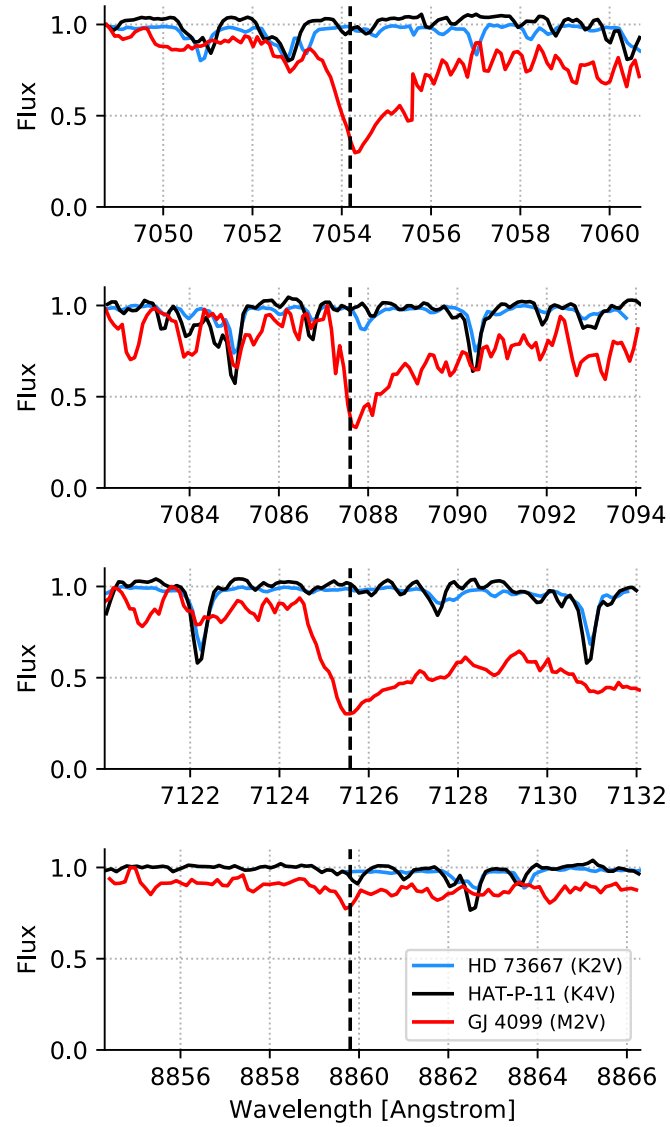


Figure 8.5: Regions of stellar spectra where TiO absorption is expected in cool star atmospheres, and perhaps from starspots.

surface (the photosphere), F_S is the spectrum representing spots, and R_λ is the ratio of the spotted to unspotted continuum blackbody flux at a given wavelength.

8.3.1 Practical application

The formalism above assumes that we have obtained template stellar spectra with exactly the same effective temperatures as the stellar photosphere. In practice, of course, we can only have stars with very similar effective temperatures, so the F_Q spectrum that we use is itself a linear combination of the hot and cool spectra such that the effective temperature of the linear combination model attempts to match the effective temperature of the spotted target star.

We use Markov Chain Monte Carlo (emcee; Foreman-Mackey et al., 2013) to vary the spot area coverage for each of four TiO absorption regions shown in Figure 8.5. For a 2 Å-wide window centered on each TiO feature, we fit for a linear combination of the hot and cool component atmospheres. At each step in the chain we regress the two-component model spectrum against the observed stellar spectrum as a function of wavelength to remove any trends that may persist after continuum normalization.

The uncertainties on the flux within each spectral channel are difficult to compute *a priori*. Thus we marginalize over the flux uncertainty for all spectral channels within the fitting window at each step in the Markov chains, with the appropriate prior penalty on the uncertainties to keep the uncertainties small.

Color Prior

We apply a prior to penalize very large spot filling factors, by enforcing that the filling factor is never large enough to skew the broadband colors of the star significantly towards the red. For each star, we compute a Gaussian prior penalty p that a star has an observed *Gaia* DR2 ($G_{BP} - G_{RP}$) color c_O , compared to the computed two-component mixture model color c_C ,

$$\ln p \propto -\frac{1}{2} \left(\frac{c_O - c_C}{\sigma_c} \right)^2, \quad (8.2)$$

where $\sigma_c = 0.006$ is a typical uncertainty on $(G_{\text{BP}} - G_{\text{RP}})$ for stars in our sample. Since the signal we are searching for is similar in amplitude to the uncertainties of the observations, fits without this prior tend to prefer non-zero spot filling factors simply because the noisy data can be better fit with two templates than one. The color prior has the important effect of ensuring that non-zero spot filling factors yield a sufficient improvement in the model likelihood to offset the penalty incurred by the color prior.

Spot covering fractions on Sun-like stars are typically small, but span orders of magnitude. In Morris et al. (2017b) we show that the Sun has typical spot coverage near 0.03%, while the K4V star HAT-P-11 has a typical spot coverage near 3%. It has been speculated that the wide range in activity could be due in part to the presence of the hot-Jupiter planet in the HAT-P-11 system (Morris et al., 2017c).

Temperature contrast

Several efforts exist in the literature to search for correlations between the effective temperatures of stars and the temperatures of their spots (e.g. Berdyugina, 2005; Mancini et al., 2014). The data sets and analyses are highly heterogeneous and apparent correlations often have several exceptions. Therefore, in order to simplify the analysis in this work, we choose plausible combinations of stellar atmospheres, informed primarily by the temperature contrast of sunspots.

Sunspots have detailed substructure dominated by the cool penumbra, and the much cooler umbra. Since the ratio of penumbral to umbral area of sunspots is roughly a factor of four, and since the intensity of the penumbra is more than a factor of two greater than the intensity of the umbra in sunspots (Solanki, 2003), in this work we will approximate starspots as being entirely composed of penumbra. On the Sun, penumbra typically have temperatures 250-400 K cooler than the mean photosphere. In most cases, we choose combinations of stellar spectra with effective temperature differences of a few hundred Kelvin, manually selecting pairs seeking to minimize the differences in metallicity and surface gravity between the template stars and the target star. Therefore one should not interpret the temperature

differences listed in Table 8.2 as detections; they were adopted *a priori* in order to measure the spot covering fraction under the assumption that starspots on G and K stars generally act like sunspots.

Control experiments

Target	T_{eff}	Comp. 1	T_1	Comp. 2	T_2	ΔT	f_S	$\Delta\chi^2$
HD 151288	4337 ± 100	G1 705	4515 ± 100	HD 209290	3876 ± 100	639	0.31 ± 0.06	197.1
GJ 702B	4359 ± 100	G1 705	4515 ± 100	GJ 4099	3682 ± 100	833	0.00 ± 0.06	
EQ Vir	4359 ± 100	G1 705	4515 ± 100	GJ 4099	3682 ± 100	833	0.26 ± 0.06	573.3
HD 175742	4980 ± 40	HD 145742	4801 ± 40	G1 705	4515 ± 100	286	0.52 ± 0.08	21.8
EK Dra	5584^{+115}_{-193}	HD 210277	5524 ± 40	HD 38230	5077 ± 40	447	0.31 ± 0.06	40.1
Kepler-63	5581 ± 40	HD 10697	5666 ± 40	HD 221639	5091 ± 40	575	0.27 ± 0.06	
HD 45088	4786^{+39}_{-36}	HD 145742	4801 ± 40	G1 705	4515 ± 100	286	0.53 ± 0.07	21.4
HD 113827	4235 ± 100	G1 705	4515 ± 100	GJ 4099	3682 ± 100	833	0.20 ± 0.06	177.5
HD 134319	5762 ± 40	HD 68017	5620 ± 40	HD 145675	5300 ± 40	320	0.00 ± 0.06	
HD 127506	4651 ± 100	HD 145742	4801 ± 100	G1 705	4515 ± 100	286	0.49 ± 0.08	14.9
HD 200560	5013 ± 40	HD 145742	4801 ± 100	G1 705	4515 ± 100	286	0.00 ± 0.06	
HD 220182	5363 ± 40	HD 145675	5300 ± 40	HD 145742	4801 ± 40	499	0.35 ± 0.06	101.8
HD 41593	5339 ± 40	HD 145675	5300 ± 40	HD 145742	4801 ± 40	499	0.35 ± 0.06	102.6
HD 82106	4726 ± 100	HD 145742	4801 ± 100	G1 705	4515 ± 100	286	0.00 ± 0.06	
HD 79555	4744 ± 100	HD 145742	4801 ± 100	G1 705	4515 ± 100	286	0.00 ± 0.06	
HD 87884	5047 ± 40	HD 221639	5091 ± 40	HD 5857	4689 ± 100	402	0.04 ± 0.10	
HD 222107	4693 ± 100	HD 6497	4568 ± 40	GJ 4099	3682 ± 100	886	0.18 ± 0.06	146.0
HD 39587	6027 ± 40	HD 50692	5919 ± 40	HD 62613	5489 ± 40	430	0.02 ± 0.06	
HD 149957	4389 ± 100	G1 705	4515 ± 100	GJ 4099	3682 ± 100	833	0.12 ± 0.06	60.5
HD 122120	4452 ± 100	G1 705	4515 ± 100	GJ 4099	3682 ± 100	833	0.14 ± 0.06	79.1
HD 47752	4613 ± 100	HD 145742	4801 ± 40	G1 705	4515 ± 40	286	0.02 ± 0.06	
HD 148467	4253 ± 100	G1 705	4515 ± 100	GJ 4099	3682 ± 100	833	0.23 ± 0.06	245.8
61 Cyg A	4336 ± 100	HD 6497	4568 ± 100	GJ 4099	3682 ± 100	886	0.38 ± 0.06	
HAT-P-11	4757^{+154}_{-111}	HD 5857	4689 ± 100	G1 705	4515 ± 40	174		
GJ 9781 A	4391 ± 100	G1 705	4515 ± 100	GJ 4099	3682 ± 100	833	0.21 ± 0.06	194.8
HD 110833	5004 ± 40	HD 145742	4801 ± 40	G1 705	4515 ± 100	286	0.00 ± 0.06	
σ Draconis	5215 ± 40	HD 42250	5344 ± 40	GJ 4099	3682 ± 100	1662	0.22 ± 0.06	156.2
HD 68017	5620 ± 40	HD 10697	5666 ± 40	HD 221639	5091 ± 40	575	0.00 ± 0.06	
HD 67767	5264 ± 40	HD 182488	5367 ± 40	GJ 4099	3682 ± 100	1685	0.15 ± 0.06	61.7
HD 73667	4800 ± 40	HD 221639	5091 ± 40	G1 705	4515 ± 100	576	0.00 ± 0.06	
Kepler-17	5913 ± 40	HD 50692	5919 ± 40	HD 62613	5489 ± 40	430	0.36 ± 0.06	
HD 62613	5489 ± 40	HD 10697	5666 ± 40	HD 221639	5091 ± 40	575	0.16 ± 0.06	10.0
HD 14039	5072^{+98}_{-73}	HD 221639	5091 ± 40	HD 5857	4689 ± 100	402	0.02 ± 0.06	
51 Peg	5817 ± 40	HD 86728	5816 ± 40	GJ 4099	3682 ± 100	2134	0.10 ± 0.06	24.9
HD 34411	5916 ± 40	HD 86728	5816 ± 40	HD 145675	5300 ± 40	516	0.00 ± 0.06	

Table 8.2: Each target star, and the hotter (T_1) and cooler (T_2) components used to model its spectrum, with spot covering fractions f_S and model comparison with the null hypothesis $\Delta\chi^2$.

We construct a simple test to ensure that the two-component model is not over-fitting the spectra, and produces reliable uncertainties. We fit a sample of inactive stars with a linear

combination of two stars: the spectrum of the same star and the spectrum of a cooler star. In this control run, we expect that the maximum-likelihood model should choose a spot covering fraction $f_S \approx 0$, since the spectrum of the target star should be a perfect fit to itself. For a sample of 10 control stars, we find typical $f_S < 0.06$ (68% confidence). We interpret this result to mean that the smallest reliable uncertainty on f_S should be ~ 0.06 ; so throughout this work, the uncertainty on f_S is the maximum of the formal uncertainty or 0.06.

We also analyze spectra of the twilight sky as a proxy for solar spectra, on a day with no sunspots. We model the solar spectrum as a linear combination of HD 10697 ($T_Q = 5654^{+36}_{-56}$ K) and HD 221639 ($T_S = 5102^{+139}_{-106}$ K) and measure $f_S \lesssim 0.001$. This measurement is so small due largely to the very high signal-to-noise of the solar observations in comparison with the stellar observations.

8.3.2 Validation on Previously Characterized Stars

In the following subsections we compare our results to previous results in the literature, summarized in Figure 8.6.

EQ Vir

EQ Virginis is a K5Ve flare star in the nearby cluster IC 2391 (50 Myr; Barrado y Navascués et al., 2004) with rotation period $P_{\text{rot}} = 3.9 \pm 0.1$ d (Montes et al., 2001; Paulson & Yelda, 2006; Suárez Mascareño et al., 2016a). Saar & Cuntz (2001) assumed $T_Q = 4380$ K and $T_S = 3550$ K, and found a spot covering fraction $f_S = 0.43 \pm 0.05$. Subsequently, O’Neal et al. (2004) adopted 61 Cyg A as the quiescent template ($T_{\text{eff}} = 4374$ K; Heiter et al., 2015), and measured $T_S = 3350 \pm 115$ K with $f_S = 0.34\text{--}0.45$.

We model the spectrum of EQ Vir as a linear combination of the spectra of Gl 705 (K2V, $T_Q = 4465^{+102}_{-66}$ K) and GJ 4099 (M2V, $T_S = 3682$ K), which is a warmer spot temperature than the prior two studies. We recover spot covering fractions $f_S = 0.25 \pm 0.06$, smaller than the spot covering fractions measured by earlier observers. In large part, the discrepancy is

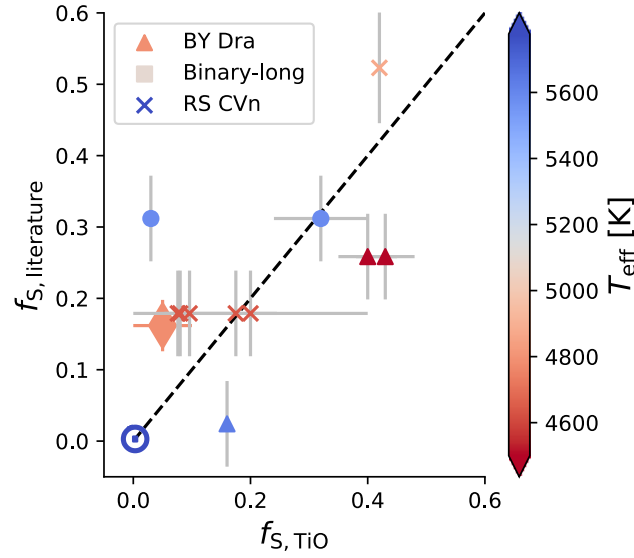


Figure 8.6: Comparison of literature spot coverage fractions to our results. The Sun is shown with the “ $\odot$ ” symbol, HAT-P-11 is shown with the large diamond. The most significant outlier is HD 134319 (IU Dra), for which we measure very small spot coverage (see Section 8.3.2). The scatter about the one-to-one correspondance line represents a combination of: (1) intrinsic variability in the spotted surface area of each star, and (2) underestimated uncertainties in one or both measurements.

due to our use of a strong prior on the color of the star (see Section 8.3.1), which places strict upper limits on the plausible spot covering fractions.

To compare our results with Saar & Cuntz (2001) and O’Neal et al. (2004), and to understand the effect of the color prior, we compute the expected *Gaia* DR2 ($G_{\text{BP}} - G_{\text{RP}}$) color of EQ Vir, given the spot properties of O’Neal et al. (2004), and compare it to its observed color. Its photospheric temperature measured via SME is $T_{\text{eff}} = 4519 \pm 200$ K, and synthetic photometry of a PHOENIX model atmosphere with this temperature has color $(G_{\text{BP}} - G_{\text{RP}})_Q = 1.4772$. O’Neal et al. (2004) assume the spotted component has temperature $T_S = 3350 \pm 115$ K, which from synthetic photometry should have color $(G_{\text{BP}} - G_{\text{RP}})_S = 2.9739$. Combining these colors with spot covering fraction $f_S = 0.43$ using Equation 8.6 yields the expected composite color $(G_{\text{BP}} - G_{\text{RP}}) = 1.8135$. The observed *Gaia* EQ Vir color $(G_{\text{BP}} - G_{\text{RP}}) = 1.4960 \pm 0.0054$ is 58σ discrepant with the Saar & Cuntz (2001) observation, and up to 62σ discrepant with the range reported by O’Neal et al. (2004). We conclude that the spot covering fraction must be $f_S < 0.43$ in order not to redden the star significantly beyond its actual color, assuming the effective temperature measured by SME is the correct photospheric temperature.

To verify that the PHOENIX model atmospheres are not responsible for this large discrepancy, we also empirically estimated the DR2 colors by constructing a color–temperature relation based on the Boyajian et al. (2012) K/M benchmark sample, which covers $3054 < T_{\text{eff}} < 5407$ K.³ This predicts $(G_{\text{BP}} - G_{\text{RP}})_S = 2.608$ for 3350 K and 1.324 for 4515 K, and we find a 20σ discrepancy with the observed color. This confirms that there is a significant discrepancy between the predicted and observed colors of EQ Vir using the O’Neal et al. (2004) spot coverage and temperatures.

For completeness, we carry out the same calculation using our maximum-likelihood model for EQ Vir. We adopt Gl 705 for T_Q with $(G_{\text{BP}} - G_{\text{RP}})_Q = 1.4388$, and GJ 4099 for T_S with $(G_{\text{BP}} - G_{\text{RP}})_S = 2.1969$. Our maximum-likelihood spot covering fraction is $f_S = 0.24$, which

³ $(G_{\text{BP}} - G_{\text{RP}}) = 11.7 - 3.91 \times 10^{-3} T_{\text{eff}} + 3.57 \times 10^{-7} T_{\text{eff}}^2$, and is valid over $3054 < T_{\text{eff}} < 5407$ K.

gives a predicted color $G_{\text{BP}} - G_{\text{RP}} = 1.4976$, which is $< 1\sigma$ consistent with the observed color of EQ Vir.

EK Dra (HD 129333)

EK Draconis is a G1.5V BY Dra variable generally thought to resemble the young Sun (Montes et al., 2001). Järvinen et al. (2007) used atomic line profiles to detect both high and low-latitude spots with $\Delta T = 500$ K. Zeeman Doppler imaging from Waite et al. (2017) reveals $P_{\text{rot}} = 2.766 \pm 0.002$ d, and an amazing variety of spots—sometimes at mid-latitudes, sometimes at the pole, covering 2-4% of the stellar surface. O’Neal et al. (2004) measured a much larger spot coverage $f_S = 0.25\text{-}0.40$ for $T_Q = 5830$ K and $T_S \gtrsim 3800$ K.

We model the spectrum of EK Dra with a linear combination of spectra from HD 210277 ($T_Q = 5535^{+42}_{-48}$ K) and HD 38230 ($T_S = 5253^{+61}_{-89}$ K). The only TiO band that yields informative constraints on the spot covering fraction is at $7054 \text{ \AA}$, predicting a spot covering fraction of $f_S = 0.28 \pm 0.06$, consistent with the lower end of the coverage measured by O’Neal et al. (2004). The higher spot covering fractions are excluded by the color prior (see previous section for a detailed discussion).

HAT-P-11

HAT-P-11 is an active K4V dwarf in the *Kepler* field with a transiting hot Jupiter. Transits of the stellar surface reveal frequent starspot occultations (Deming et al., 2011; Sanchis-Ojeda & Winn, 2011), which yield spot covering fractions $f_S = 0.0\text{-}0.1$ within the transit chord; while rotational modulation predicts $f_S \gtrsim 0.03^{+0.06}_{-0.01}$ (Morris et al., 2017b). HAT-P-11 appears to have a ~ 10 year activity cycle, and may be modestly more chromospherically active than planet hosts of similar rotation periods (Morris et al., 2018a). Recent ground-based photometry of spot occultations within the transit chord yielded spot coverage $f_S = 0.14$ (Morris et al., 2018g).

It is a valuable validation exercise to apply the TiO molecular band modeling technique to HAT-P-11 and to compare with the results of spot occultation analysis. We model the

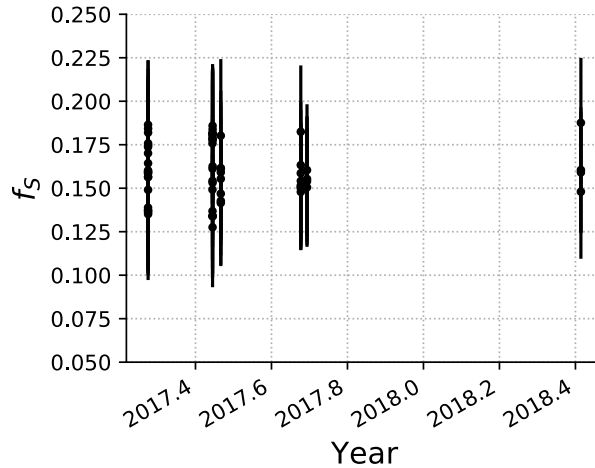


Figure 8.7: The spot covering fraction f_S of HAT-P-11 inferred via TiO absorption from starspots in the spectrum of HAT-P-11 as a function of time.

spectrum of HAT-P-11 as a linear combination of the spectra of HD 5857 ($T_Q = 4712^{+67}_{-71}$ K) and Gl 705 ($T_S = 4465^{+102}_{-66}$ K), giving the spots $\Delta T_{\text{eff}} = 250$ K, similar to typical sunspot penumbra. We find a consistent spot covering fraction between observations separated by a year near $f_S \approx 0.15 \pm 0.06$, see Figure 8.7. This is broadly consistent with the spot covering fractions measured in transit by Morris et al. (2017b), if on the high end, and consistent with the more recent observations of Morris et al. (2018g). The TiO estimate might be slightly larger than the typical transit chord crossing spot filling factor because of the small temperature difference that we have assumed here (250 K)—a larger temperature difference would produce a correspondingly smaller spot covering fraction. Perhaps this is evidence that the correct spot temperature should be a bit cooler than our assumed T_S .

HD 222107 (λ And)

λ Andromedae is a single-lined spectroscopic binary (SB1) with an old disk giant primary identified as an RS CVn variable with rotation period $P_{\text{rot}} = 54$ d, which has at least two large starspots (Bopp & Noah, 1980; Calder, 1938; Drake et al., 2011; Landis et al., 1978;

Padmakar & Pandey, 1999; Pandey & Singh, 2012; Parks et al., 2014; Poe & Eaton, 1985). *BV* photometry of the rotational modulation predicts one large spot covering 8% of the stellar surface, with an estimated temperature $T_S = 4000 \pm 300$ K (Donati et al., 1995). O’Neal et al. (1998) modelled TiO molecular band absorption ranging $f_S = 0.14$ -0.21. Mirtorabi et al. (2003) developed a TiO photometric index to measure the spot covering fraction over several years and found spot coverage varying from a few to $\lesssim 40\%$. Frasca et al. (2008) measured simultaneous photometry and spectroscopy of λ And and found $f_S = 0.076^{+0.023}_{-0.014}$. Using the CHARA array, Parks et al. (2014) found $f_S = 0.096$.

We model λ And with a combination of HD 6497 ($T_Q = 4514^{+82}_{-71}$ K) and GJ 4099 ($T_S = 3846^{+181}_{-190}$ K). We find $f_S = 0.18 \pm 0.06$, consistent with Donati et al. (1995, 2003); Frasca et al. (2008); O’Neal et al. (1998); Parks et al. (2014).

HD 45088 (OU Gem)

This is a double-lined spectroscopic binary (SB2), with an orbital period $P_{\text{orb}} = 6.99$ d (Bopp & Noah, 1980; Griffin & Emerson, 1975). Glazunova et al. (2014) solved its orbit, characterized the components, and found the following properties for the primary and secondary, respectively: $T_{\text{eff}} = 5025$ and 4508 K, $\log g = 4.3$ and 4.5 dex, and $[\text{Fe}/\text{H}] = -0.2$ dex.

O’Neal et al. (2001) accounted for the secondary in their analysis and fixed the primary and secondary temperatures to 4925 K and 4550 K, then fit for a third component assumed to have a temperature of 3525 K and a spectrum from Gl 96, and found $f_S = 0.20 - 0.35$. Glazunova et al. (2014) also noted temporal changes in chemical abundances consistent with substantial spot coverage.

We modeled the TiO features of HD 45088 as a combination of HD 145742 ($T_Q = 4851^{+13}_{-75}$ K) and Gl 705 ($T_S = 4465^{+102}_{-66}$ K), ignoring the binarity, found apparent “spot covering fraction” $f_S = 0.52 \pm 0.14$, which in this case can be instead interpreted as the fractional flux contributed by the secondary component. According to a 3 Gyr PARSEC isochrone model with $[\text{Fe}/\text{H}] = -0.2$ dex (Bressan et al., 2012b), the stellar radii at our component temperatures are $R_A = 0.69 R_{\odot}$ and $R_B = 0.63 R_{\odot}$; the ratio of the cooler area from

the secondary to the total area of both stars is then 0.48, which is consistent with the spot covering fraction we inferred. The difference between O’Neal et al. (2001) and our procedure is that we did not account for the secondary’s flux, but instead fit its photosphere and returned the relative stellar areas instead of the spot covering fraction. This exercise validates our TiO fitting procedure, at least in this “heavily spotted” regime, as the spot area fractions are consistent with the stellar flux contributions that are expected for this stellar binary.

HD 175742 (V775 Her)

HD 175742 (K0V) is also an RS CVn variable, with rotation period $P_{\text{rot}} = 2.88$ d (Rutten, 1987). Alekseev & Kozlova (2000) estimated the spectral type of the companion to be M3V ($\Delta T \approx 1900$ K), then measured the spot covering fraction via rotational modulation and estimated $f_S \lesssim 0.42$ with $\Delta T = 900$ K.

We model HD 175742 with a combination of HD 145742 ($T_Q = 4851^{+13}_{-75}$ K) and Gl 705 ($T_S = 4465^{+102}_{-66}$ K) and find $f_S = 0.54 \pm 0.13$, consistent with Alekseev & Kozlova (2000).

Kepler-17

Bonomo & Lanza (2012); Davenport (2015b); Désert et al. (2011) measure positions and differential rotation of spots for this star with $P_{\text{rot}} = 12.2$ d. Estrela & Valio (2016) measure activity cycle $P_{\text{cyc}} = 1.12 \pm 0.16$ year. We measure $f_S = 0.16 \pm 0.06$, qualitatively consistent with the relatively large spot covering fraction necessary to produce spot occultations in nearly every transit, though we could not find a precise spot coverage number in the literature.

HD 134319 (IU Dra)

Messina et al. (1998) use rotational modulation to predict a spot covering fraction of at least $f_S \gtrsim 0.16$ for this BY Dra-type variable. Adaptive optics imaging revealed that HD 134319

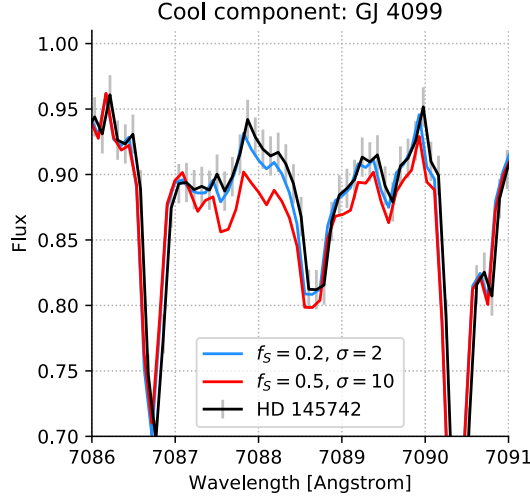


Figure 8.8: Synthetic two-component spectra created by combining HD 145742 with various spot coverages represented by the spectrum of GJ 4099. The flux-weighting of the spots conspires to make it extremely difficult to measure small spot coverage, though larger spot coverages can be measured robustly.

has a M4.5V companion (Mugrauer et al., 2004), but its late type and large separation from the host star of (55) makes it unlikely that it is a significant source of contaminating flux. We model HD 134319 with a combination of HD 210277 ($T_Q = 5535^{+42}_{-48}$ K) and HD 38230 ($T_S = 5253^{+61}_{-89}$ K), and find $f_S = 0.0 \pm 0.06$.

8.4 Discussion

8.4.1 Major caveats

The spot coverage that we infer from this TiO modeling technique is explicitly a function of the spot temperature that we assume. In this work, we have simply adopted a spot temperature contrast for each star, typically of a few hundred Kelvin, which neglects to explore the degeneracy between spot coverage and spot temperature. Our spot coverage uncertainties are therefore necessarily underestimated by not accounting for the uncertainty

in the spot temperatures.

Another point of clarification must be made about from where we expect TiO absorption to originate, which is different for G and K stars. TiO forms at temperatures below $T \lesssim 4000$ K. On the Sun, umbrae are 3900-4800 K and penumbrae are 5400-5500 K (Solanki, 2003). Therefore in a Sun-like star, we should expect TiO absorption to only be generated by the umbrae of starspots. However, if we assume that starspots have a similar temperature contrast on a mid-K star with 4400 K, penumbrae may have temperatures near 4000 K, implying that the entirety of starspots, umbrae and penumbrae together, generate TiO absorption. As a result, the spot coverages for stars earlier than $\sim K5$ should be interpreted as umbral spot coverages, while spot coverages for stars later than $\sim K5$ may be interpreted as penumbral-plus-umbral spot coverages.

The challenge of making TiO absorption from $R \approx 31,500$ spectroscopy is illustrated in Figure 8.8, where we have constructed two artificial spotted spectra from HD 145742 by adding cooler components with the spectrum of GJ 4099 via Equation 8.1. Spot coverages as large as 20% make insufficient differences from the original unspotted spectrum to robustly claim a spot coverage, and it is only in the $\sim 50\%$ coverage regime that truly significant spot coverages make obvious changes in the observed spectrum of the spotted star. It is also clear how sensitive the technique may be to continuum normalization, as any misinterpreted curvature in the continuum could easily over- or under-estimate the spot coverage in TiO bandheads. Using ARCES spectra and the technique presented here, we caution the reader that our spectra are sensitive enough to robustly identify spot coverage $> 30\%$ (5σ) or more, and give suggestive results for small spot coverages which are primarily constrained by the *Gaia* color prior rather than the echelle spectroscopy.

8.4.2 $\log R'_{\text{HK}}$ as a proxy for spottedness

We compare the spot covering fractions f_S with the chromospheric activity index $\log R'_{\text{HK}}$ in Figure 8.9. We use the $\log R'_{\text{HK}}$ index rather than the S -index to account for the different baseline photospheric emission in stellar atmospheres as a function of effective temperature;

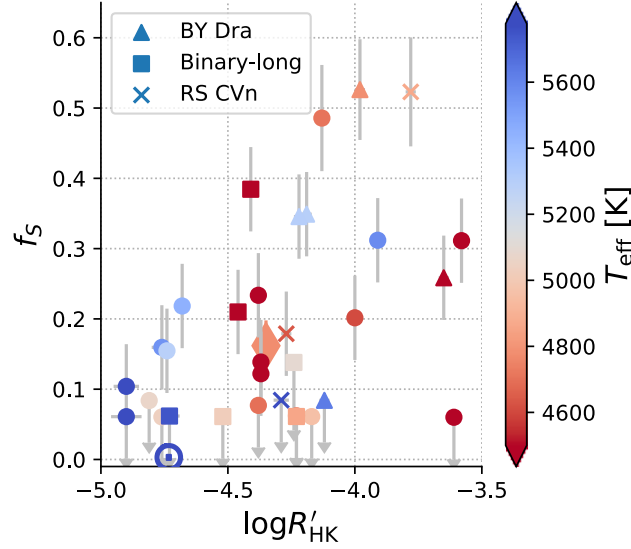


Figure 8.9: Spot covering fraction f_S as a function of $\log R'_{\text{HK}}$. The “ $\odot$ ” is the Sun, the large rhombus is HAT-P-11. Circular points mark stars that have no special classification.

and indeed the results appear to be independent of stellar T_{eff} . There is a dearth of stars with high spot covering fractions and low $\log R'_{\text{HK}}$, in other words, stars with relatively inactive chromospheres tend to have relatively small spot coverages. As chromospheric activity increases, the maximum observed spot coverage increases, with stars distributed throughout a broad range of spot coverages at each chromospheric activity level.

We note the apparent discrepancy between the measured spot coverages for HAT-P-11 measured via starspot occultations (Morris et al., 2017b) and TiO absorption (orange diamond), for which there are several explanations. The spot coverage measured in transit via spot occultations varied between $0 < f_S < 0.1$ from transit to transit between 2009-2013. The echelle spectra presented here were collected from 2017-2018, at a different phase in the stellar activity cycle (Morris et al., 2017c), where the apparent spot coverage measured in transit is somewhat higher, $f_S \sim 0.14$ (Morris et al., 2018g). The later spot coverage estimate is consistent with the spot coverage measured from molecular band modeling, $f_S \sim 0.12 \pm 0.06$.

Several of the spot coverage measurements are consistent with $f_S \gtrsim 0.5$, which begs the question: are we measuring spot coverage or evidence for a different mean photospheric temperature (i.e. the Zebra effect, Pettersen et al. 1992)? Given recent detailed observations by Gully-Santiago et al. (2017) which yield $f_S \sim 0.8$, we follow their example and simply state the coverage f_S of the apparently cooler surface, noting that in the large coverage regime ($f_S \gtrsim 0.5$), it might be perilous to think of f_S as “starspot coverage” and instead it would be more accurate to think of it as the “cool atmosphere component filling factor.” It is also possible that an unseen late-type companion could be contributing to the apparently large spot covering fraction.

The most active stars are HD 175742 ($f_S = 0.54 \pm 0.13$), HD 45088 ($f_S = 0.54 \pm 0.13$) and Gl 702 B ($f_S = 0.45 \pm 0.06$), two of which are short-period spectroscopic binaries. These three K stars are also some of the fastest rotators (Table 8.3).

We note that none of the stars studied here are candidates for Maunder minima stars (Wright, 2004). The template spectra of stars with $\log R'_{\text{HK}} \lesssim -5.1$ are consistent with having evolved off the main sequence, judging by measured surface gravities and their positions on the color magnitude diagram in Figure 8.3.

8.4.3 Spottedness as a function of rotation

The spot covering fraction as a function of stellar rotation period is shown in Figure 8.10, with rotation periods listed in Table 8.3. Figure 8.10 is essentially the reverse of Figure 8.9, since rotation period and chromospheric activity are inversely related via the activity–Rossby number relation (i.e., faster rotators are more active; Noyes et al., 1984). At short rotation periods there is a broad range of spot coverages, while the coverage generally declines with increasing rotation period.

One exception is an active star with a long period – the G8IVk star HD 222107 (λ And) with $P_{\text{rot}} = 54$ d (Rutten, 1987). This star is discussed in detail in Section 8.3.2, so we simply note here that it may have a non-zero spot coverage despite its long rotation period because it has been classified as an RS CVn variable.

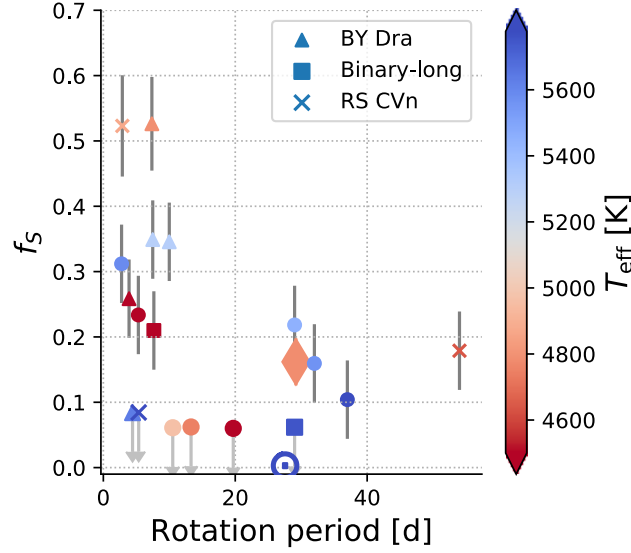


Figure 8.10: Spot covering fraction f_S as a function of $\log R'_{\text{HK}}$. The $\odot$ is the Sun, the large rhombus is HAT-P-11. The outlier at the longest rotation period is the RS CVn star λ And (HD 222107), see Section 8.3.2 for more details.

It is interesting to note that the transition to significantly spotted stars near $\log R'_{\text{HK}} > -4.3$ roughly corresponds to the transition noted in Rossby number– $\log R'_{\text{HK}}$ space by Mamajek & Hillenbrand (2008). The authors find that stars with $\log R'_{\text{HK}} > -4.3$ show a weak correlation with Rossby number, while the correlation is much tighter for more negative $\log R'_{\text{HK}}$ (see Figure 7 of Mamajek & Hillenbrand 2008).

8.4.4 The photosphere-chromosphere connection

Let us now connect these synoptic measurements with the small-scale magnetic activity occurring on the surfaces of these stars. Figure 8.9 is essentially comparing the chromospheric emission in plages, measured in terms of $\log R'_{\text{HK}}$, to the photospheric absorption by starspots, in terms of f_S . Plages are magnetically active regions which are bright in stellar chromospheres, leading to emission in the Ca2 H & K line cores (Hall, 2008). Starspots are

Target	P_{rot} [d]	Reference
EK Dra	2.766	Waite et al. (2017)
HD 175742	2.88	Rutten (1987)
EQ Vir	3.9	Suárez Mascareño et al. (2016a)
HD 134319	4.43	Wright et al. (2011)
HD 148467	5.31	Houdebine et al. (2016)
HD 39587	5.36	Wright et al. (2011)
Kepler-63	5.407	McQuillan et al. (2013)
HD 45088	7.36	Rutten (1987)
HD 220182	7.49	Wright et al. (2011)
GJ 9781A	7.66	Houdebine et al. (2016)
HD 41593	10.0	Isaacson & Fischer (2010)
HD 200560	10.526	Strassmeier et al. (2000)
Kepler-17	12.159	McQuillan et al. (2013)
HD 82106	13.3	Pizzolato et al. (2003)
GJ 702B	19.7	Wright et al. (2011)
σ Draconis	29.0	Pizzolato et al. (2003)
HD 68017	29.0	Isaacson & Fischer (2010)
HAT-P-11	29.2	Morris et al. (2017b)
HD 62613	32.0	Isaacson & Fischer (2010)
51 Peg	37.0	Wright et al. (2011)
HD 222107	54.0	Rutten (1987)

Table 8.3: Literature rotation periods.

regions of intense magnetic fields where convection is suppressed in the photosphere (Solanki, 2003).

On the Sun, we can spatially resolve plages and sunspots, and we see: (1) that plages emerge in the same active latitudes as sunspots throughout the solar activity cycle; (2) plage regions are generally larger than sunspots; and (3) sunspots are accompanied by plage regions, while the reverse is not always true (plages may emerge without accompanying sunspots) (Mandal et al., 2017).

We propose that the observations in Figure 8.9 show a related trend in the ensemble of stars. Stars with relatively small $\log R'_{\text{HK}}$ host plage regions, which generate the observed Ca2 H & K emission. A transition occurs near $\log R'_{\text{HK}} \sim -4.3$, where some of the magnetic active regions on the star must now be large enough to produce both plages *and* substantial coverage by starspots, resulting in the observed response in f_S for $\log R'_{\text{HK}} \gtrsim -4.3$.

This may explain why the spot coverage f_S does not increase monotonically with increasing $\log R'_{\text{HK}}$, since plages are not always accompanied by starspots, so a range of spot coverages can be consistent with a particular $\log R'_{\text{HK}}$. This may also explain the dearth of stars with substantial spot coverage f_S but small $\log R'_{\text{HK}}$, since starspots are always accompanied by plages.

8.4.5 *BY Draconis variability*

Several of the stars with non-zero spot coverages have already been noted as BY Draconis-type variable stars, indicating that they show rotational modulation generally attributed to asymmetric starspot coverage (Chugainov, 1966; Jaschek & Jaschek, 1990; Kron, 1950). Some of the stars in the sample have not been identified as BY Dra-type variables despite having significant spot coverage, such as HD 151288 and Gl 702 B, which may indicate one of two scenarios: either time-series photometry has yet to reveal the rotational modulation of these stars, or perhaps the distribution of starspots is axisymmetric, causing minimal rotational variability.

The latter scenario—where symmetric spot distributions produce little rotational variabil-

ity but apparently significant TiO absorption—highlights an important feature of molecular band modeling for starspot hunting. Molecular modeling does not need the distribution of spots to be asymmetric in order to detect starspots.

It is worth asking if the BY Draconis variable designation has meaning in the age of *Kepler* photometry, which has revealed that innumerable stars are rotationally variable once sufficiently precise photometry is available (e.g.: Giles et al., 2017; McQuillan et al., 2013, 2014; Walkowicz & Basri, 2013). We propose that the BY Dra label be reserved for stars with large rotational variability, for example, greater than 0.01 mag. This might preserve the BY Dra designation for only those targets with unusually large rotational variability, without admitting most main-sequence stars into the class.

8.5 Conclusions

Detailed, independent analyses of the effective temperatures of our sample of 55 F, G, K, and M stars using both SME and MOOG show good agreement with the *Gaia* DR2 effective temperature catalog (Andrae et al., 2018). The *Gaia* effective temperatures inferred from broadband colors appear not to be strongly affected by stellar activity or spectral type, reaffirming the importance and accuracy of the full Andrae et al. (2018) catalog.

We have used molecular band modeling of four strong TiO absorption features in the optical to measure spot coverage on active G and K stars. We find consistent spot coverages with previous results on several benchmark stars, and provide uniform spot coverage measurements for a sample of 29 active stars spanning a range of activity levels. We find that color priors are critical for constraining the spot coverage on active stars while preserving their observed broadband colors.

There appears to be a dearth of stars with low chromospheric activity and high spot covering fractions. These observations are consistent with the solar perspective that plagues are associated with large starspots, and plagues can appear without starspots.

Overall however, we caution users of the TiO absorption technique that moderate signal-to-noise spectra at $R \approx 31,500$ provide only weak detections of TiO absorption due to

starspots. Using both higher resolution and higher signal-to-noise spectra in addition to light curve modelling (as in Gully-Santiago et al., 2017, for example) is preferable for robust spot covering fractions.

8.A *Stellar properties*

In the following subsections, we will enumerate some references to stars in the sample.

8.A.1 *70 Oph B (Gl 702 B)*

The smaller component in a nearby binary system (5 pc) discovered by Herschel & Watson (1782), 70 Ophiuchi B (Gl 702 B) is a $0.73M_{\odot}$ star with $T_{\text{eff}} = 4390 \pm 200$ K (Eggenberger et al., 2008).

8.A.2 *51 Peg*

51 Peg hosts a hot Jupiter (Mayor & Queloz, 1995). Henry et al. (1997) measured a small upper limit on the amplitude of the rotational modulation of $\Delta(b + y)/2 < 0.0002 \pm 0.0002$ mag. Mittag et al. (2016) estimated the age of 51 Peg at 6.1 ± 0.6 Gyr, which may explain why it is significantly less active than the Sun (e.g., Mamajek & Hillenbrand, 2008).

8.A.3 *σ Draconis*

This K0 star has a radial velocity periodicity that correlates with activity, indicating a stellar activity cycle with period $P_{\text{cyc}} = 6$ years (Butler et al., 2017). It is bright and near enough ($G = 4.38$, 5.8 pc) that if it has large spots, they could be detectable as astrometric jitter in *Gaia* observations (Morris et al., 2018e).

8.A.4 *HD 39587 (χ^1 Ori)*

HD 39587 is a spectroscopic binary with $M_A = 1.01 \pm 0.13M_{\odot}$, and $M_B = 0.15 \pm 0.02M_{\odot}$ (König et al., 2002), and the primary star has a rotation period $P_{\text{rot}} = 5.36$ d (Wright et al.,

2011). One can draw interesting comparisons to the young Sun, since the semimajor axis is 4.33 AU and the stars are unlikely to be tidally interacting.

8.A.5 HD 68017

HD 68017 is a G4V $M = 0.85^{+0.04}_{-0.03} M_{\odot}$ star with an M5 companion at ≈ 06 , which at 21.8 pc translates to a projected separation of 13 AU (Crepp et al., 2012). It is likely that our spectrum contains both the primary and secondary stars, but the secondary star’s flux at 7000 Å should be 4% of the primary star’s flux, and so we treat the system as a single star for the purposes of starspot modeling, which has little effect on our interpretation of the overall results (as we will find that the apparent spot covering fraction is consistent with zero).

8.A.6 HD 110833

HD 110833 is a K3+K3 binary with orbital period $P_{\text{orb}} = 271$ d, and a tertiary mid-M dwarf 16 away (Rodriguez et al., 2015).

8.A.7 HD 127506

HD 127506 hosts a non-transiting substellar companion with orbital period $P_{\text{orb}} = 7.1$ years discovered via radial velocities (Reffert & Quirrenbach, 2011).

8.A.8 HD 87884

The K2V star HD 87884 (α Leo B) is remarkable for being the primary with a faint M4V companion, the pair of which may orbit Regulus (Eggen, 1982; Jankov et al., 2017; McAlister et al., 2005). The faint secondary should contribute $\lesssim 10\%$ of the flux of the primary at 7000 Å, so we note with some caution that the small, but non-zero coverage in this system might arise from significant TiO absorption in the spectrum of the secondary component.

8.A.9 HD 79555

This young (35 Myr) K4V star is in a long period astrometric binary separated by $0.7''$ in the Castor moving group (Maldonado et al., 2010; Mason et al., 2001).

8.A.10 HD 73667

This star was identified by Wright (2004) as a potential Maunder minimum star (Eddy, 1976) for its low chromospheric activity ($\log R'_{\text{HK}} = -4.97 \text{ dex}$).

8.A.11 GJ 9781 A

This K7 star has an astrometric binary companion with separation 1478 and $\Delta V = 9.13$, which is easily separated in our ARCES spectroscopy (Lépine & Bongiorno, 2007).

8.B Color combinations

From Neff et al. (1995), the composite flux F_{total} from a linear combination a quiescent spectrum F_Q and a spotted spectrum F_S , with spot covering fraction f_S is

$$F_{\text{total}} = \frac{f_S R_\lambda F_S + (1 - f_S) F_Q}{f_S R_\lambda + (1 - f_S)}, \quad (8.3)$$

where R_λ is the ratio of continuum fluxes of the spotted and unspotted spectra at wavelength λ . Thus the linear weighting functions for the quiescent and spotted components respectively are:

$$W_Q = (1 - f_S) / [(f_S R_\lambda) + (1 - f_S)], \quad (8.4)$$

$$W_S = (f_S R_\lambda) / [(f_S R_\lambda) + (1 - f_S)]. \quad (8.5)$$

Therefore the composite apparent magnitude of a star, composed of a combination of atmospheres with two different colors c_Q and c_S , is given by applying the linear weighting in flux space and transforming back to magnitude space:

$$m = 2.5 \log_{10} (W_Q 10^{c_Q/2.5} + W_S 10^{c_S/2.5}). \quad (8.6)$$

8.C MOOG results

For details on how these results were derived, see Section 8.2.4.

Target	$T_{\text{eff,MOOG}}$	$\log g$	Micro.	[Fe1/H]	[Fe2/H]
51 Peg	5800 ± 115	4.42 ± 0.05	1.05 ± 0.17	0.14 ± 0.02	-0.07 ± 0.10
GJ 702 B	4385 ± 65	4.64 ± 0.05	1.01 ± 0.13	0.29 ± 0.02	0.68 ± 0.02
GJ 9781 A	4500 ± 55	4.63 ± 0.05	0.97 ± 0.10	0.07 ± 0.02	0.57 ± 0.17
HAT-P-11	4790 ± 175	4.61 ± 0.05	1.03 ± 0.29	-0.06 ± 0.02	0.21 ± 0.10
HD 10697	5480 ± 35	4.51 ± 0.10	0.93 ± 0.10	-0.05 ± 0.01	0.0 ± 0.12
HD 110833	5130 ± 85	4.54 ± 0.05	1.17 ± 0.10	0.08 ± 0.01	-0.12 ± 0.11
HD 113827	4510 ± 65	4.63 ± 0.05	1.15 ± 0.10	-0.14 ± 0.02	-0.07 ± 0.15
HD 122120	4960 ± 65	4.6 ± 0.05	1.89 ± 0.36	-0.20 ± 0.02	
HD 127506	4955 ± 70	4.6 ± 0.05	1.38 ± 0.22	-0.10 ± 0.01	-0.27 ± 0.10
HD 129333	5490 ± 40	4.51 ± 0.05	2.07 ± 0.10	-0.15 ± 0.01	0.22 ± 0.03
HD 134319	5640 ± 70	4.47 ± 0.05	1.47 ± 0.11	-0.08 ± 0.02	0.01 ± 0.10
HD 148467	4500 ± 75	4.63 ± 0.05	1.08 ± 0.10	-0.10 ± 0.02	
HD 151288	4395 ± 90	4.65 ± 0.05	1.8 ± 0.52	-0.32 ± 0.03	
HD 175742	4930 ± 85	4.6 ± 0.05	1.57 ± 0.39	0.04 ± 0.02	0.20 ± 0.09
HD 182488	5320 ± 65	4.54 ± 0.05	0.77 ± 0.10	0.16 ± 0.01	0.09 ± 0.08
HD 200560	4800 ± 105	4.61 ± 0.05	1.04 ± 0.12	0.08 ± 0.01	0.15 ± 0.10
HD 209290	4020 ± 50	4.73 ± 0.05	0.71 ± 0.40	-0.46 ± 0.02	
HD 210277	5490 ± 30	4.51 ± 0.05	0.90 ± 0.29	0.24 ± 0.01	0.10 ± 0.06
HD 220182	5090 ± 65	4.58 ± 0.05	0.88 ± 0.10	-0.03 ± 0.01	0.18 ± 0.07
HD 221639	4900 ± 40	4.6 ± 0.05	0.94 ± 0.14	0.33 ± 0.01	0.54 ± 0.10
HD 222107	4590 ± 30	4.58 ± 0.05	0.97 ± 0.40	-0.19 ± 0.01	
HD 266611	4230 ± 40	4.67 ± 0.05	0.79 ± 0.38	-0.26 ± 0.02	
HD 34411	5920 ± 50	4.36 ± 0.05	1.34 ± 0.15	0.02 ± 0.01	
HD 38230	5130 ± 70	4.58 ± 0.05	0.93 ± 0.35	-0.24 ± 0.01	-0.15 ± 0.23
HD 39587	5800 ± 110	4.42 ± 0.05	1.16 ± 0.10	-0.15 ± 0.01	-0.03 ± 0.07
HD 41593	5040 ± 75	4.58 ± 0.05	0.76 ± 0.16	-0.06 ± 0.01	0.07 ± 0.11
HD 42250	5400 ± 45	4.53 ± 0.05	0.99 ± 0.12	-0.01 ± 0.01	-0.11 ± 0.09
HD 47752	4800 ± 30	4.61 ± 0.05	0.53 ± 0.22	-0.07 ± 0.01	-0.14 ± 0.10
HD 50692	5930 ± 50	4.39 ± 0.05	1.21 ± 0.10	-0.26 ± 0.01	-0.44 ± 0.07
HD 5857	4820 ± 30	3.44 ± 0.10	1.81 ± 0.10	-0.12 ± 0.01	-0.14 ± 0.10
HD 62613	5430 ± 50	4.53 ± 0.05	0.93 ± 0.10	-0.14 ± 0.01	-0.35 ± 0.11
HD 6497	4510 ± 80	2.37 ± 0.10	1.41 ± 0.10	-0.11 ± 0.05	-0.18 ± 0.10
HD 68017	5690 ± 45	4.49 ± 0.05	0.99 ± 0.10	-0.39 ± 0.01	-0.55 ± 0.06
HD 73667	5090 ± 30	4.62 ± 0.05	0.84 ± 0.12	-0.63 ± 0.01	-0.73 ± 0.14
HD 86728	5790 ± 50	4.43 ± 0.05	0.99 ± 0.10	0.23 ± 0.01	0.10 ± 0.10
HD 87884	4920 ± 40	4.6 ± 0.05	0.77 ± 0.14	-0.16 ± 0.01	-0.08 ± 0.14
HD 88230	4310 ± 50	4.65 ± 0.10	0.24 ± 0.10	-0.13 ± 0.01	
HD 89744	6070 ± 110	4.18 ± 0.05	1.42 ± 0.10	0.04 ± 0.01	0.34 ± 0.01
HD 98230	5580 ± 70	4.52 ± 0.05	0.8 ± 0.12	-0.41 ± 0.02	-0.13 ± 0.05
σ Draconis	5130 ± 40	4.58 ± 0.05	0.73 ± 0.10	-0.24 ± 0.01	-0.08 ± 0.08

Chapter 9

POSSIBLE BRIGHT STARSPOTS OF TRAPPIST-1

In Chapter 7 we found that starspots and faculae are likely spatially associated with one another on the active young G star KIC 9652680, while we did not find a convincing correlation between the total flux and chromospheric emission for two mid-K stars in Praesepe, EPIC 211928486 and EPIC 211966629. Despite their range in rotation periods, these three stars are all “Sun-like” in that they have similar masses to the Sun, and have both convective and radiative zones, providing for the radiative-convective interface known as the tachocline that lies at the heart of the $\alpha\Omega$ dynamo paradigm (refer back to Section 1.5 for a brief review of the solar dynamo).

In this chapter we seek to infer the stellar surface properties of a very different star – TRAPPIST-1 (Gillon et al., 2016, 2017). TRAPPIST-1 is an M8 dwarf, and thus should be fully-convective. Lacking a radiative-convective boundary, the dynamo that powers magnetic activity on TRAPPIST-1 may be significantly different from the one that operates within the Sun. In this chapter we use two-color broadband photometry to infer the stellar surface brightness inhomogeneities of this active star. As we will discover, there is evidence that bright, hot regions occupy the stellar surface, which will contaminate transit observations of the exoplanets at optical wavelengths. The bright regions will limit our ability to characterize the potentially habitable exoplanets of TRAPPIST-1 with optical spectroscopy.

This chapter was first published in the *Astronomical Journal* (Morris et al., 2018b).

9.1 Introduction

TRAPPIST-1 is an M8V star and host to at least seven Earth-sized planets (Gillon et al., 2016, 2017). It was observed with *Spitzer* at the IRAC-2 4.5 μm band for 20 days (Delrez

et al., 2018a; Gillon et al., 2017), and 76 days later it was observed by NASA’s *Kepler* spacecraft during K2 Campaign 12 for another 79 days (Luger, 2017). The K2 observations of TRAPPIST-1 show quasi-periodic flux modulations with a period of 3.3 days (Delrez et al., 2018a; Luger et al., 2017b), which has been interpreted as a signal of stellar rotation as starspots rotate into and out of view (Vida et al., 2017). Modeling these variations faces the vexing computational problem of fitting stellar rotational flux modulation with a forward model (Aigrain et al., 2015; Davenport et al., 2015). One challenge in modeling rotational modulation is that often a light curve can be fit equally well with a few bright spots *or* with a few dark spots. This degeneracy has been referred to as the “zebra effect” (Pettersen et al., 1992): is the star bright with a few dark spots, or dark with a few bright spots?

Although star spots are usually dark due to magnetic field pressure balancing thermal pressure, one star with a mostly dark surface and a few bright regions is *T Tauri* star LkCa 4 (Gully-Santiago et al., 2017). Near-infrared spectroscopy of LkCa 4 shows a heterogeneous atmosphere — 80% of the star has $T_{\text{eff}} \sim 2800$ K, and the other 20% has $T_{\text{eff}} \sim 4000$ K. Modern Zeeman Doppler Imaging is most sensitive to large scale features in stellar magnetic fields, so it is generally unclear what small-scale magnetic structures may exist on fully-convective stars (see e.g. Morin et al., 2013).

Another difficulty in interpreting the TRAPPIST-1 brightness variations is whether the periodicity is due to rotation at all. Reiners & Basri (2010) measure a rotational velocity of 6 ± 2 km sec⁻¹, while the 3.3-day period would predict a maximum rotational velocity of 1.8 km sec⁻¹. The spots on TRAPPIST-1 evolve with time, and so it will require long-term monitoring of the 3.3-day periodicity to determine whether it is time-steady, which would argue for a rotational origin, and would call into question the measurement of the rotational velocity.

Another means of studying spots is via occultation during planetary transits, which has been studied in detail on HAT-P-11 (Morris et al., 2017b). To date, no significant spot occultations have been observed in either the *Kepler* or *Spitzer* transit light curves of TRAPPIST-1 (Delrez et al., 2018a) — this implies that if spots are responsible for the

rotational modulation, they must either reside outside of the transit chords of the planets, or be smaller than the size of the planets, which would reduce the probability and amplitude of a spot occultation.

In this paper we present a model for the K2 and Spitzer variations based upon a spot variability model, and examine its relation to the stellar flares that are frequently seen in both datasets. In section 9.2 we discuss the spot model for stellar variability. In section 9.3 we compare this model with extant K2 and *Spitzer* data. In section 9.4 we discuss a possible relation between bright flares and the bright spots. We end with discussion and conclusions.

9.2 Rotational variability model

9.2.1 Monochromatic variability

We compute spot variability at a given wavelength with a simplified model assuming small spots with radii smaller than 10% of the stellar radius. We first integrate the total stellar flux of the unspotted, limb-darkened star,

$$F_{\star, \text{unspotted}} = D^{-2} \int_0^{R_{\star}} 2\pi r I(r) dr, \quad (9.1)$$

where r is the radial coordinate from the center of the star, D is the distance to the star, $I(r)$ is the specific intensity at radius r . We model the specific intensity with a quadratic limb-darkening law, using the limb-darkening parameters of Luger et al. (2017b): $(u1, u2) = (1.0, -0.04)$.

We describe each spot with an ellipse with centroid $\mathbf{r}_i = (x_i, y_i)$ at radial coordinate $r_i = |\mathbf{r}_i|$. We then compute the flux contribution from each spot by computing the approximate spot area and spot contrast based on the ratio of Phoenix model atmospheres integrated over a given bandpass, which we assume is independent of inclination angle of observation. From the observer's perspective, each spot has semimajor axis R_{spot} along the azimuthal direction, and semiminor axis $R_{\text{spot}} \sqrt{1 - (r_i/R_{\star})^2}$ in the radial direction, due to foreshortening. Since these spots are small compared to the stellar radius, $R_{\text{spot}}/R_{\star} \ll 1$, we adopt a constant limb-darkened contrast for the entire spot, $c_{ld} = (c-1)I(r_i)/I(0)$, where

c is the monochromatic contrast in the spot relative to the adjacent photosphere flux; $c = 1$ for an unspotted region. The integrated spot flux of each spot is then given by

$$F_{\text{spot},i} = D^{-2} \pi R_{\text{spot}}^2 c_{ld} I(0) \sqrt{1 - (r_i/R_\star)^2}, \quad (9.2)$$

where the spotted flux of the star is

$$F_{\star,\text{spotted}} = F_{\star,\text{unspotted}} + \sum_{i=1}^N F_{\text{spot},i}. \quad (9.3)$$

As the star rotates, the flux of the spots varies due to foreshortening, limb-darkening, and disappearance behind the edge of the limb. Spots straddling the limb are ignored until they rotate onto the observer-facing hemisphere. This approximation is valid for spots that are small compared to the stellar radius, and small compared to the scale of limb-darkening variation across the stellar disk. We then compute the flux observed as the star rotates, by rotating the positions of the spots and recalculating the fluxes.

We find the posterior uncertainties on spot positions (latitude and longitude), radii and contrast in the *Kepler* bandpass with Markov Chain Monte Carlo (Foreman-Mackey et al., 2013).

9.2.2 Spot contrasts in *Kepler* and *Spitzer*

One might expect that the periodicity observed with *Kepler* at 3.3 days would be present in *Spitzer* observations at $4.5 \mu\text{m}$, but after removing flares and transits from the *Spitzer* light curve, little signal of rotation is present Delrez et al. (2018a), see Figure 9.1. We compute the autocorrelation function and Lomb-Scargle periodogram for the *Spitzer* light curve and find one periodic component near 0.5 days – similar to the timescale of super-granulation on the Sun (Aigrain et al., 2003) – in addition to periodicity near 4 days.

To measure the significance of the peaks in the Lomb-Scargle periodogram, we generate 100 simulated light curves – each light curve was a Gaussian process sample drawn from the maximum-likelihood kernel fit to the *Spitzer* observations – and found that 33% of

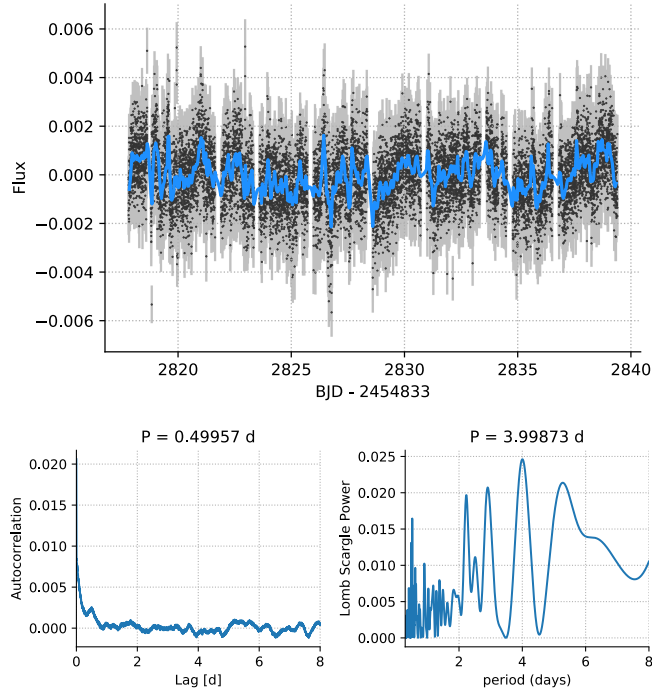


Figure 9.1: *Upper*: *Spitzer* observations of TRAPPIST-1 after transits and flares have been removed (black circles) (Delrez et al., 2018a), and a fit with a Gaussian process assuming a simple-harmonic oscillator kernel (blue curve). *Lower*: The autocorrelation function and Lomb-Scargle periodogram for the *Spitzer* observations show a characteristic peak at periods near 0.5 days.

the random light curves produced LS peaks with at least as much power as the 4 d peak, suggesting that all signals in the LS periodogram are insignificant.

We choose a small section of the *Kepler*/K2 EVEREST light curve to fit with the spot model, see Figure 9.2 (Luger, 2017). We begin by normalizing the light curve by a quadratic, and median-filter the fluxes over a five-cadence kernel to remove most flares. We select a portion of the light curve (black points) that has a repeated pattern across more than one stellar rotation. There are very few repeated flux patterns in the *Kepler* light curve,

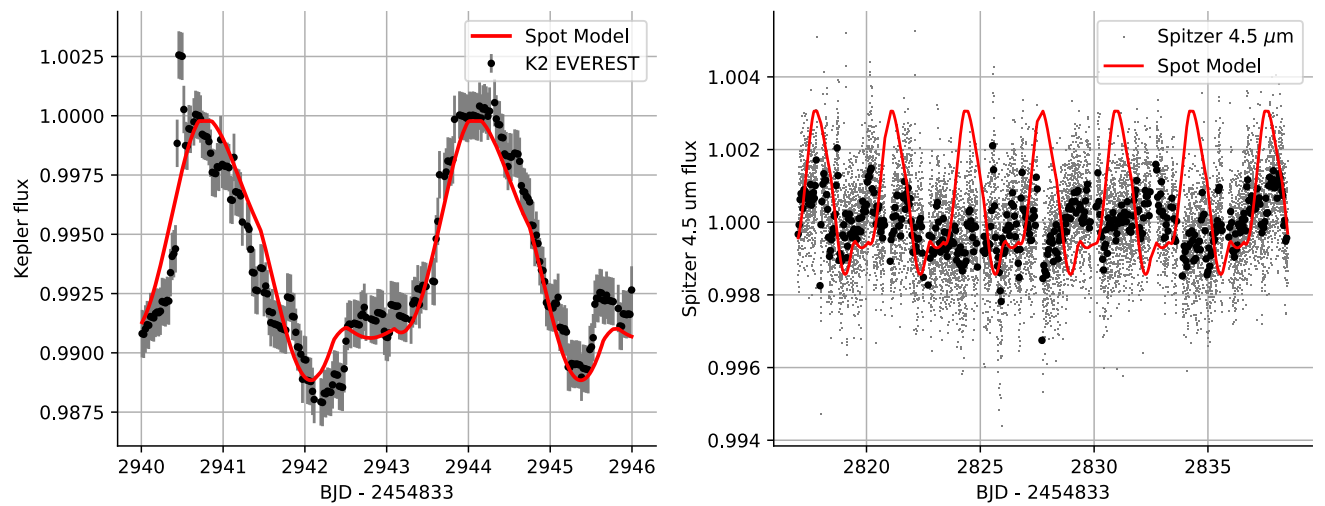


Figure 9.2: *Left*: Maximum-likelihood spot model fit (red curve) to a segment of the *K2* light curve (black points) assuming that the rotational modulation is driven by dark spots. *Right*: the same spot modulation extrapolated out to the *Spitzer* 4.5 μm band (red curve). The gray dots show the *Spitzer* observations, the black circles are one-hour bins. The *Spitzer* light curve does not show this variability, suggesting that dark spots may not be driving the photometric variability in the *Kepler* band.

indicating that the spot evolution timescale is likely shorter than the rotation period. We construct a spot model with three spots and allow their positions, radii and contrast to vary, with the contrast bounded on $0 < c < 1$. The blue curves in Figure 9.2 are models drawn from the posterior samples, indicating that the three spots have radii near $R_{\text{spot}}/R_{\star} \sim 0.12$ and contrast $c = 0.6$.

The prior applied to ensure that starspots are dark ($c < 1$) is informed by our studies of the Sun and sunlike stars, which have dark starspots (see e.g. Morris et al., 2017b; Solanki, 2003). However, bright spots have been observed on nearby brown dwarf the Luhman 16A via Doppler imaging (Crossfield et al., 2014), and on the *T Tauri* star LkCa 4 (Gully-Santiago et al., 2017).

To investigate the theoretical effects of bright spots or dark spots, we compute the contrast of a spot with spectrum $\mathcal{F}_{\text{spot}}$ on a star with spectrum $\mathcal{F}_{\text{photosphere}}$, using spectra drawn from the PHOENIX+BT Settl model (Husser et al., 2013). We find that

$$c = \frac{\int \mathcal{F}_{\lambda, \text{spot}} \mathcal{T}_{\lambda} d\lambda}{\int \mathcal{F}_{\lambda, \text{photosphere}} \mathcal{T}_{\lambda} d\lambda} \quad (9.4)$$

where λ is wavelength, and $\mathcal{T}$ is the filter transmission curve for *Kepler* or *Spitzer*. We compute c for spots on a star with $T_{\text{eff}} = 2500$ K in Figure 10.2. For *Kepler* contrasts $0 < c < 1$, the *Spitzer* contrast is $0.5 < c < 1$ — in other words, the spot contrast of dark spots in the *Kepler* band is similar to the spot contrast of dark spots in the *Spitzer* band. This result is in contradiction with the observed spot modulation in the *Kepler* bandpass and the undetected modulation in the *Spitzer* light curve.

Alternatively, the contrast of *bright* spots in the *Spitzer* 4.5 μm band increases very slowly as the spot contrast in the *Kepler* bandpass exceeds $c > 1$ (Figure 10.2). A spot 100x brighter than the photosphere in the *Kepler* band would only be 3x brighter in the *Spitzer* band. This slow increase in the contrast of bright spots at long wavelengths could produce large flux modulations in the *Kepler* bandpass and very small modulations in the *Spitzer* bandpass for very small spots.

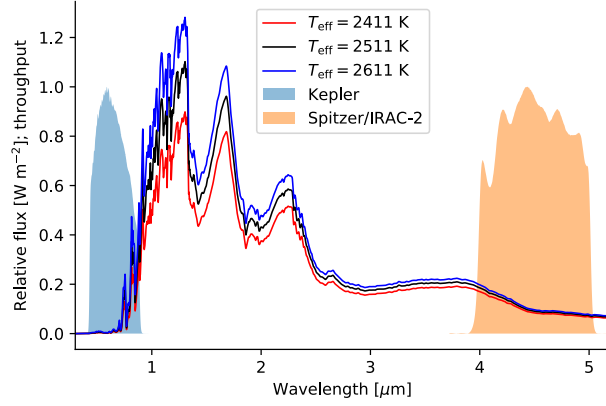


Figure 9.3: Comparison of the *Spitzer* and *Kepler* bandpasses with a PHOENIX model atmosphere with $T_{\text{eff}} = 2511$ K (TRAPPIST-1 has $T_{\text{eff}} = 2511 \pm 37$ K, see Delrez et al. 2018a).

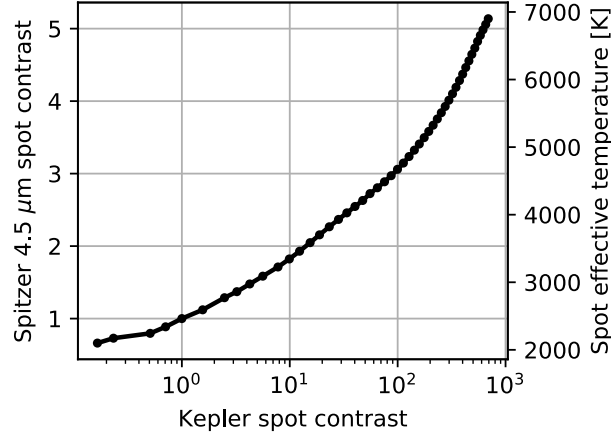


Figure 9.4: Equivalent spot contrasts in the *Spitzer* and *Kepler* bandpasses, and the spot temperatures that produce those contrasts, for a star with $T_{\text{eff}} = 2500$ K using PHOENIX+BT Settl model spectra, as described in Equation 9.4.

9.3 Simultaneous fits to the *Kepler* and *Spitzer* light curves

We fit the spot model to the *Kepler* light curve and a segment of the *Spitzer* observations of the same duration, using the empirical relation from Figure 10.2 to convert spot contrasts in the *Kepler* bandpass to contrasts at $4.5 \mu\text{m}$. We fit both light curves simultaneously, even though the observations were not simultaneous, so that the *Spitzer* light curve will constrain the spot radii and contrasts to be consistent with the typical variability in the infrared. The *Kepler* observations ended 76 days before the *Spitzer* observations started. We assume that the variability of the star did not change significantly over those 76 days because: (1) the variability does not seem to change significantly throughout the duration of either the *Kepler* or *Spitzer* light curves, and (2) the elapsed time between observations is short compared to the length of activity cycles of M stars (on the order of years – Suárez Mascareño et al. see e.g. 2016b).

We must first choose the minimum number of spots required to reproduce the K2 light curve. We fit the K2 light curve for $n = 1, 2, \dots, 6$ spots, allowing the spot positions, radii, and contrast to vary, and evaluate the reduced χ^2 and total spotted area of each fit. We find that the reduced χ^2 plateaus near a minimum after 3 or more spots have been added. If more than three spots are modelled, the radii of the spots are decreased in order to keep the total spotted area approximately constant. We therefore fix our spot number to 3 spots since that minimizes the χ^2 and the number of free parameters.

If there are many small spots distributed isotropically on the stellar surface, we would not detect them through rotational modulation. As a result, the rotational modulation fits are only sensitive to the longitudinal asymmetries in the spot distribution. Consequently, the spotted areas inferred from this model should be considered lower limits on the spotted area on the star.

We impose a prior to ensure that the addition of bright, hot spots does not change the color of TRAPPIST-1 significantly. We measure the color of the star from the optical spectrum $V - I_c = 4.7$ (Burgasser et al., 2015). At each step in our Markov chains, we add

to the prior a penalty for significant color deviations from the observed color,

$$\log p \propto -\frac{1}{2} [(V - I_c)_{\text{model}} - (V - I_c)_{\text{observed}}]^2.$$

The maximum-likelihood bright spot model fit to the *Kepler* and *Spitzer* light curves¹ is shown in Figure 9.5. The relative flux is normalized to its minimum, which assumes that the minimum flux within this segment of the light curve represents the unspotted flux. The variability in the *Kepler* band is reproduced by the spot model, and the corresponding variability in the *Spitzer* band is comparable to the observational uncertainties.

One spot has radius $R_{\text{spot}}/R_{\star} = 0.02 \pm 0.002$ and the other two have $R_{\text{spot}}/R_{\star} = 0.013 \pm 0.002$. We measure the *Kepler* contrast $c_k = 230 \pm 40$, which corresponds to *Spitzer* $4.5 \mu\text{m}$ contrast of $c_s = 3.7 \pm 0.1$, and a spot temperature of $T_{\text{spot}} \gtrsim 5300 \pm 200$. The uncertainty in the minimum spot temperature is likely underestimated, since the Markov chains prefer a narrow range of spot contrasts to fit the *Kepler* light curve, but the *Spitzer* light curve weakly constrains the lower limit on the spot temperature. The total bright spot area coverage is 16 microhemispheres (one hemisphere is half the surface area of the star) – which is small compared to the typical dark spot area coverage on the Sun (Morris et al., 2017b).

We repeat this analysis using a different segment of the K2 light curve to ensure that the results are reproducible at different times throughout the rotation of TRAPPIST-1. We choose the fluxes over two rotations spanning $2457762 < \text{BJD} < 2457769$ and find spot sizes and contrasts consistent with the results from the other segment of the K2 light curve (both regions are labeled on Figure 9.7).

The autocorrelation function of the *Spitzer* observations plus the maximum-likelihood spot model serves as a sanity-check on the amplitude of the signal introduced by the inferred bright spots. If injecting the maximum-likelihood spot model into the *Spitzer* light curve introduces significant periodicity, we should see an uptick in the autocorrelation function at $P_{\text{rot}} = 3.3 \text{ d}$. Shown in Figure 9.6, the autocorrelation function is relatively unchanged by

¹ See Figure 9.11 in the Appendix for the complete posterior sample corner plot.

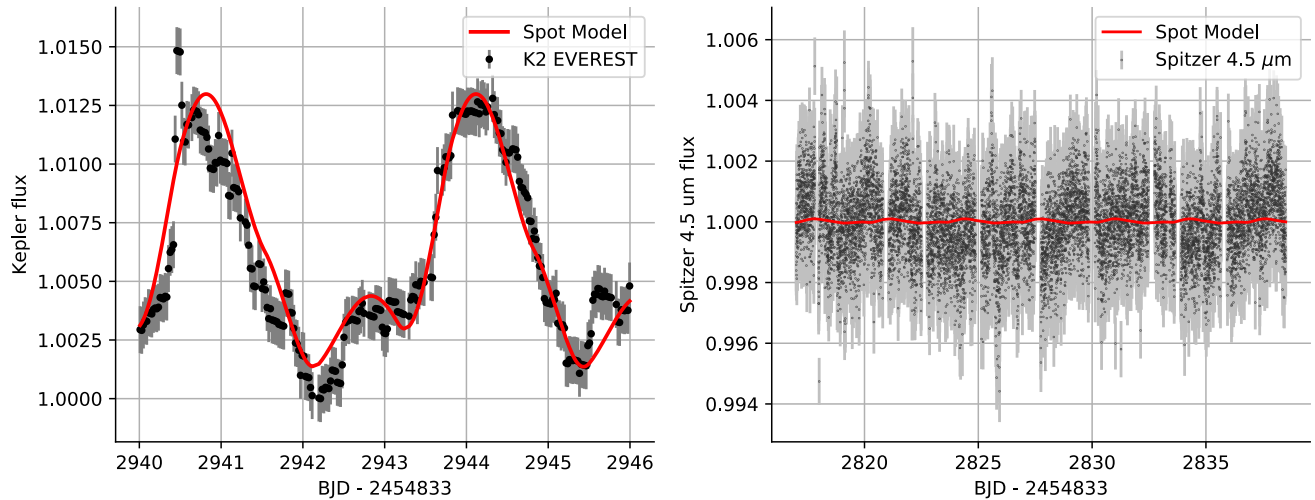


Figure 9.5: Maximum-likelihood model fit for bright spots on TRAPPIST-1 (red curve), fitting the *Kepler* (left) and *Spitzer* (right) light curves (black points) simultaneously.

the injection of the spot modulation from the maximum-likelihood spot model, and which suggests that this spot model is plausibly consistent with the *Spitzer* observations.

9.4 Correlation between bright spots and flares

The flares of active M4 dwarf GJ 1243 have been studied in detail (Davenport et al., 2014; Hawley et al., 2014). The authors searched for a correlation between flare occurrence and starspot phase by comparing the quiescent flux of the star just before a flare to the mean flux. If flares occur near starspots, the quiescent flux of the star just before the flare should be less than the mean. No such correlation emerged, which the authors suggest indicates that the positions of flares and spots are uncorrelated. They also searched for correlation with rotational phase, which could be connected to long-lived polar spots, and found no correlation.

We carried out a similar analysis to investigate if the flares are correlated with starspot phase for TRAPPIST-1, as was briefly noted in Vida et al. (2017). We manually identified

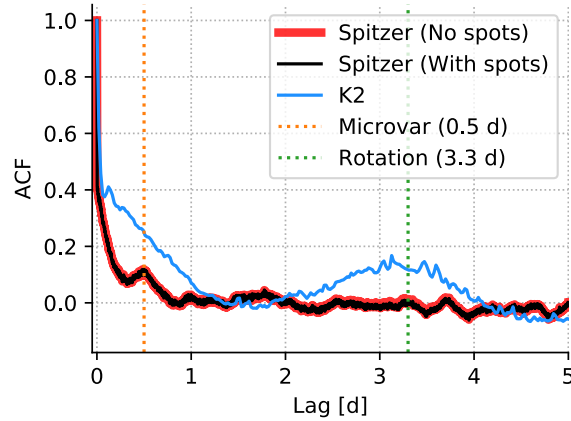


Figure 9.6: The autocorrelation function of the *Spitzer* observations (red), the *Spitzer* observations plus the maximum-likelihood spot model (black), and the K2 observations (blue), with special timescales noted for microvariability and stellar rotation.

the nine largest flares in the K2 EVEREST light curve, and masked them out – see Figure 9.7. We removed a fifth order polynomial to remove systematic trends without removing stellar variability. To measure the flux of the star at the time of the flares, we fit the rotational modulation with a Gaussian process using a simple harmonic oscillator kernel, and extrapolate the model to the times of flares.

We find that the stellar flux at the time of flares is greater than the typical flux, see Figure 9.8. The two sample T-test yields $p = 0.005$ for the two flux distributions, indicating some significance to the difference in mean fluxes. In other words, the star is typically brighter just before a flare event than the mean flux. This might suggest that the bright active regions are spatially correlated with the flares on TRAPPIST-1.

The flares also tend to occur when the change in brightness is most positive (see Figure 9.7). If we interpret the 3.3 day periodicity as rotational modulation, then the preference for flares to occur on the leading edge of the brightening events would indicate that flares are most likely to occur at a particular stellar longitude, in contradiction with the flare analysis

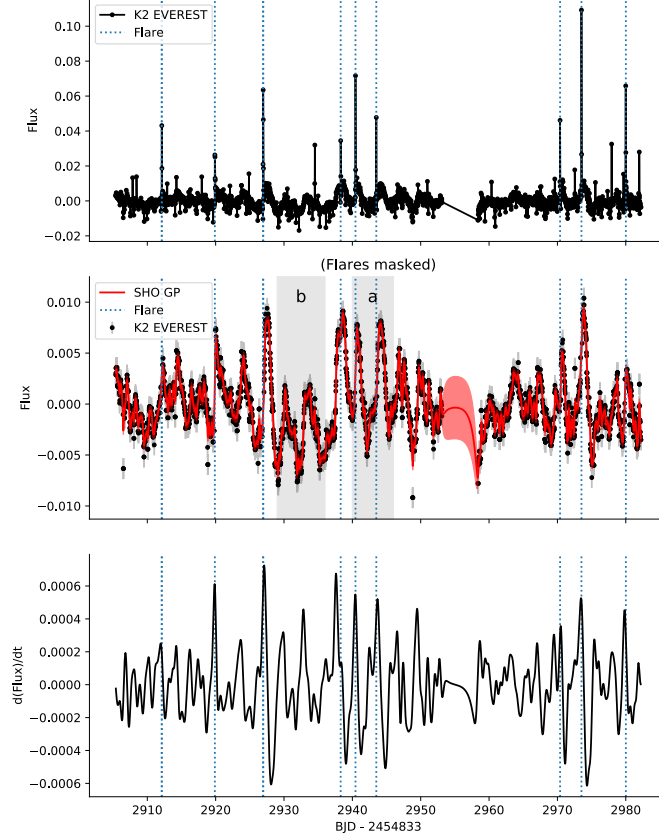


Figure 9.7: *Upper*: We manually flag flares (blue dashed lines) in the K2 EVEREST light curve (black curve). *Middle*: We investigate whether or not they preferentially occur at times of high flux by masking out flares and inferring the flux at the time of the flare with a Gaussian process model using a simple harmonic oscillator kernel (Foreman-Mackey et al., 2017). We find that flares occur preferentially at times of high flux (see Figure 9.8). The region labeled “a” is the segment of the light curve in Figures 9.2 and 9.5, the region labeled “b” is the validation segment where we repeated the bright spot analysis. *Lower*: It also appears that the flares occur on the leading edge of the brightening events. We show the numerical derivative of the Gaussian process model in the middle panel, and find that the flares tend to occur when the flux is increasing most rapidly (see also Figure 9.9).

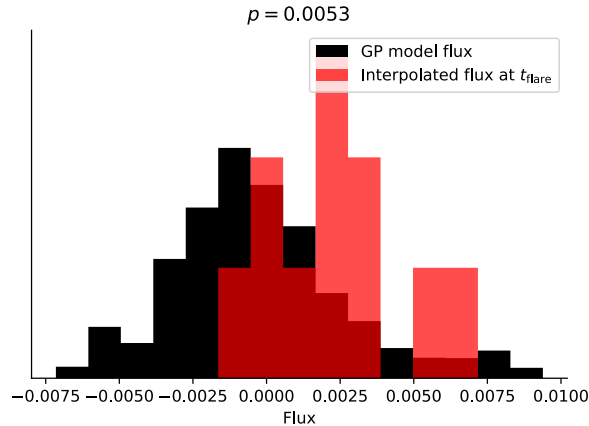


Figure 9.8: Distribution of fluxes with flares masked (black), compared with the distribution of fluxes at the times of flares after flares have been masked out and interpolated with a Gaussian process model (red). The flares typically occur when the star is bright.

of Vida et al. (2017). If we instead interpret the 3.3 day periodicity as the characteristic lifetimes of bright active regions on the star, then the 1% brightening events may be localized brightening associated in time and space with the flaring activity. Until a robust measurement of the stellar rotation period has been made, we cannot rule out the possibility that the 3.3 d period is not the stellar rotation period.

9.5 Discussion

Bright spots on the Sun referred to as faculae arise due to the magnetic fields and viewing geometry of convective granules (Spruit, 1976, 1977). Solar faculae have sizes comparable to convective cells (Keller et al., 2004), and intensity contrasts relative to the mean photosphere that are small ($c \sim 1.5$) compared to the spot contrast we observe on TRAPPIST-1 in the *Kepler* band. The characteristic granule size on late-M dwarfs is likely to be ~ 80 km across (Ludwig et al., 2002), while the spots on TRAPPIST-1 are ~ 600 km in diameter. We suggest that the spots on TRAPPIST-1 should not be considered faculae.

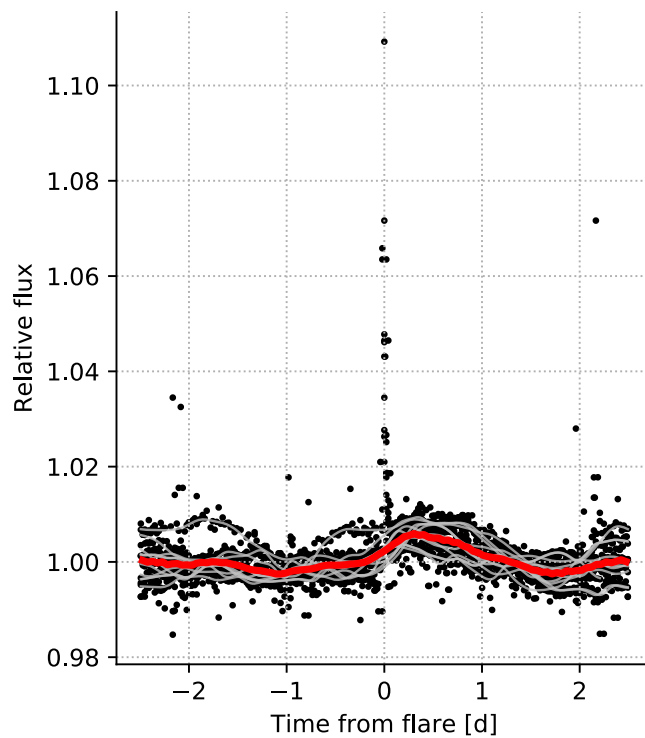


Figure 9.9: K2 light curve (black circles) and the maximum-likelihood Gaussian process models (gray curves), folded at the times of flares. The red curve is the mean of the Gaussian process models. It appears that the flares occur preferentially during the rise in brightness (see also Figure 9.7).

Few observations have revealed small scale active regions on fully-convective stars. The global-scale magnetic fields of late-M dwarfs have been studied in detail using Zeeman-Doppler Imaging (Donati et al., 2003; Morin et al., 2010, 2011, 2013). One exception is the fully convective star V374 Peg which shows 2% dark spot coverage (Morin et al., 2008).

We can compare our results with Rackham et al. (2017) and Zhang et al. (2018), who computed the spot and faculae covering fractions for TRAPPIST-1. Both studies find that the stellar spectrum is best described by a heterogeneous surface, with persistent spectral components at different temperatures. Our constraints, based upon two-band photometry, also imply that the star is best described as a heterogeneous mixture, described by bright spots and a dimmer photospheric component. We are proposing bright spots with higher temperatures, smaller covering factor, and shorter lifetimes than the steady spotted and facular components of Rackham et al. (2017) or Zhang et al. (2018). It is possible that the star has some combination of all of these features (bright spots, dark spots, and faculae).

In the previous section, we proposed that the apparent time-correlation between the occurrence of luminous flares and the brightness of the star is due to a physical association between the positions of bright spots which are associated with flares. An alternative hypothesis is that the $\sim 1\%$ flux variations are not rotational modulation, but rather transient, bright active regions which accompany flares. If that is the case, then the 3.3 d periodicity in the K2 light curve should be interpreted as a characteristic active region timescale rather than a rotation period. In fact, if the bright spots were due to rotational variability, this might imply that the luminous flares preferentially occur at the same stellar longitude. This seems implausible given that magnetic activity on the surface of the star shouldn't be connected to the inertial frame. Thus, we feel that the possible correlation between the bright flares and spots may argue against the spot variation being due to rotation.

Hydrogen Balmer line emission ($H\alpha$) is common in late M dwarfs and variable $H\alpha$ emission could potentially explain the 3.3-day modulations observed by *Kepler*; as $H\alpha$ is not within the *Spitzer* bandpass, this would naturally explain the lack of a 3.3-day feature in the *Spitzer* lightcurve. The optical spectrum of TRAPPIST-1 of Burgasser et al. (2015) shows that the

flux in $H\alpha$ is only 0.3% of the flux integrated over the Kepler bandpass. However, Kruse et al. (2010) found that $H\alpha$ equivalent widths vary by up to a factor of five for M8V stars, indicating that it is plausible that extreme $H\alpha$ variability (by a factor of ~ 5) could explain the *Kepler* variability. Further observations of $H\alpha$ emission from TRAPPIST-1 are required to investigate this possibility.

9.6 Conclusions

We simultaneously model photometry of TRAPPIST-1 from *Kepler* and *Spitzer* to measure the properties of its putative starspots. We find that if the 3.3 day periodicity is due to stellar rotation, TRAPPIST-1 likely has a few bright spots rather than dark spots, and the spots have characteristic temperatures $T_{eff} \gtrsim 5300$ K and radii $R_{spot}/R_{\star} \sim 0.004$.

The bright spots add a source of flux dilution to the transit light curves of each planet. We provide a correction factor for the transit depths of each planet, and propagate those depths to revise planet radii and densities; however, we note that other sources of variability and/or stellar inhomogeneity likely dominate this correction in the infrared (Delrez et al., 2018a; Zhang et al., 2018).

We note that flares occur preferentially when the star is bright, and when the brightness is increasing most rapidly. This may suggest that the flares are associated with the hot spots. Alternatively, the brightness variations could be the growth and decay of bright active regions on the stellar surface with a characteristic timescale of 3.3 days.

Though the nature of the proposed stellar activity is still unclear, the observations suggest that TRAPPIST-1 has bright spots rather than dark ones. Even if the continual spot variability observed by K2 were due to transient photospheric spots, rather than stellar rotation, the rapid appearance and disappearance of *dark* photospheric spots would produce a signal which was not observed by *Spitzer*.

9.A The effect of bright spots on transit light curves

Typically the transit depth is assumed to be the ratio of the cross-sectional areas of the projected planet on the star,

$$\delta_{\text{unspotted}} = \frac{\pi R_p^2}{\pi R_\star^2}, \quad (9.5)$$

where we use the equality sign because we are ignoring limb-darkening in this example. If there are bright unocculted spots on the star, the measured depth will be

$$\delta_{\text{spotted}} = \frac{\pi R_p^2}{\pi R_\star^2 + (c - 1)\pi R_{\text{spot}}^2} \quad (9.6)$$

where c is the spot contrast relative to the photosphere. Rearranging, we find

$$\frac{\delta_{\text{unspotted}}}{\delta_{\text{spotted}}} = 1 + (c - 1)(R_{\text{spot}}/R_\star)^2. \quad (9.7)$$

This correction for the unocculted bright spots in the *Kepler* and *Spitzer* bands are $\delta_{\text{unspotted}}/\delta_{\text{spotted}} = 1.004 \pm 0.001$ and 1.00006 ± 0.00001 , respectively. These transit depth dilution corrections allow us to update the observed planet radii reported by Gillon et al. (2017) with K2, which we list in Table 9.1. If the are of bright spots is confined to the three spots we modeled, then the dominant systematic affecting planet radii from the *Spitzer* observations is the microvariability observed in Figure 9.1, rather than the bright spot variability. However, we note that this may be a lower limit on the effect of bright spots as our three-spot model only measures the *variable* component of the bright spots. We have carried out a test in which we added numerous small spots distributed in longitude, which produces an equally good fit to the variable light curve, but with much larger areal coverage of bright spots.

The flux dilution due to the bright spots on TRAPPIST-1 will cause the transit depths to appear a shallower than they truly are. In Table 9.1 we list the revised planet properties – all revisions are within the uncertainties of the measurements. The effect as a function of wavelength is plotted in Figure 9.10.

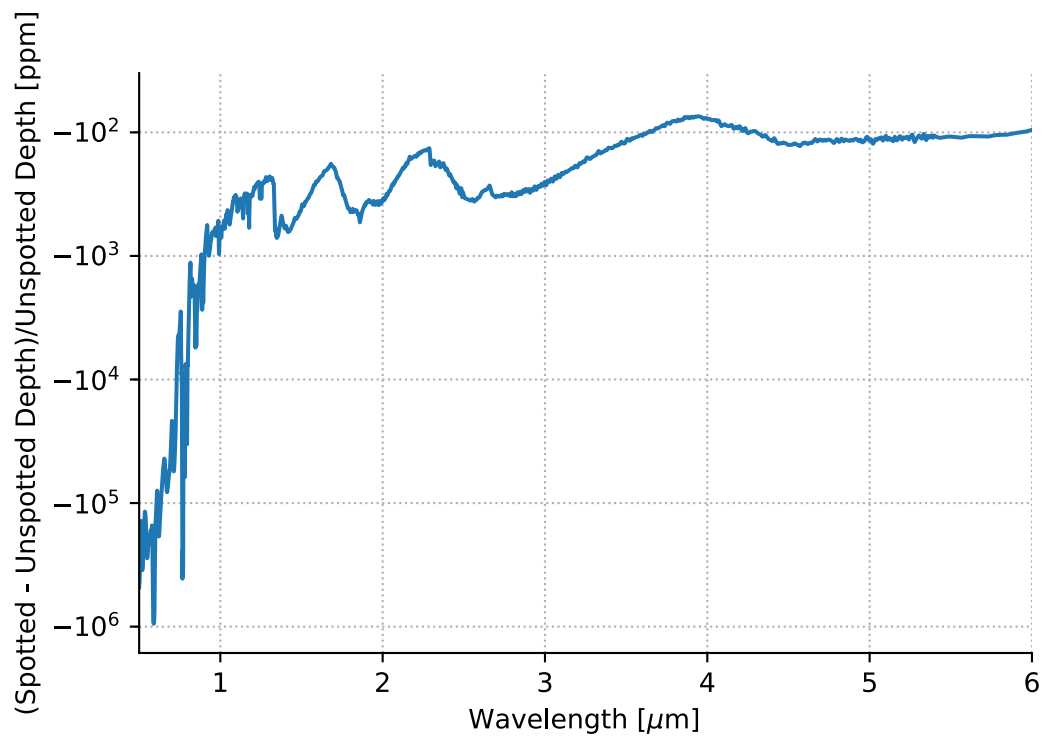


Figure 9.10: Fractional change in transit depth in the spotted vs. unspotted case.

	Depth (%) (G17)	Depth (%) (this work)	Radius [$R_{\oplus}$] (G17)	Radius [$R_{\oplus}$] (this work)	Density [$\rho_{\oplus}$] (G17)	Density [$\rho_{\oplus}$] (this work)
b	0.727 ± 0.009	0.729 ± 0.009	1.086 ± 0.035	1.090 ± 0.034	0.660 ± 0.560	0.656 ± 0.556
c	0.687 ± 0.010	0.690 ± 0.010	1.056 ± 0.035	1.060 ± 0.034	1.170 ± 0.530	1.159 ± 0.512
d	0.367 ± 0.017	0.368 ± 0.017	0.772 ± 0.030	0.775 ± 0.030	0.890 ± 0.600	0.882 ± 0.581
e	0.519 ± 0.026	0.521 ± 0.026	0.918 ± 0.039	0.921 ± 0.037	0.800 ± 0.760	0.793 ± 0.742
f	0.673 ± 0.023	0.676 ± 0.023	1.045 ± 0.038	1.049 ± 0.037	0.600 ± 0.170	0.589 ± 0.156
g	0.782 ± 0.027	0.785 ± 0.027	1.127 ± 0.041	1.131 ± 0.040	0.940 ± 0.630	0.927 ± 0.609
h	0.352 ± 0.033	0.353 ± 0.033	0.755 ± 0.034	0.759 ± 0.042	—	—

Table 9.1: Revised planet properties in the *Kepler* bandpass accounting for the flux dilution due to bright spots on TRAPPIST-1. Here we take planet masses and the definition of Depth = $(R_p/R_{\star})^2$ as in Gillon et al. (2017).

9.B Posterior distributions

The full posterior distributions on all fit parameters in the bright spot model are shown in Figure 9.11.

9.C Probability of spot occultations

Occultations of the bright spots by the planets would allow us to infer the spot properties independently, as we showed for HAT-P-11 in Morris et al. (2017b). We calculate an upper-limit on the probability that the proposed bright spots will be occulted by planets in the TRAPPIST-1 system. If we assume that the spots are infinitely long-lived, each spot is visible for half of the stellar rotation. We convert the posterior samples for spot latitudes to posterior samples of impact parameters p_b , and integrate the posterior samples for b over the range of impact parameters occulted by each planet (b_0 , b_1), normalized by the integral

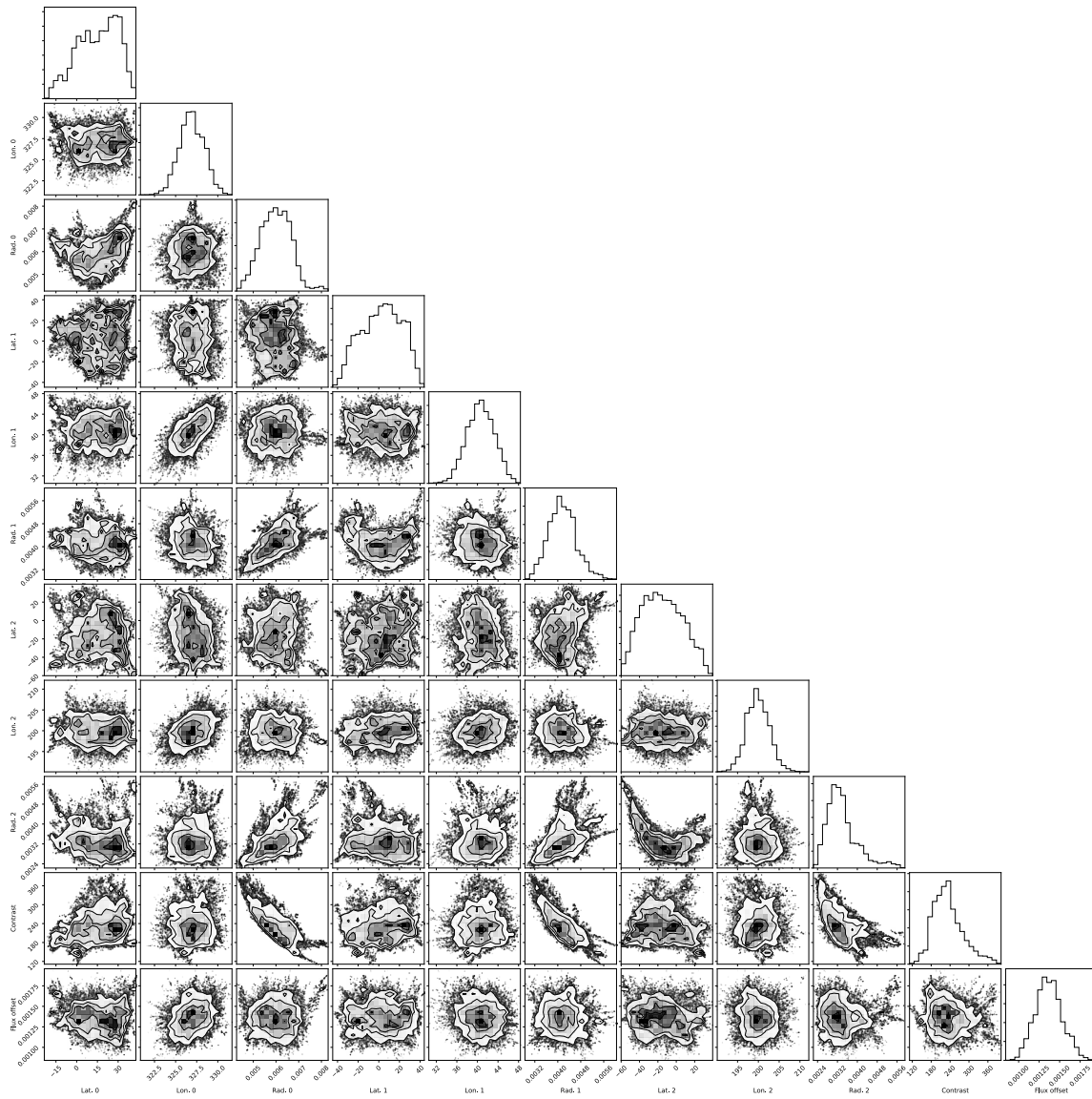


Figure 9.11: Posterior samples for the three, bright spot model.

Planet	$P_{\text{occult,max}}$
b	0.08
c	0.08
d	0.05
e	0.06
f	0.06
g	0.08
h	0.05

Table 9.2: Maximum probability of a spot occultation for each planet in the TRAPPIST-1 system, assuming infinitely long-lived spots.

of the posterior samples over all impact parameters,

$$P_{\text{occult}} \approx \frac{\int_{b_0}^{b_1} p_b dp}{2 \int p_b dp} \quad (9.8)$$

The spot latitude solutions are degenerate: the spots could be on either side of the stellar equator and produce the same rotational modulation, and the planet impact parameter is similarly degenerate in that the planets could be occulting the northern or southern stellar hemisphere. As a result, we compute each probability of occultation twice: once assuming the planets occult the northern stellar hemisphere and once assuming they occult the southern hemisphere, and report the maximum spot occultation probability in Table 9.2.

The K2 light curve shows evolution of the flux modulation on timescales of days, indicating that spots are not infinitely long-lived. Thus these conservative upper limits are likely much greater than the probability of a spot occultation for transient spots on TRAPPIST-1.

Chapter 10

SPOTTING STELLAR ACTIVITY CYCLES WITH GAIA

In the previous chapters of this Part (Chapters 5-7), we have explored the effects of stellar activity on photometric and spectroscopic observations. There is a third dimension, in addition to time and wavelength, that we can use to probe stellar activity – astrometry. Stars are *not* point sources, and as starspots rotate into and out of view, the astrometric centroid of a star will appear to shift slightly in response to the localized flux deficits. The astrometric precision required to measure this type of starspot-induced centroid shift is staggering, but may be within reach for the revolutionary ESA *Gaia* mission, as we will see in this chapter. For very active stars, it is possible that the astrometric centroid shifts due to stellar magnetic activity can be a dominant source of astrophysical noise in astrometric searches for planets orbiting bright, nearby stars, possibly limiting the ranges of orbital periods and planet sizes that can be detected with astrometry.

This chapter was first published in the *Astronomical Journal* (Morris et al., 2018a).

10.1 Introduction

The ESA *Gaia* mission will accurately measure the astrometric positions of many of the nearest stars in the Milky Way (Gaia Collaboration et al., 2016). With time-resolved astrometry from *Gaia*, it will be possible to detect the reflex motions of stars in binary or multi-star systems, and stars in systems with massive planets.

One source of noise that will inflate the observed scatter in astrometric measurements is stellar activity. Stars like the Sun have starspot covering fractions of order 0.03% in the optical. The distribution of dark spots on the stellar surface changes as the star rotates and as starspots evolve, so the center of light or centroid of a star will vary with time in the optical.

The effects of stellar surface inhomogeneities on Gaia astrometry has been considered as a source of noise in planet searches for main sequence stars (Catanzarite et al., 2008; Eriksson & Lindegren, 2007; Lanza et al., 2008), and in parallax measurements of red supergiants (Chiavassa et al., 2011).

We consider here the potential for detecting magnetic activity cycles from the apparent astrometric shifts of stars due to starspots. The solar activity cycle (as it would be observed in astrometric jitter) lasts about 11 years (see review by Hathaway, 2015), which is similar to the extended mission duration of Gaia. Many of the nearest Gaia astrometry targets are low mass main sequence stars, and those with observed activity cycles have periods from a few to ~ 10 years (Gomes da Silva et al., 2012; Robertson et al., 2013; Suárez Mascareño et al., 2016b).

We estimate the starspot-induced astrometric jitter produced by the starspots of stars with well-constrained spot asymmetries, the Sun, the active M4 dwarf GJ 1243, and the young G-star KIC 7174505 in Section 10.3. We compute the anticipated scale of the spot-induced astrometric jitter for nearby main sequence stars in the Gaia sample, and compare the jitter to Gaia’s anticipated astrometric precision in Section 10.3.4. We conclude with a brief review of the literature on the stellar activity of the most promising Gaia targets in Section 10.4.

10.2 Centroid estimating algorithm

We approximate the stellar centroid for a star with non-overlapping circular spots using either an analytic or numerical approximation. Here we briefly outline each technique, and validation between the two techniques. An implementation of these algorithms in Python is available online¹.

¹ <https://github.com/bmorris3/mrspoc>

10.2.1 Analytic centroid approximation

If all spots are smaller than $R_{\text{spot}}/R_{\star} = 0.1$ we apply the analytic approximation to compute the stellar centroids. We first integrate the total stellar flux of the unspotted, limb-darkened star,

$$F_{\star, \text{unspotted}} = \int_0^{R_{\star}} 2\pi r I(r) dr, \quad (10.1)$$

where $I(r)$ is a quadratic limb-darkening law and r is in units of angle, so that $2\pi r dr$ is solid angle. For all stars, we use the solar limb-darkening parameters.

We define cartesian sky-plane coordinates (x, y) , with the origin placed at the center of the star, $\hat{x}$ aligned with the stellar equator, and $\hat{y}$ aligned with the stellar rotation axis. We describe each starspot with an ellipse with centroid $\mathbf{r}_i = (x_i, y_i)$, and $r_i = |\mathbf{r}_i|$. We can compute the (negative) flux contribution from each spot by computing the approximate spot area and contrast. A circular spot will be foreshortened near the stellar limb. The foreshortened circular spot can be approximated with an ellipse with semi-major axis R_{spot} and semi-minor axis $R_{\text{spot}}\sqrt{1 - (r_i/R_{\star})^2}$.

Since these spots are small compared to the stellar radius ($R_{\text{spot}}/R_{\star} < 0.1$), we adopt one limb-darkened contrast for the entire spot, $c_{ld} = (1 - c)I(r)$, where c is the flux contrast in the spot relative to the photosphere flux. We discuss reasonable values of c in Section 10.2.4.

The integrated spot flux is

$$F_{\text{spot}, i} = -\pi R_{\text{spot}}^2 c_{ld} \sqrt{1 - (r_i/R_{\star})^2}, \quad (10.2)$$

and accounting for all N spots, the position of the stellar centroid (x_c, y_c) is

$$x_c = \left(\sum_{i=1}^N x_i F_{\text{spot}, i} \right) / F_{\star, \text{spotted}} \quad (10.3)$$

$$y_c = \left(\sum_{i=1}^N y_i F_{\text{spot}, i} \right) / F_{\star, \text{spotted}}, \quad (10.4)$$

where the spotted flux of the star is

$$F_{\star, \text{spotted}} = F_{\star, \text{unspotted}} + \sum_{i=1}^N F_{\text{spot}, i}. \quad (10.5)$$

This approximation is valid for spots that are small compared to the stellar radius, or small compared to the scale of limb-darkening variation across the stellar disk.

10.2.2 Numerical centroid approximation

For a spot configuration with large spots $R_{\text{spot}}/R_{\star} > 0.1$, we compute the stellar centroid with a simple numerical approximation. We create a square grid with 3000 pixels on a side, and calculate the flux within each pixel given the quadratic limb darkening law for the star, $I(r)$. We define the boundaries of foreshortened spots using the same geometric approximation as in the previous section, but this time we multiply all pixels within the spot by the spot contrast c .

This numerical method is more computationally expensive than the analytic method, but it does not assume one limb-darkened contrast for the entire spot, and thus it is a better approximation for large spots.

10.2.3 Validation

We confirm that the numerical and analytic approximations produce similar results by computing the stellar centroids for example spot configurations with both methods. The maximum fractional difference between centroids for spots of various sizes, and for numerical approximations with different numbers of pixels, in Figure 10.1. We find that the centroid agreement between methods is better than 6% for pixel grids with 3000 pixels on a side or more.

10.2.4 Starspot Contrasts

Since spot flux contrasts vary as a function of spectral type and filter transmittance, we find a relationship between stellar effective temperature and spot contrasts in temperature and flux. In Figure 10.2, we show the observed starspot temperature contrasts of 47 stars reported by Berdyugina (2005), and we fit a quadratic to the spot temperature contrasts as

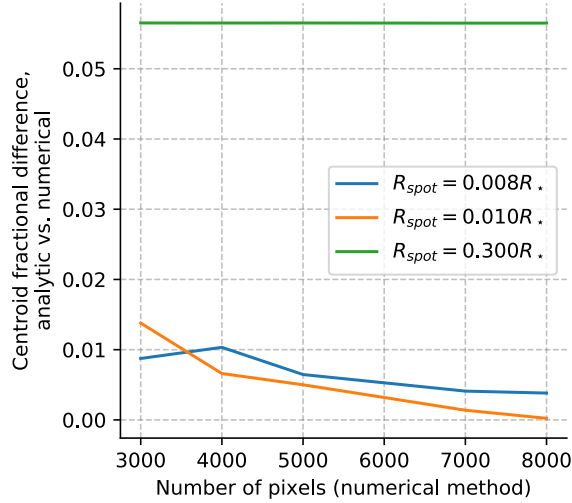


Figure 10.1: We validate the two centroid approximations against one another, finding that the stellar centroids agree to better than 6% for all spots considered in this work.

a function of the stellar photosphere effective temperature. We estimate the spot contrast in the Gaia G -band by integrating blackbody radiance curves with the temperatures of the photosphere and spot convolved, with the G filter transmittance.

The Sun’s spot contrast in the G band, weighting by the relative areas in the penumbrae and umbrae, is $c \sim 0.7$. The best-fit quadratic is consistent with $c = 0.7 \pm 0.1$ for stars with spectral types M2 to G2. Given that 73% of the stars considered in this paper are within that range of spectral types, we choose to use spot contrast $c = 0.7$ for all stars (more on the star sample in Section 10.3.4).

10.3 Simulating starspot-induced astrometric jitter

We compute stellar centroid jitter for the starspot distributions of the Sun, GJ 1243 and KIC 7174505. These stars represent different examples of magnetic activity — the Sun has many small, short-lived spots; GJ 1243 has a few large, long-lived spots; and KIC 7174505 may have extremely large spots. The differences in activity may arise from different dynamo

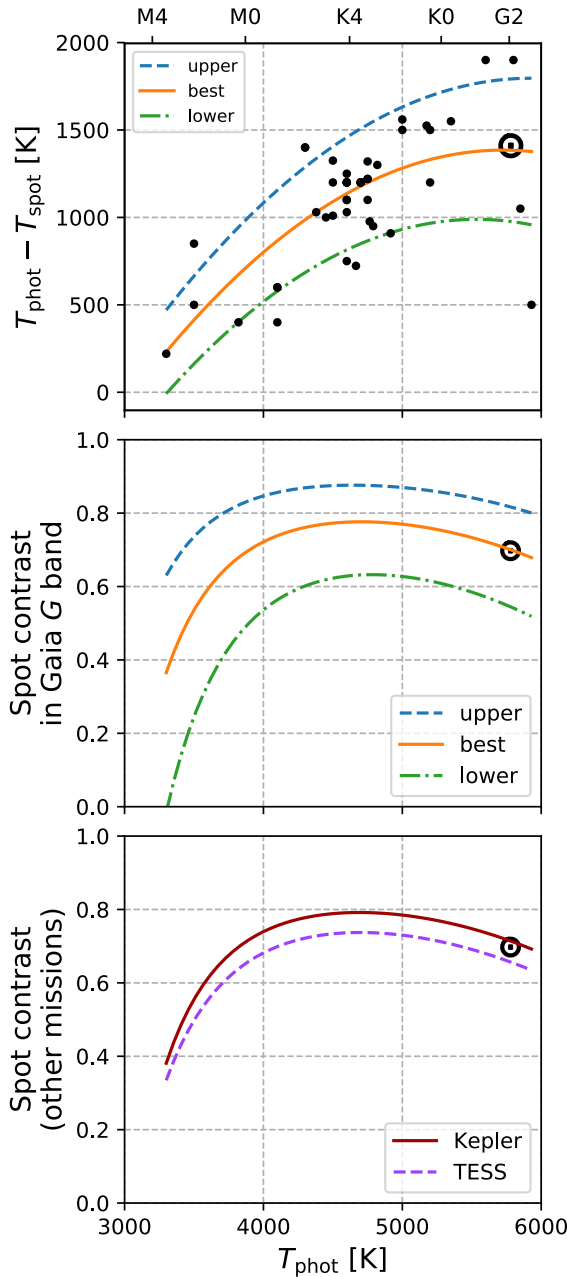


Figure 10.2: *Upper*: Measured temperature difference between the the mean stellar photosphere temperature T_{phot} and the starspot temperature T_{spot} , as a function of T_{phot} (black circles), compiled by Berdyugina (2005). The middle curve labeled “best” is a quadratic fit to the spot contrasts. The “min,” and “max” curves roughly approximate the lower and upper envelopes of the spot contrast observations. The Sun’s contrast is marked with the symbol $\odot$. *Middle*: Spot flux contrasts, approximated by integrating blackbody radiance curves with the temperatures of the photosphere and spot, convolved with the Gaia G bandpass. The area-weighted mean sunspot contrast is $c = 0.7$, marked with $\odot$. Stars from spectral types M2 to G2 are consistent with $c = 0.7 \pm 0.1$, so we adopt $c = 0.7$ for all stars considered in Section 10.3.4. *Lower*: Starspot flux contrasts, this time integrated over the Kepler (red curve) and TESS (purple dashed curve) bandpasses. Here we show only the contrast curves for the best-fit quadratic spot temperature relation labeled “best” in the uppermost panel. Spot contrasts observed with both the *Kepler* and TESS missions are within 5% of the Gaia mission spot contrast.

mechanisms for each star, since the Sun has a convective envelope, and GJ 1243 may be fully convective. The configuration of spots on KIC 7174505 and GJ 1243 can be significantly more asymmetric than sunspots, thus producing much larger astrometric signals. In general, the stellar inclination angles for a stars is not known, so we assume that best-case scenario the stars all have stellar inclination $i_s = 90^\circ$, with their rotation axes aligned with the sky plane.

A third star with a well-characterized spot distribution the K4V star HAT-P-11. We do not consider HAT-P-11 because its spectral type and activity is an intermediate case between the Sun and GJ 1243. It has a Sun-like distribution of spots, and spot coverage between that of the Sun and GJ 1243 (Davenport et al., 2015; Morris et al., 2017b,c).

10.3.1 The Sun

The Sun will always be the star with the longest-running record of starspot positions and sizes, so we begin by estimating the sunspot-induced astrometric jitter for a distant observer.

We collect sunspot positions and areas from the Mount Wilson Observatory (MWO) sunspot catalog of Howard et al. (1984), which spans seven activity cycles from 1917–1985. The sunspot umbral areas are reported in units of solar hemispheres A_{umb} , which are related to the total spot radii R_{spot} in units of solar radii $R_\odot$ by

$$\frac{R_{\text{spot}}}{R_\odot} = \sqrt{2(A_{\text{umb}} + A_{\text{pen}})}, \quad (10.6)$$

where A_{pen} is the area in penumbrae. Following Solanki (2003), we adopt the the penumbral-to-umbral area ratio to be approximately $A_{\text{pen}}/A_{\text{umb}} \sim 4$, so $A_{\text{umb}} + A_{\text{pen}} = 5A_{\text{umb}}$, and

$$R_{\text{spot}} \approx \sqrt{10A_{\text{umb}}} R_\odot. \quad (10.7)$$

Also following Solanki (2003), we chose the mean flux emitted by a sunspot to be 70% of the flux of the mean photosphere.

We define the centroid of the Sun as the flux-weighted mean astrometric position of the Sun in the sky plane for an observer with perfect seeing. We compute the solar centroid

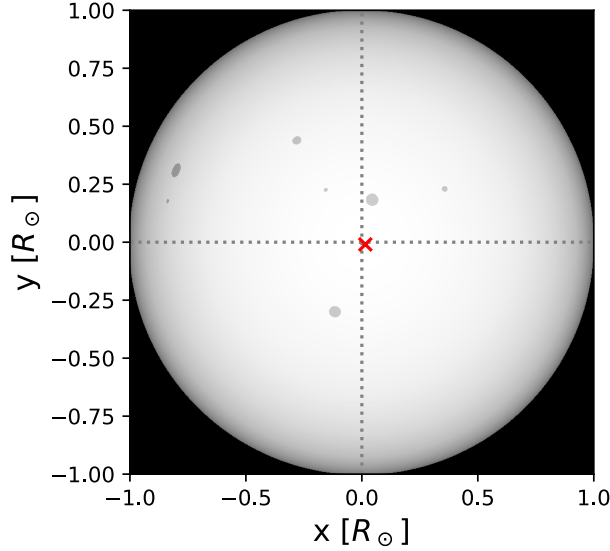


Figure 10.3: Example sunspot record of the Sun on 1959 May 10 UTC. The gray circles represent sunspots, the white disk represents the solar photosphere. The red “x” represents the solar centroid in this image, exaggerated by a factor of 100 to make its offset from the origin visible on the diagram.

by integrating over the Earth-facing solar surface, using all spots reported by Howard et al. (1984).

A typical entry in the MWO catalog records about three spots in a day, reaching up to 14 spots on the most active day recorded. The median sunspot radius is $R_{\text{spot}} \approx 0.01R_{\odot}$. Recorded spot longitudes span the range $[-60^{\circ}, 51^{\circ}]$ and latitudes span $[-44^{\circ}, 51^{\circ}]$. We plot an example sunspot record from 1959 May 10 UTC in Figure 10.3.

The simple sunspot model does not account for faculae, which are bright components of active regions on the Sun. We ignore faculae in our models of the rotationally modulated stellar centroid calculations for two reasons. First, sunspots dominate the Sun’s variability in the optical (though the total solar irradiance integrated over all wavelengths is actually greater at active maximum than minimum) (Shapiro et al., 2016). In addition, the impact

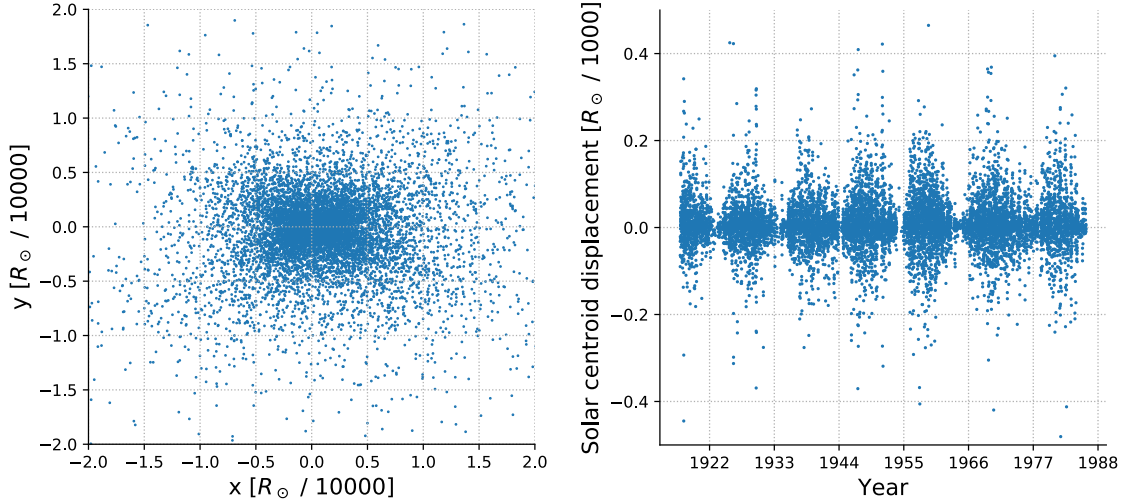


Figure 10.4: *Upper*: Position of the solar centroid from 1917–1985, accounting only for astrometric shift due to sunspots. The y coordinate is aligned with the solar rotation axis, and the spread in centroids is broader about the equatorial coordinate. *Lower*: The absolute centroid displacement from the true solar centroid, $r = \sqrt{x^2 + y^2}$, throughout seven activity cycles. Near activity maximum, the centroid displacement is greater than at minimum.

of faculae on solar brightness modulations would be greatest for an observer viewing the Sun pole-on (Radick et al., 1998; Shapiro et al., 2016), but we consider equator-on configurations in this work.

The distribution of centroids of the Sun at each date in the Howard et al. (1984) catalog is shown in Figure 10.4. The median absolute deviation of the centroids in the x and y directions are 24 and $15\mu R_\odot$, respectively.

For comparison, the reflex motion of the Sun about the barycenter due to Jupiter’s orbit is roughly the size of the solar radius. The Sun’s reflex motion due to the Earth is about $600\mu R_\odot$, which is still larger than the scale of sunspot-induced astrometric jitter. Once Keplerian orbits are removed from the astrometric measurements of planet-hosting stars, the residual scatter may contain the signals stellar activity discussed here.

10.3.2 GJ 1243

The distribution of sunspots on the solar photosphere is dictated by the physics of the solar dynamo (see reviews by Charbonneau, 2014; Hathaway, 2015). Mid- to late-M dwarfs are expected to have fully-convective envelopes, and thus their dynamo activity must be driven by different physical mechanisms than the Sun’s (Morin et al., 2010). The distribution of small starspots on fully-convective stars (as a function of age) is not yet known, in general.

One low mass star with a constrained spot distribution is the M4 dwarf GJ 1243. Davenport et al. (2015) fit the *Kepler* photometry of GJ 1243 with a spot model, and found that the rotational modulation is consistent with two starspots rotating differentially, with lifetimes of order $\sim$ years. The authors estimated that the spots could be as large as $R_{\text{spot}} \sim 0.3R_{\star}$ — significantly larger than the largest sunspots relative to the solar radius. The spot latitudes are degenerate with the stellar inclination, so the precise spot latitudes are unknown. The best-fit spot models of Davenport et al. (2015) prefer one spot near the pole, and one spot at lower latitudes. We note that small spots analogous in scale to sunspots may also be present on GJ 1243, but the rotational modulation was dominated by the two largest spots, so we study the astrometric jitter caused by those dominant spots (Davenport et al., 2015).

We adopt the low-latitude starspot of GJ 1243 as another prototype for producing astrometric jitter. When compared with the relatively small sunspots, the large, low-latitude spot observed on GJ 1243 can drive significantly more centroid jitter. To construct a best-case scenario for observing spot-induced jitter, we place a spot with radius $R_{\text{spot}} = 0.3R_{\star}$ on the stellar equator, and view it with stellar inclination $i_s = 90^\circ$.

We compute the centroid of GJ 1243 throughout a full rotation following the procedure in Section 10.3.1. The maximum displacement of the centroid of GJ 1243 is $0.01R_{\star}$ — roughly a factor of 10 greater than the maximum observed solar astrometric jitter.

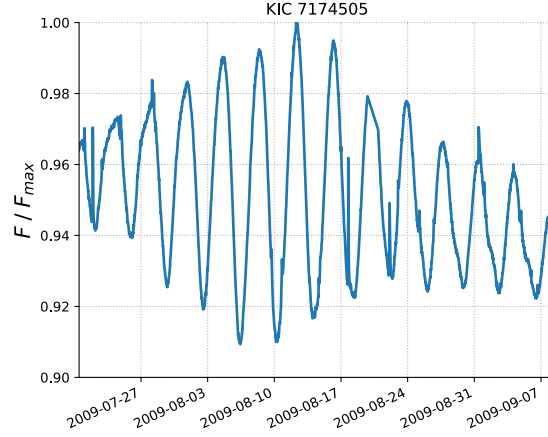


Figure 10.5: A portion of the *Kepler* light curve of superflare star KIC 7174505, which shows large flux modulation with the rotational period of the star, $P_{\text{rot}} = 3.832 \pm 0.005$ days (McQuillan et al., 2014).

10.3.3 KIC 7174505

Young G stars in the *Kepler* field which produce superflares have been the subjects of extensive follow-up observations in the literature (see e.g.: Karoff et al., 2016; Maehara et al., 2017, 2012; Notsu et al., 2015a,b, 2013). One star with large rotational flux modulation is the superflare star KIC 7174505, with $T_{\text{eff}} \approx 5411$ K and rotation period $P_{\text{rot}} = 3.832 \pm 0.005$ days (Mathur et al., 2017; McQuillan et al., 2014). *Kepler* observed 29 large flare events on this star, with energies ranging from 7×10^{34} to 2×10^{35} ergs (Shibayama et al., 2013). A portion of the *Kepler* light curve of KIC 7174505 is shown in Figure 10.5.

Shibayama et al. (2013) estimate the spot covering fraction on KIC 7174505 from the rotational modulation of the *Kepler* light curve. Their estimate of the minimum spotted area is roughly 20% of the stellar hemisphere, which could be concentrated into one or many spots. If we calculate the radius of a single, circular spot with an area equivalent to 20% of the stellar hemisphere, we have $R_{\text{spot}}/R_{\star} = 0.63$. We use this extremely large spot as a limiting case in our calculations for spot-induced astrometric jitter.

We compute the centroid of KIC 7174505 throughout a full rotation following the procedure in Section 10.3.1. The maximum displacement of the centroid of KIC 7174505 is $0.05R_*$ — a factor of five greater than the maximum observed astrometric jitter of GJ 1243.

10.3.4 *Expected starspot-induced jitter*

We calculate the expected starspot-induced jitter for bright, cool, main sequence stars that will be observed by Gaia. To select stars meeting these criteria, we choose stars with Gaia magnitude $G < 7$ from the Tycho-Gaia Astrometric Solution (TGAS) catalog (Michalik et al., 2015). TGAS combines early Gaia astrometry with measurements from the Tycho-2 astrometric mission to solve for parallaxes of millions of nearby stars. We use Tycho photometry in the VT and BT bands, and the combined Tycho-2/Gaia parallaxes to construct a color-magnitude diagram of the bright TGAS stars. We narrow our sample to stars on the main sequence with colors $0.6 < B - V < 2$. These 8,896 stars are highlighted in red on the color-magnitude diagram in Figure 10.6. It is likely that there are binaries in this sample of stars. We include all stars in our analysis until reporting the best-case targets in Table 10.1, which have been filtered to remove known binaries.

The TGAS sample does not include the brightest stars in the sky (Michalik et al., 2015). Ongoing efforts throughout the beginning of the Gaia mission have made progress towards measuring astrometry of naked-eye stars, and it is possible that ultimately there will be no bright limit for Gaia astrometry (Martin-Fleitas et al., 2014; Sahlmann et al., 2016). Since the final mission bright limit is not yet established, we choose to consider only the stars with Gaia astrometry already published in TGAS, and ignore the brighter stars which may be accessible to Gaia astrometry in the future.

We calculate Gaia’s expected end-of-mission astrometric precision, σ_{Gaia} , for the stars in the bright sample. Perryman et al. (2014) outline an algorithm for calculating the expected Gaia astrometric precision for any star, which we reproduce here. The astrometric signal-

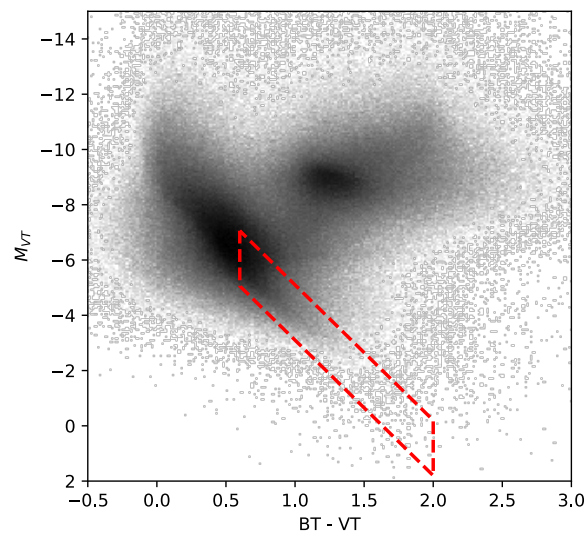


Figure 10.6: Color-magnitude diagram for stars brighter than $G < 12$ in the TGAS catalog, where the shading is the logarithm of density of stars in each pixel. BT and VT are the Tycho-2 bandpasses, similar to Johnson-Cousins B and V . We select only stars within the red polygon, which are likely main sequence stars of approximately solar spectral type or later.

to-noise achieved in a single Gaia visit σ_{fov} can be computed with:

$$\sigma_{\text{fov}}^2 = \sigma_{\eta}^2/9 + \sigma_{\text{att}}^2 + \sigma_{\text{cal}}^2 \quad (10.8)$$

where the contributions from attitude errors σ_{att} and calibration errors σ_{cal} are both approximately $\sigma_{\text{att}} \approx \sigma_{\text{cal}} = 20 \mu\text{arcseconds}$, and the centroiding error σ_{η} for each of Gaia's nine CCDs is

$$\sigma_{\eta}^2 = 53000z + 310z^2. \quad (10.9)$$

z is a function of the inverse number of photons in the image, which is a function of a star's G magnitude,

$$z = 10^{0.4(\max[G, 12] - 15)}. \quad (10.10)$$

The number of expected visits at a given star over the nominal five-year mission N'_{fov} is a function of the galactic latitude b of the star (see Perryman et al. 2014 Table 1 for N'_{fov} estimates at each b). The maximum number of photons received from stars brighter than $G < 12$ is capped by CCD gating, which prevents saturation (Perryman et al., 2014). One consequence of this observing strategy is that the astrometric precision is roughly uniform for all targets brighter than $G < 12$.

Thus, we can approximate the Gaia end-of-mission astrometric precision for each bright star in the sample with

$$\sigma_{\text{Gaia}}(G, b) = \sigma_{\text{fov}}(G) / \sqrt{N'_{\text{fov}}(b)}. \quad (10.11)$$

In other words, the distribution of the Gaia-measured centroids of a single, inactive star without companions will have RMS width σ_{Gaia} . Barring unanticipated systematics, scatter measured in the centroid of a star exceeding σ_{Gaia} may be interpreted as the signature of stellar multiplicity, massive planets, or starspots.

10.3.5 Sun-like distribution of starspots

We calculate the spot-induced centroid jitter for the bright TGAS main sequence stars, assuming a Sun-like distribution of spots. We convert the centroid jitter observed on the

Sun, in units of $R_{\odot}$, to the expected RMS angular astrometric jitter σ_{jitter} by observing the solar centroid offsets at the distance of each star in the TGAS sample. Then we normalize the observed jitter by the expected Gaia astrometric uncertainty.

The expected astrometric jitter produced by a Sun-like distribution of starspots on the stars in the bright TGAS main sequence sample is shown in Figure 10.7. The spot-induced jitter σ_{jitter} is normalized by the cumulative, end-of-mission astrometric uncertainty of Gaia, after considering the single-measurement astrometric precision on that star, and the total number of measurements during the nominal five-year mission. Even for the brightest star in the sample, the K0V star σ Draconis ($G = 4.71$), the spot-induced jitter is only 1% of the expected astrometric uncertainty. Measurements of astrometric starspot jitter from Sun-like spot distributions are thus beyond the reach of the nominal five-year Gaia mission.

10.3.6 GJ 1243-like distribution of starspots

We calculate the spot-induced centroid jitter for the bright TGAS main sequence stars, assuming a GJ 1243-like distribution of spots. We convert the centroid jitter observed on GJ 1243, in units of $R_{\star}$, to the expected RMS angular astrometric jitter σ_{jitter} by observing the stellar centroid offsets at the distance of each star in the TGAS sample. We estimate stellar radii for each star using the color–radius relations of Boyajian et al. (2012), and for a small subset of the stars, we combine the interferometric stellar angular diameters from Boyajian et al. (2012) with TGAS parallaxes (Michalik et al., 2015). Then we normalize the observed jitter by the expected Gaia astrometric uncertainty.

The expected astrometric jitter produced by a GJ 1243-like distribution of starspots on the stars in the bright TGAS main sequence sample is shown in Figure 10.7. The starspot jitter is comparable or less than the predicted astrometric uncertainty for all stars considered here. At the end of the nominal five-year mission, Gaia astrometry could not detect GJ 1243-like activity on these stars.

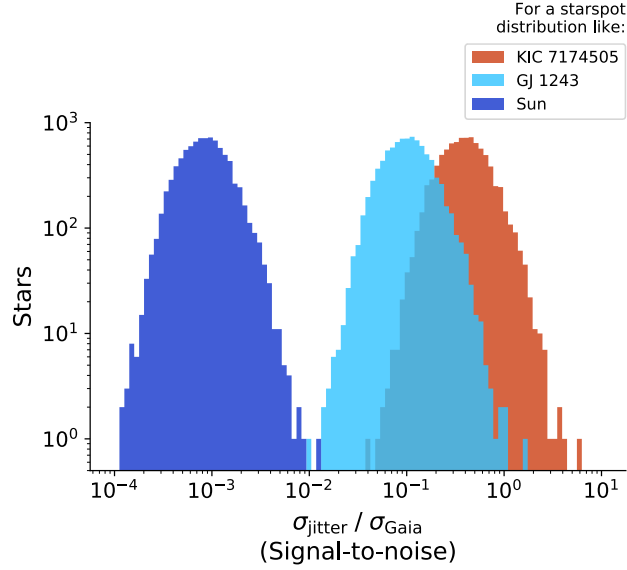


Figure 10.7: Maximum expected starspot-induced jitter for 8,896 nearby Gaia stars in TGAS, normalized by the estimated astrometric uncertainty for a nominal 5 year mission, assuming starspot distributions like the Sun, GJ 1243, and KIC 7174505. These maximum jitter estimates only consider stellar inclination $i_s = 90^\circ$. Details for the eight best non-binary stars are enumerated in Table 10.1.

10.3.7 KIC 7174505-like distribution of starspots

We calculate the spot-induced centroid jitter for the bright TGAS main sequence stars with a distribution of starspots like KIC 7174505 following the procedure outlined in Section 10.3.6. The expected astrometric jitter is shown in Figure 10.7. The starspot jitter is larger than the predicted astrometric uncertainty by a factor of three for six stars in the sample, and the jitter exceeds the noise by a factor of six for one non-binary star: AX Mic. We discuss these stars in more detail in Section 10.4. Gaia astrometry can detect the most extreme centroid offsets even in a fraction of the nominal five-year mission.

10.3.8 Comparison with other works

Eriksson & Lindegren (2007) and Catanzarite et al. (2008) devise starspot jitter models based on observations of the Sun and other stars. Both groups report a maximum centroid jitter of about $\sim 2 \mu\text{AU}$ for solar-like activity, which is a bit smaller than our maximum estimate of the solar centroid offset based on the observations of Howard et al. (1984) of $\sim 3 \mu\text{AU}$. Eriksson & Lindegren (2007) also estimate the centroid offsets for M2–M9V type stars in the range $0.4 - 10 \mu\text{AU}$, which is smaller than our expectation for the jitter from a GJ1243-like spot distribution, which contributes $\sigma_{\text{jitter}} \approx 35 \mu\text{AU}$. We are unable to find analogous estimates in the literature of starspot jitter from superflare stars like KIC 7174505, which can produce apparent jitter of $100 \mu\text{AU}$.

10.3.9 Activity cycles

The number of sunspots and their latitude distribution changes throughout the solar activity cycle. Near activity minimum, there are sometimes no spots on the Sun at all, and near maximum there can be more than ten. A distant observer could measure centroid offsets due to starspots near activity maximum, but the jitter would diminish at activity minimum – Figure 10.4 shows the varying scatter in the solar centroid throughout seven solar activity cycles based on real solar observations.

We showed in Section 10.3 that sunspots would be undetectable by astrometric jitter, jitter from GJ 1243-like spots may be detectable, and jitter from KIC 7174505 would be detected handily for the nearest stars. Is the astrometric signal-to-noise and sampling in time sufficient to measure changes in astrometric jitter throughout stellar activity cycles?

Here we consider the best-case scenario for detecting activity cycles on stars with spots like KIC 7174505. We seek to determine the difference in astrometric jitter near activity minimum, when $\sigma_{\text{jitter}} \rightarrow 0$, and near activity maximum, when we assume the maximum jitter is achieved by the starspot distribution observed on KIC 7174505.

Suppose KIC 7174505-like stars have an activity cycle period $P_{\text{cyc}} \sim 10$ years, and spend

five years near maximum and five years near minimum. If the Gaia extended mission observed that star over an extended mission lasting 10 years, it will measure the stellar centroid N'_{fov} times near activity minimum, when the astrometric centroid scatter will be entirely contributed by random and systematic errors. We simulate these observations by drawing N'_{fov} samples from the distribution $\mathcal{N}(0, \sigma_{\text{fov}}^2)$. Then we observe each star another N'_{fov} times near activity maximum during a five-year extended mission, when the astrometric scatter will be the quadrature sum of the random errors σ_{fov} and the spot-induced jitter σ_{jitter} . We simulate these observations by drawing N'_{fov} samples from the distribution $\mathcal{N}(0, \sigma_{\text{fov}}^2 + \sigma_{\text{jitter}}^2)$. We compute the confidence of the cycle detection measurement with the two-sample Anderson-Darling and Komolgorov-Smirnov (KS) tests to measure the difference in centroid distributions observed at activity maximum and minimum.

In Table 10.1 we list the statistical significance of the difference between the distribution of centroids near active maximum and minimum, for the bright TGAS sample in an extended 10 year Gaia mission. The stars considered show insignificant detections of an activity cycle in this highly-optimized scenario for detecting activity cycles through Gaia astrometry, where we assumed a highly asymmetric spot distribution and an ideal stellar inclination of $i_s = 90^\circ$. We comment on the properties of the star with the best detection of any activity, AX Mic, in the next section.

The activity cycle detection confidences in Table 10.1 assume that we can unambiguously split the astrometric measurements into maximum and minimum activity subsets. In practice, we will not know the phase of each star's activity cycle *a priori*. However, Gaia radial velocity spectra of the calcium infrared triplet may allow us to independently identify phases in activity cycles. The calcium infrared triplet is a calibrated indicator of chromospheric activity (see e.g.: Boro Saikia et al., 2016; Cauzzi et al., 2008; Cenarro et al., 2001; Chmielewski, 2000; Martin et al., 2017; Robertson et al., 2016; Žerjal et al., 2013). True cycles in astrometric jitter should be accompanied by increased emission in the infrared triplet (Andretta et al., 2005; Busà et al., 2007). A possible third independent measurement of activity cycles from Gaia is the time-series photometry it will collect, which may yield

long-baseline photometry similar to the *Kepler* full-frame images, which Montet et al. (2017) used to search for activity cycles in *Kepler* stars.

10.3.10 Sensitivity to spot coverage

It is common to use stellar variability as an estimate of the spot coverage of stars; this is adequate for stars that are affected by a single spot, or two anti-podal spots since only one spot is present on the visible disk at a time. Unfortunately, more than two spots that are distributed in longitude cause a weaker amplitude variability: as one spot rotates off of the visible disk of the star, another rotates onto it, causing a reduction in the overall amplitude of variability. A similar effect has been pointed out in the context of planetary mapping: the odd spherical harmonics induce no change in brightness (Cowan & Agol, 2008).

In particular, a distribution of three spots with 120° separation can lead to a very small amplitude of variability. However, the astrometric signal of three spots can still be strong despite weak flux variability. Figure 10.8 shows the relative amplitude of variability of the total flux for one, two and three equatorial spots, distributed evenly in longitude, and viewed at $i_s = 90^\circ$. In the one- and two- spot cases, the relative amplitude of variability is similar for photometry and astrometry. However, in the three-spot case, the photometric variability is suppressed by a factor of 6.5 relative to the astrometric variability.

10.4 Best targets for activity detection with Gaia

We evaluate the astrometric signal-to-noise expected from the nominal five year Gaia mission for the brightest, nearest main sequence stars in the TGAS sample, and list the results for the eight best candidates in Table 10.1. The last column of the table denotes the expected scale of starspot jitter normalized by Gaia’s astrometric precision $\sigma_{\text{jitter}}/\sigma_{\text{Gaia}}$, in the extreme case of a KIC 7174505-like starspot configuration, observed with stellar inclination $i_s = 90^\circ$. This should be treated as an upper-limit on the astrometric signal that starspots could produce on main sequence stars. In the sections that follow, we examine measurements of each star’s activity in the literature.

Star	HIP	Spectral Type	$R_\star$ [$R_\odot$]	G [mag]	Distance [pc]	N'_{fov}	σ_{jitter} [μas]	$\sigma_{\text{jitter}}/\sigma_{\text{Gaia}}$ (S/N)	Best-case cycle sig.:	
									KS	Anderson
AX Mic	105090	M1V	0.589 ^a	5.881	3.98	107.4	20.0	6.1	0.45	0.37
σ Dra	96100	K0V	0.789 ^a	4.711	5.76	58.5	18.5	4.1	0.5	0.43
GX And	1475	M2V	0.459 ^b	7.096	3.56	55.6	17.4	3.8	0.48	0.43
HD 79211	120005	M0V	0.572 ^b	6.948	6.29	107.4	12.3	3.7	0.51	0.45
LHS 3531	99701	M0V	0.564 ^a	7.134	6.16	69.1	12.4	3.0	0.51	0.45
HD 222237	116745	K3+V	0.772 ^a	6.669	11.39	107.4	9.2	2.8	0.51	0.47
HD 36395	25878	M1.5Ve	0.531 ^b	6.986	5.65	55.6	12.7	2.8	0.53	0.48
Gl 625	80459	M1.5V	0.431 ^a	8.995	6.49	107.4	9.0	2.7	0.5	0.46

Table 10.1: Expected signal-to-noise for the astrometric jitter due to KIC 7174505-like starspots for the best non-binary targets. The columns are: the Hipparcos number, spectral type, Gaia G band magnitude, distance computed from the TGAS parallax, anticipated number of Gaia visits to that particular star N'_{fov} , astrometric jitter from KIC 7174505-like starspots σ_{jitter} , the ratio of the starspot-induced astrometric jitter to the expected astrometric precision over five years of Gaia observations $\sigma_{\text{jitter}}/\sigma_{\text{Gaia}}$. The astrometric precision the targets above (and for Gaia targets brighter than $G < 12$) is constant, $\sigma_{\text{fov}} = 34.2 \mu\text{arcseconds}$. The last two columns list the expected statistical significance of the astrometric detection of stellar activity cycles for each star over a 10 year extended mission. Radii marked ^a are estimates from color-radius relation of Boyajian et al. (2012); radii marked ^b are computed from interferometry by Boyajian et al. (2012), combined with parallaxes from TGAS (Michalik et al., 2015).

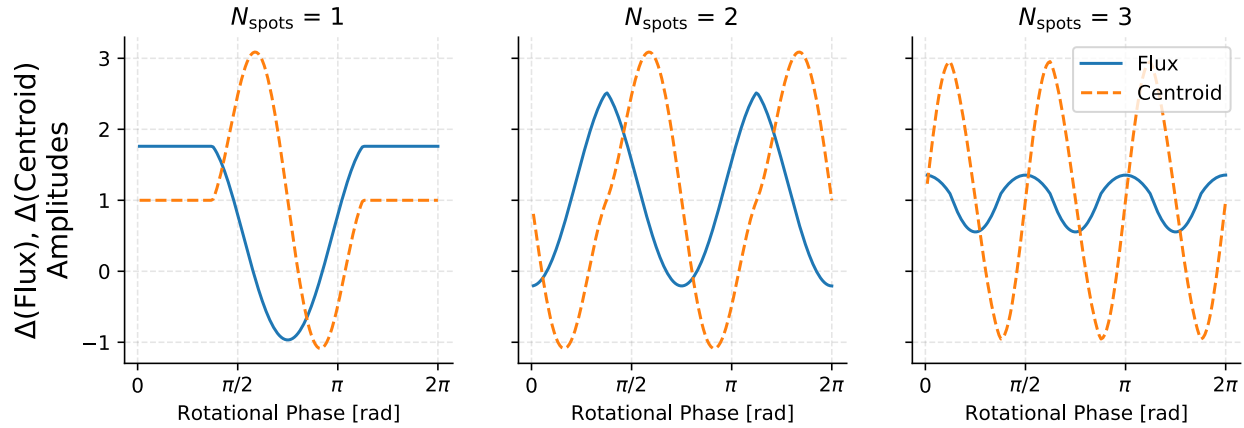


Figure 10.8: Relative amplitude of variability for one (left), two (middle) and three (right) spots of equal radii, in flux (blue) and astrometric angle (orange dashed).

10.4.1 *AX Mic (HD 202560, Gl 825)*

AX Microscopii is a single M1V flare star, with a TGAS distance of 3.9 pc (Byrne, 1981; Young et al., 1987). Byrne & Doyle (1989) measured the X-ray flux of AX Mic, and found that its transition region emission is similar to the Sun’s, despite being significantly smaller than the Sun. The authors suggest that AX Mic’s strong X-ray emission per unit surface area could be achieved with a few active regions on the stellar surface with a filling factor of 0.02% — similar to the typical solar spot filling factor. Isaacson & Fischer (2010) measured small variations in the chromospheric emission of AX Mic within the range $1.223 < S < 1.386$ with Keck/HIRES.

10.4.2 *σ Draconis (HD 185144)*

σ Draconis is a K0V star which was extensively monitored by the Lick-Carnegie Exoplanet Survey Team (LCES) HIRES/Keck Precision Radial Velocity Exoplanet Survey (Butler et al., 2017). The 784 spectra of σ Dra reveal an apparent magnetic activity cycle with period $P_{\text{cyc}} \approx 6$ years.

10.4.3 *GX And (HD 1326, Gl 15 A)*

GX Andromedae is a M2V flare star at a TGAS distance of 3.6 pc, which hosts at least one exoplanet, usually referred to as Gl 15 A b. The mean chromospheric emission from GX And is $\langle S \rangle = 0.524$, and S varies on two timescales. The shorter timescale is likely the stellar rotation period at $P_{\text{rot}} = 44$ d, and the authors suggest that the longer periodicity is a magnetic activity cycle, with period $P_{\text{cyc}} = 9 \pm 2.5$ yr.

10.4.4 *HD 79211 (Gl 338 B)*

HD 79211 is a M0Ve flare star. Pace (2013) report significantly variable chromospheric emission on the range $1.55 < S < 2.02$, which is in good agreement with the range observed by Isaacson & Fischer (2010), from $1.556 < S < 1.961$. If the variations in chromospheric emission are driven by rotational modulation from active regions, there may be spot-induced jitter to observe in the Gaia astrometry.

10.4.5 *HD 36395 (Gl 205)*

HD 36395 is a weakly active M1V star. Hébrard et al. (2016) collected Zeeman-Doppler imaging of HD 36395, and measured the rotation period $P_{\text{rot}} = 33.63 \pm 0.37$ d. The authors found that the star’s large-scale magnetic field is mostly poloidal, and the radial velocity periodogram showed signal at multiple periods, separated by about 10 d. They suggest that the multiple periods could arise from dark spots rotating differentially – one near the pole and one nearer to the equator, in a configuration reminiscent of GJ 1243.

10.4.6 *Gl 625 (G 202-48)*

Gl 625 is an M2V star with one known planet — a super-Earth which orbits at the inner edge of the stellar habitable zone (Suárez Mascareño et al., 2017). There are several signals in the periodogram of the S -index of Gl 625, which may be the signature of an activity cycle with period $P_{\text{cyc}} = 3.4$ yr.

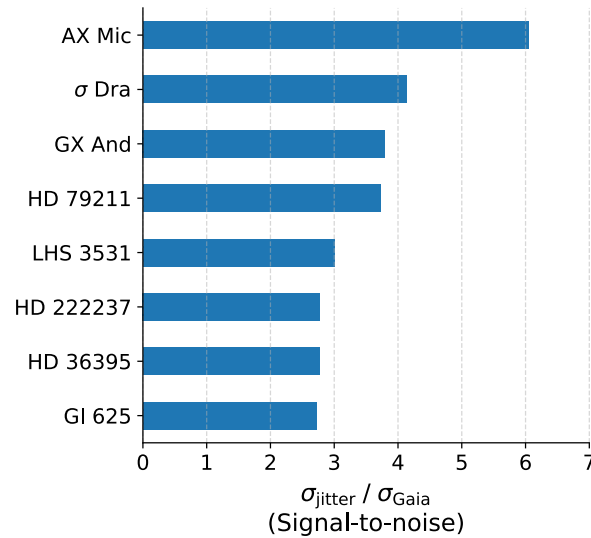


Figure 10.9: The ratio of the starspot-induced astrometric jitter to the expected astrometric precision over five years of Gaia observations $\sigma_{\text{jitter}}/\sigma_{\text{Gaia}}$ for the targets in Table 10.1.

10.5 Conclusion and Discussion

The ESA Gaia mission will measure astrometry of bright nearby stars with unprecedented precision. We show that Gaia’s astrometric precision will be sufficient to measure the astrometric shifts in the centroids of stars due to dark starspots on some of the nearest low-mass stars, which were included in the TGAS sample. The best candidate for the detection of astrometric jitter induced by starspots is AX Mic, an active M1V flare star. In the most optimistic scenario — where each star hosts large KIC 7174505-like spots which vary on a 10 year activity cycle — the variation in astrometric jitter throughout the stellar activity cycles is not detectable with Gaia astrometry alone. The top three targets for astrometric detections of activity (included in the TGAS sample) are: AX Mic, σ Dra, and GX And. Upcoming efforts to measure astrometry of the brightest stars with Gaia may expand the sample of stars with detectable activity cycles (Martin-Fleitas et al., 2014; Sahlmann et al., 2016).

Other possible applications of astrometric spot variability detection may include: 1). estimating the total spot coverage since astrometry is relatively more sensitive to longitudinally-distributed spots compared total flux (which can affect transit transmission spectra for stars that host planets); 2). deriving the sky-projected angle of inclination of stars, which may help to constrain alignment of spin axes of stars; 3). constraining the 3-D inclination of stars; 4). constraining the North-South asymmetry of spot distributions. We leave these ideas for future investigation.

Part III

THE EFFECTS OF STELLAR ACTIVITY ON PLANET CHARACTERIZATION

Lo, the darting bowling orb!

Lo, the brother orbs around, all the clustering suns and planets,

All the dazzling days, all the mystic nights with dreams,

Pioneers! O pioneers!

— Walt Whitman

In Part II we discussed observations of stellar magnetic activity on a variety of stars. These investigations were crucial for setting the stage for studying the effects of stellar magnetic activity on exoplanet characterization, a topic of ever-increasing importance in the age of the James Webb Space Telescope and thirty-meter-class telescopes, which will inevitably make advances in stellar astrophysics on their way to measuring properties of exoplanets.

In this Part, we explore the effects of stellar activity on characterization of exoplanets. In Chapter 11 we introduce the “self-contamination” transit light curve parameterization that can account for bright or dark starspots which contaminate transit observations, and apply the technique to observations of ten transiting exoplanets. In Chapter 12 we apply the self-contamination technique to recent *Spitzer* photometry of the TRAPPIST-1 planets to look for evidence of starspot contamination. Finally in Chapter 13, we bring together our expertise on stellar activity and transiting exoplanets in order to generate simulated observations of transiting exoplanets which orbit active stars for observations with JWST/NIRSpec.

Chapter 11

ROBUST TRANSITING EXOPLANET RADII IN THE PRESENCE OF STARSPOTS FROM INGRESS AND EGRESS DURATIONS

In Chapter 5 we used the transiting exoplanet HAT-P-11 to characterize the starspots that it occulted. In that chapter, we had to take extra care to measure the photometric transit depth from the *Kepler* photometry, because spot occultations occurred frequently, contaminating most transits towards shallower depths. In this chapter, we address this problem head-on: suppose you had a star with a dense band of starspots or a bright ring beneath the transit chord of the exoplanet? Such a surface inhomogeneity might be incorrectly interpreted as a smaller or larger planet. We find that the ingress and egress durations of transiting exoplanets provide an independent check on the radius of the exoplanet, which is not contaminated by starspots in the transit chord.

This chapter was first published in the *Astronomical Journal* (Morris et al., 2018e).

11.1 Introduction

Precise and accurate radii of exoplanets are critical to understanding their habitability. Radii are often used as a proxy for bulk composition when masses aren't available, informed by population studies which suggest that planets smaller than $R \lesssim 1.5R_{\oplus}$ are more likely rocky than gaseous (Fulton et al., 2017; Rogers, 2015; Weiss & Marcy, 2014). Since bulk densities are sensitive to the radius to the third power, accurate radii are required in order to infer accurate bulk densities.

The radii of transiting exoplanets are typically constrained by the transit depth, which is interpreted as the ratio of the cross-sectional areas of the planet and star $\Delta\mathcal{F}/\mathcal{F} = (R_p/R_{\star})^2$

(ignoring limb-darkening). The transit depth accuracy as a measure of the planet’s radius, however, is sensitive to stellar surface inhomogeneities. When planets pass over dark star spots, for example, the transit light curve is biased towards shallower transit depths during the transit (see e.g. Csizmadia et al., 2013; Oshagh et al., 2013). As we discover more planetary systems of late type stars like TRAPPIST-1 (Gillon et al., 2016, 2017; Luger et al., 2017b), the time- and wavelength-dependent variability of these active stars and non-uniformity is likely to limit the accuracy and precision of our measurements of the planet radii, especially as a function of wavelength (Morris et al., 2018b; Rackham et al., 2018; Roettenbacher & Kane, 2017; Zhang et al., 2018).

Particularly insidious are nearly axisymmetric stellar inhomogeneities and/or inhomogeneities which are comprised of odd harmonics. These do not lead to variability in the total flux of the star, and do not necessarily cause spot-crossing features in the transit light curve; yet they will still affect the depth of transit, and hence the inferred planet-star radius ratio and transmission spectrum. Consequently, even without indications of star-spot activity in the light curve of a star, spots (or other inhomogeneities) can still affect the depths of transits; this phenomenon is referred to as the “transit light source effect” in the recent work by Rackham et al. (2018). These forms of time-steady “activity” might be due to a multitude of star spots (such as along a particularly active latitude), due to gravity darkening, or due to a strong global magnetic field. The message of this paper is that if one measures the duration of ingress as compared to the total transit duration, this time-dependent quantity will be less affected by the presence of spots on the rest of the photosphere, and thus may give a more precise, albeit less accurate, measurement of the planet-star radius ratio compared with measuring the radius ratio from the depth of transit. However, in most cases it does require an independent constraint upon the impact parameter of the transit, as well as a careful handling of limb-darkening.

In Section 11.2 we reparameterize the transit light curve formalism of Mandel & Agol (2002) for more robust planet radii in the presence of significant starspot coverage, and elaborate on the degeneracies in the model in Section 11.3. In Section 11.4, we validate

the new transit model with fits to synthetic light curves of simulated spotted stars. We fit real transit light curves of a variety of planets including TRAPPIST-1 and GJ 1214 in Section 11.5, and discuss the results and conclusions in Sections 11.6 and 11.7.

11.2 Self-contamination and the transit light curve

Following Mandel & Agol (2002), the ratio of unocculted flux to occulted flux F is given by

$$F^e(p_0, z, u_1, u_2) = 1 - \lambda^e(p_0, z, u_1, u_2), \quad (11.1)$$

where $p_0 = R_p/R_\star$, z is the projected sky separation between the centers of the star and planet (in units of the stellar radius), and u_1 and u_2 are the quadratic limb-darkening parameters. One way to interpret the transit light curve – for a star known to have little contamination from other nearby stars – is to create a flux contamination term which will account for bright or dark regions of the surface of the star known to be transited. We introduce the new parameter p_1 and renormalize the λ term as:

$$F^e(p_1, p_0, z, u_1, u_2) = 1 - \left(\frac{p_1}{p_0}\right)^2 \lambda^e(p_0, z, u_1, u_2). \quad (11.2)$$

It follows that $p_1 \approx \sqrt{\delta}$ where δ is the transit depth (the approximation becomes an equivalence for the uniform case where $u_1 = u_2 = 0$). We emphasize here that p_1 is not a radius ratio parameter like p_0 ; p_1^2 is related to the observed transit depth in the presence of bright or dark spot contamination. A measured difference between p_0 and p_1 is in principle sensitive to starspots, even with an axisymmetric distribution, unlike rotational modulation.

This renormalization is equivalent to the analysis often performed on *Kepler* planet candidate host stars in order to search for contaminating light from a second, unresolved star (Morton, 2012; Teske et al., 2018; Torres et al., 2011). Typically in the external contamination case, the light from the background star dilutes the flux of the exoplanet host star, decreasing the transit depth, modifying the inferred impact parameter, and leading to underestimated the planet radii, if the contamination is unaccounted for.

In equation 11.2, we are essentially allowing for a contaminating light source on the host star itself, which can be positive *or* negative due to bright or dark regions on the stellar surface, thus increasing or decreasing the transit depth p_1^2 with respect to the expectation given the planet’s radius p_0 . Typically for contaminating nearby sources, the ratio of the unocculted flux to occulted flux is given by

$$F^e = (1 - \lambda^e)(1 - \epsilon) + \epsilon, \quad (11.3)$$

where ϵ is the flux of the contaminating source. In this parameterization,

$$\left(\frac{p_1}{p_0}\right)^2 = 1 - \epsilon \quad (11.4)$$

We focus our attention in this work on the “self-contamination” effect of bright or dark regions on the host star itself.

We have implemented the algorithm in CPython called **robin**, based on a fork of the **batman** code by Kreidberg (2015), which is publicly available¹.

11.3 Constraining the radius ratio from durations of the transit and of ingress/egress

Given the untoward effect of contamination on measurement of the planet-star radius ratio, we require some additional constraint to derive this ratio in the presence of a heterogenous stellar photosphere or blending with other sources of light. This can be provided by a purely geometrical constraint: the ratio of ingress duration to transit duration. However, to implement this requires a knowledge of (or constraint upon) the impact parameter of the transit, b , which we describe in this section.

The duration of ingress for an eccentric orbit is given approximately by:

$$\tau = \frac{2R_p}{v \sin \theta}, \quad (11.5)$$

where θ is the angle between the tangent of the limb of the star and the path of the planet (projected onto the sky plane) and v is the sky velocity of the planet relative to the star

¹ Open source, available online: <https://github.com/bmorris3/robin>

during transit, which we take to be constant in this section. The duration of the transit, T , from mid-ingress to mid-egress is given by

$$T = \frac{2R_* \sin \theta}{v}, \quad (11.6)$$

Now $\sin \theta = \sqrt{1 - b^2}$, so

$$\tau = 2(1 - b^2)^{-1/2} \frac{R_p}{R_*} \frac{R_*}{v}, \quad (11.7)$$

$$T = 2(1 - b^2)^{1/2} \frac{R_*}{v}. \quad (11.8)$$

These formulae assume that $a \gg R_*$ and $R_p \ll R_*$, neglecting the curvature of the orbit and the stellar limb (see Winn et al. (2010) or the appendix for more complete relations).

The transit and ingress/egress durations are simply a function of time, and do not depend upon the transit depth, and hence will not be affected by dilution by star spots or flux from a blend, such as a companion star. Thus, a precise measurement of τ and T can in principle give another means of constraining the radius ratio of the planet to the star which will be less affected by blending or a heterogeneous stellar photosphere.

There are two ways to solve for this radius ratio, the first of which is derived from the ratio of ingress to duration of transit,

$$\frac{R_p}{R_*} = \frac{\tau}{T}(1 - b^2). \quad (11.9)$$

This requires a constraint upon the impact parameter, b . The *shape* of ingress and egress depends weakly on the impact parameter; however, this is generally too subtle to measure, even with the highest signal-to-noise transits. Note that a given measured value of τ and T imply a maximum value of R_p/R_* , which is the value this ratio would have if $b = 0$. This could be useful for placing upper limits on the radii of planets given measured properties of the transit; this constraint is independent of the eccentricity and period of an orbit and independent of the density of the star. If the depth of transit (as parameterized by p_1^2) implies a radius ratio that is greater than this maximum value, then this likely implies that both a small impact parameter and that non-transited star spots must be present (or that

the planet transits a bright chord) to cause a larger transit depth, or that the planet is significantly oblate (see next section).

The second means of solving for the radius ratio from time-dependent quantities is given by

$$\frac{R_p}{R_*} = \frac{\tau T}{4} \left(\frac{v}{R_*} \right)^2, \quad (11.10)$$

which requires a measurement of the normalized sky velocity, given by:

$$\frac{v}{R_*} = \frac{2\pi}{P} \frac{a}{R_*} \frac{1 + e \sin \omega}{\sqrt{1 - e^2}}, \quad (11.11)$$

$$\frac{a}{R_*} = \left[\frac{G\rho_* P^2}{3\pi} \right]^{1/3}, \quad (11.12)$$

where ρ_* is the stellar density, e is the orbital eccentricity, and ω is the longitude of periastron of the star measured along the orbital path from when the star crosses the sky plane away from the observer.² Thus, if a/R_* is constrained, for example, from asteroseismology or asterodensity profiling (which requires additional transiting planets), and if the eccentricity vector, $\vec{e} = \{e \cos \omega, e \sin \omega\}$ is constrained, for example, from radial velocity measurements or transit-timing variations, then the transit chord, $d/R_* = 2\sqrt{1 - b^2}$ (in units of R_*), and hence the impact parameter, can be constrained from the transit duration.

In practice, then, the radius ratio may only be determined in cases for which there is a prior on the impact parameter, and generally this is derived from the dependence of the transit duration upon the stellar density and the eccentricity of the planet's orbit, as well as other well-measured quantities such as the planet's orbital period. The formulae above are only approximate as they neglect the curvature of the orbit and the curvature of the limb of the star (see the Appendix 11.A for more general expressions), but these relations are generally good approximations, while the full relation can be accounted for with a full orbital transit model.

² For nearly edge-on orbits, transits occur when the true longitude of the star is $\theta = \pi/2$. The relative velocity of the star and planet is maximum at periastron, and if the time of periastron coincides with the time of transit, then $\omega = \pi/2$, at which time the velocity is $\sqrt{(1+e)/(1-e)}$ of the mean orbital velocity.

11.3.1 Planetary Oblateness

The preceding analysis assumes that a planet is spherical. However, the transit depth and the duration of ingress and egress are also affected by the shape of a planet. If a planet is distorted, for example, due to oblateness, then the area of a planet and the distance a planet moves during ingress and egress are not simply related to the mean radius of the planet. Oblateness can be induced by rotation of a planet, causing a bulging of the equator due to centripetal acceleration Barnes & Fortney (2003), or by thermal structure of a planet, causing a larger scale height at the hotter equator relative to the poles (Dobbs-Dixon et al., 2012). There are several references in the literature which fully consider the transits of oblate planets, and we refer the interested reader to Barnes & Fortney (2003); Biersteker & Schlichting (2017); Carter & Winn (2010); Hui & Seager (2002); Zhu et al. (2014).

In addition to bright or dark active regions and contaminating light sources, planetary oblateness can cause a mismatch between the observed values of p_0 and p_1 . Here we derive a relationship between p_0, p_1 , and the oblateness of the planet,

$$f = \frac{R_{\text{eq}} - R_{\text{pole}}}{R_{\text{eq}}}. \quad (11.13)$$

The projected ellipsoid of an oblate planet with semimajor axis α (in units of $R_\star$) and semiminor axis β makes first contact with the star at point P , see Figure 11.1, which is an angle θ from the semimajor axis of the planet (or the $+\hat{X}$ axis in the planet-centered coordinate system). The angle from the $+\hat{X}$ -axis to the normal of the tangent of the ellipse $\phi = \sin^{-1}(b)$, where b is the impact parameter.

The definition of the elliptical outline of the planet r is

$$r^2 = \alpha^2 \cos^2 \theta + \beta^2 \sin^2 \theta, \quad (11.14)$$

and the slope of a tangent line which meets the ellipse at point P is

$$m = -\frac{\beta}{\alpha} \cot \theta = -\cot \psi. \quad (11.15)$$

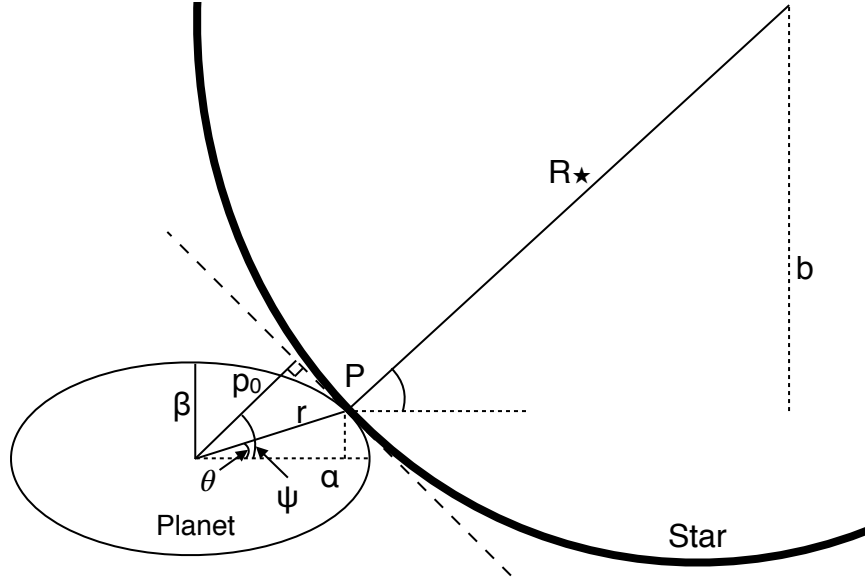


Figure 11.1: Oblate planet model, for a planet with projected semimajor axis α and semiminor axis β .

We assume for simplicity the major axis of the oblate planet is aligned along its direction of motion relative to the star, so $\alpha = R_{eq}/R_*$ and $\beta = R_{pole}/R_*$. Now we can solve for p_0 given

$$p_0 = r \cos(\psi - \theta) \quad (11.16)$$

where ψ is the angle measured up from the $+\hat{X}$ axis to p_0 . Solving for p_0 in terms of α, β ,

$$p_0 = \alpha \frac{\sqrt{1 - b^2 + b^2(1 - f)^4}}{1 - b^2 + b^2(1 - f)^2} (1 - b^2 f) \quad (11.17)$$

Note that in the oblate planet case $f > 0$, $p_0 \neq \alpha$ for non-zero b . The depth of the transit will be the ratio of the cross-sectional area of the planet to the star,

$$p_1^2 = \alpha\beta, \quad (11.18)$$

so the general form of the relation between p_0, p_1, b and f is:

$$\left(\frac{p_1}{p_0}\right)^2 = \frac{(1 - f)(1 - b^2 + b^2(1 - f)^2)^2}{(1 - b^2 f)^2(1 - b^2 + b^2(1 - f)^4)} \quad (11.19)$$

$$\approx 1 - f(1 - 2b^2), \quad (11.20)$$

where the last expression is valid for $f \ll 1$. In the special case where $b = 0$, this simplifies to

$$\left(\frac{p_1}{p_0}\right)^2 = 1 - f, \quad (11.21)$$

implying that $p_0^2 = \alpha^2 = R_{\text{eq}}^2/R_*^2$ and $p_1^2 = \alpha\beta = R_{\text{pole}}R_{\text{eq}}/R_*^2$.

11.4 Validation on simulated light curves

To estimate the ability to measure the planet-star radius ratio in the presence of a heterogeneous stellar photosphere, we used the reparameterized transit light curve to fit simulated light curves generated with STSP (Hebb et al. 2018³). STSP synthesizes transit light curves of spotted stars by analytically computing the overlap between the planet, starspots, and the star, with limb darkening approximated by concentric circles of constant surface brightness.

We consider two axisymmetric starspot distributions: the first in which the planet’s orbital angular momentum is aligned with that of the star in the sky plane, and the planet crosses an active latitude with dark spots, and the second in which active latitudes are present with dark spots, but not transited by the planet. This first case causes shallower transits relative to a uniform star, which is equivalent to contamination by an additional source with $\epsilon > 0$, while the second case causes deeper transits, and is equivalent to dilution by a source with *negative* flux, $\epsilon < 0$, which is the deficit of stellar flux caused by the darker spots.

11.4.1 Occultation of an active latitude

We synthesize a transit light curve of a star with a dense band of spots that blankets the stellar equator using STSP with $c = 0.7$ – see Figure 11.2. We observe the transit at one second cadence with uncertainties of 48 ppm for each flux measurement, which is similar in scale to the oscillations in flux at the “bottom” of the transit light curve, such that fits to the transit light curve with the standard (Mandel & Agol, 2002) model yield a reduced-

³ Open source, available online: <https://github.com/lesliehebb/stsp>

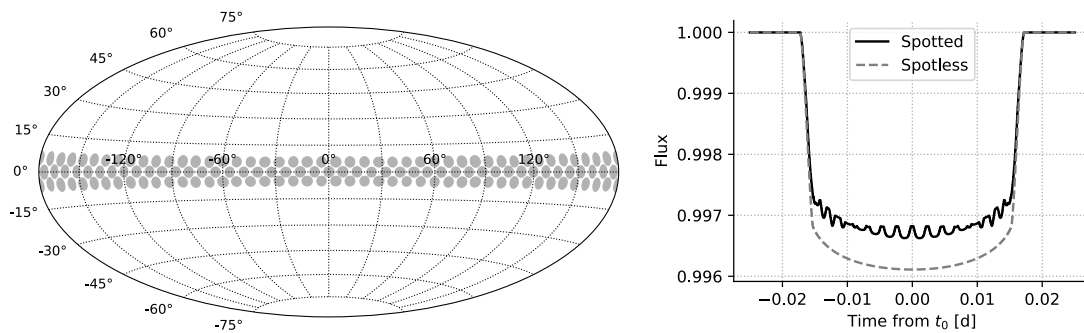


Figure 11.2: *Left:* Hypothetical spot map for a dense band of spots in an active latitude at the stellar equator. *Right:* Transit of a small planet across the star with the spot map on the left, with $i_o = 90^\circ$ and $\lambda = 0^\circ$ and other parameters set to those of TRAPPIST-1 g (black curve), compared with the transit of the same system without spots (gray dashed curve). At lower S/N, or for different spot geometries, the bottom of the spotted transit might simply appear flat and relatively shallow, but the ingress and egress durations are the same for both light curves, allowing us to recover the true planet radius from timing, independent of the transit depth which is affected by starspots.

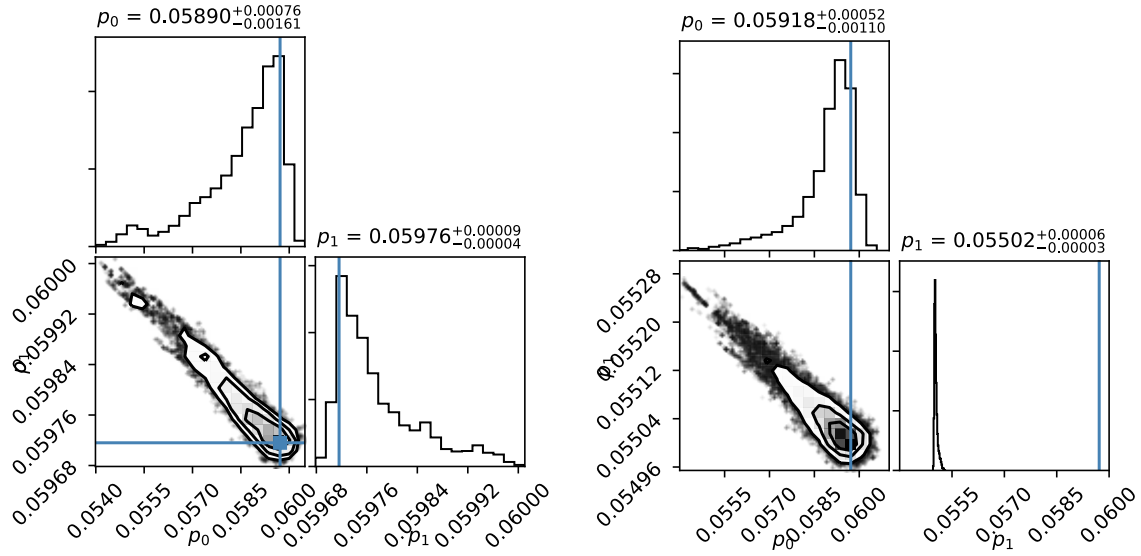


Figure 11.3: *Left:* posterior distributions from a fit to the spotless transit light curve in Figure 11.2, showing agreement between the radius measurement from the ingress/egress duration, $p_0 = R_p/R_\star$, and the radius measurement from the transit depth $p_1 \approx \sqrt{\delta}$ where δ is the transit depth. *Right:* posterior distributions from a fit to the spotted transit light curve in Figure 11.2, demonstrating $p_0 > p_1$, and that the duration-dependent radius measurement p_0 recovers the true radius (vertical blue line).

$\chi^2 = 0.95$. This is a very high signal-to-noise example, even exceeding reasonable S/N estimates for bright targets observed with JWST. The corresponding transit light curve for a planet with impact parameter $b = 0$ and projected spin-orbit alignment $\lambda = 0^\circ$ (i.e. the planet transits the stellar equator) is *shallower* than the transit of the same system without starspots. The duration of ingress and egress independently encode the radius of the planet.

Figure 11.3 shows the posterior distributions of fits for the parameters p_0, p_1 for the spotless (left) and spotted (right) light curves, allowing the impact parameter and transit duration T_{14} to vary, and holding the limb darkening parameters fixed at their true values. In the spotless light curve case, as expected, we find that $p_0 = p_1$. In the case of transiting an active latitude of dark spots, $p_0 > p_1$, indicating that the transit depth is being decreased by occultations of dark starspots. The solution for p_0 is consistent with the injected transit radius $p_0 = R_p/R_\star = 0.05971$.

The degeneracy between p_0 , the limb-darkening parameters, and the impact parameter becomes increasingly important as one decreases the S/N of the observations. For example, we inflated the uncertainties on each observation by a factor of three, and we found that the uncertainties on the p_0 , impact parameter, and limb-darkening parameters increased by factors of 5, 2, and 2, respectively. This exercise demonstrates the importance of having independent measurements of the impact parameter or $a/R_\star$, as discussed in Section 11.3.

11.4.2 Occultation of a bright latitude

We approximate a bright latitude centered on the stellar equator with STSP by creating active latitudes of spots centered on $\pm 30^\circ$ latitude, see Figure 11.4, while keeping the same planet properties and uncertainties as in Section 11.4.1. The planet transits a relatively bright region of the stellar surface, so in this example the transit light curve for the spotted star is *deeper* than expected for the spotless case.

Figure 11.5 shows the posterior distribution of fits for the parameters p_0, p_1 for the spotless (left) and spotted (right) light curves, allowing the impact parameter and transit duration T_{14} to vary, and holding the limb darkening parameters fixed at their true values, as in

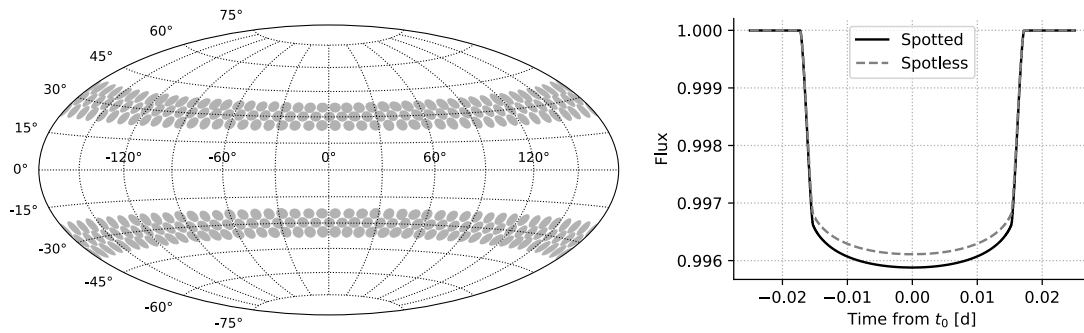


Figure 11.4: *Left*: Hypothetical spot map for two dense active latitudes of spots centered on $\pm 30^\circ$ latitude. *Right*: Transit of a small planet across the star with the spot map on the left, with $i_o = 90^\circ$ and $\lambda = 0^\circ$ and other parameters set to those of TRAPPIST-1 g (black curve, Delrez et al. 2018a), compared with the transit of the same system without spots (gray dashed curve). The bottom of the spotted transit might simply appear deeper, but the ingress and egress durations are the same for both light curves, allowing us to recover the true planet radius from timing, independent of the transit depth which is affected by starspots.

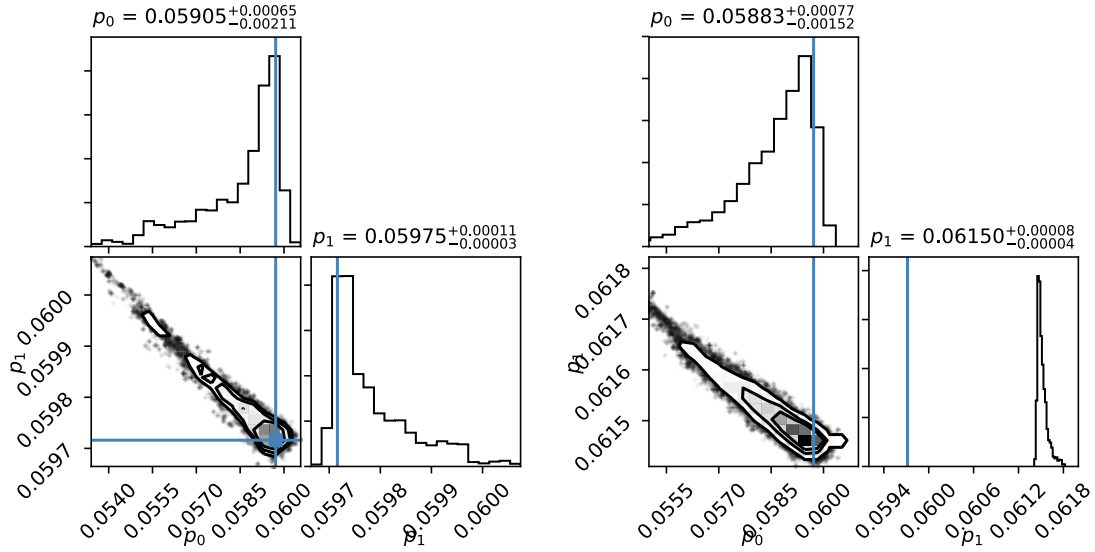


Figure 11.5: *Left:* posterior distributions from a fit to the spotless transit light curve in Figure 11.4, showing agreement between the radius measurement from the ingress/egress duration, $p_0 = R_p/R_\star$, and the radius measurement from the transit depth $p_1 \approx \sqrt{\delta}$ where δ is the transit depth. *Right:* posterior distributions from a fit to the spotted transit light curve in Figure 11.4, demonstrating $p_0 < p_1$, and that the duration-dependent radius measurement p_0 recovers the true radius (vertical blue line).

Section 11.4.1. In the spotless light curve case, we again find that $p_0 = p_1$. In the case of transiting a bright latitude, $p_0 < p_1$, indicating that the transit depth is being increased by the spot distribution. The solution for p_0 is again consistent with the injected transit radius $p_0 = R_p/R_\star = 0.05971$.

We consider further limiting cases with extreme spot distributions in Appendix 11.B, which suggests that plausible limits for self-contamination are $-0.5 \lesssim \epsilon \equiv 1 - (p_1/p_0)^2 \lesssim 0.5$.

11.4.3 Required Precision

It is important to note that extremely high S/N light curves are required in order to produce meaningful constraints on the difference between p_0 and p_1 , similar to the S/N assumed in the previous two subsections. Descriptions of the uncertainties on p_0 and p_1 in terms of planetary system and observing parameters are detailed in the Appendix. Here we will take the examples of the previous two subsections and ask what photometric precision is necessary to measure significant deviations between p_0 and p_1 .

Figure 11.6 shows the confidence interval for detecting $p_0 < p_1$ when crossing a dark latitude with the spot map from Section 11.4.1, as a function of photometric precision on one-second cadence observations of TRAPPIST-1 g (left); and the confidence interval for detecting $p_0 > p_1$ when crossing a bright latitude with the spot map from Section 11.4.2 (right). For the TRAPPIST-1 g system in particular, extremely high S/N precision – 10s of ppm uncertainty per flux measurement – would be required to significantly detect the occultation of a dark latitude. The situation is a bit less severe for the occultation of a bright latitude – 100s of ppm uncertainty per flux measurement are sufficient to significantly detect $p_0 < p_1$ in this case. In each case, we note that the required precision is similar to or better than the precision achievable with phase-folded *Kepler* observations, so we anticipate that any detections of spot distributions with the self-contamination technique from *Kepler* observations (Section 11.5.1) will yield only marginal significance, and higher S/N observations, like those of JWST, may be able to achieve the precision necessary to unambiguously separate the posterior distributions of p_0 and p_1 .

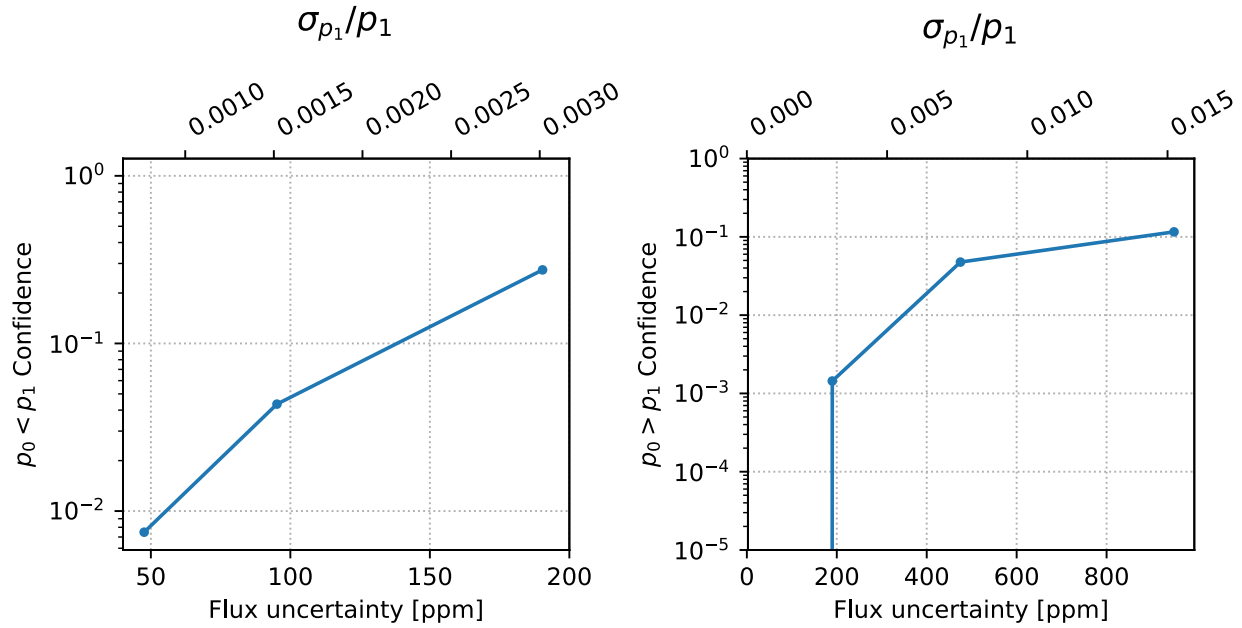


Figure 11.6: Posterior probabilities – for $p_0 < p_1$ given the spot distribution in Section 11.4.1 (crossing a dark latitude, *left*), and for $p_0 > p_1$ given the spot distribution in Section 11.4.2 (crossing a bright latitude, *right*) – as a function of the photometric uncertainty on one-second cadence observations of TRAPPIST-1 g. Photometric uncertainties must be smaller than 50 ppm for a significant detection (3σ) of the spot distribution in Section 11.4.1, or smaller than 300 ppm for a significant detection of the spot distribution in Section 11.4.2. The upper axis translates the flux uncertainty into relative uncertainty on the p_1 parameter.

11.5 Application to Observations

11.5.1 Kepler Light Curves

We apply the new parameterization to the highest S/N transit light curves available – those of the transiting planets Kepler-1, Kepler-2 and Kepler-3 (a.k.a. TrES-2, HAT-P-7 and HAT-P-11). Each of these light curves have short cadence observations throughout the *Kepler* mission, short period planets, and very bright host stars ($K_p = 9.84, 9.33, 7.00$, respectively). As a result, these light curves should yield some of the best constraints on ingress and egress durations available. We also explore some exceptional cases: the highly spotted star Kepler-17, the potentially oblate planet Kepler-39 b, and a planet with a very high impact parameter, and thus long ingress/egress durations, Kepler-412.

For Kepler-1 through -3, the Kepler Input Catalog estimated contamination in the *Kepler* aperture is $\lesssim 1\%$, so a third light source can likely be ruled out as the cause for discrepancies between p_0 and p_1 for these targets (Brown et al., 2011). For Kepler-17, -39 and -412, the contamination is $\lesssim 6\%$, so discrepancies larger than 6% are required to invoke stellar activity as the culprit for disagreement between p_0 and p_1 .

For each *Kepler* transit light curve, we normalize the SAP flux by a quadratic fit to the out-of-transit flux. We assume the periods, midtransit epochs, eccentricities and arguments of periastron for each target listed in the NASA Exoplanet Archive.

TrES-2 (Kepler-1)

TrES-2 is a G0V star with $T_{\text{eff}} = 5960 \pm 100$ K and $\log g = 4.4 \pm 0.2$ (O'Donovan et al., 2006; Sozzetti et al., 2007). Asteroseismology indicates $M = 0.94 \pm 0.05 M_{\odot}$ and $R = 0.95 \pm 0.02 R_{\odot}$, and the stellar age is 5.8 ± 2.2 Gyr (Barclay et al., 2012). The Rossiter-McLaughlin effect shows the orbit of its hot-Jupiter is prograde (Winn et al., 2008). TrES-2 is an especially enticing target because its high impact parameter, $b = 0.84$, provides us with long ingress and egress durations and therefore tighter constraints on p_0 .

We fit the transit light curve in Figure 11.7 for $p_0, p_1, i_o, a/R_{\star}$, holding the quadratic limb

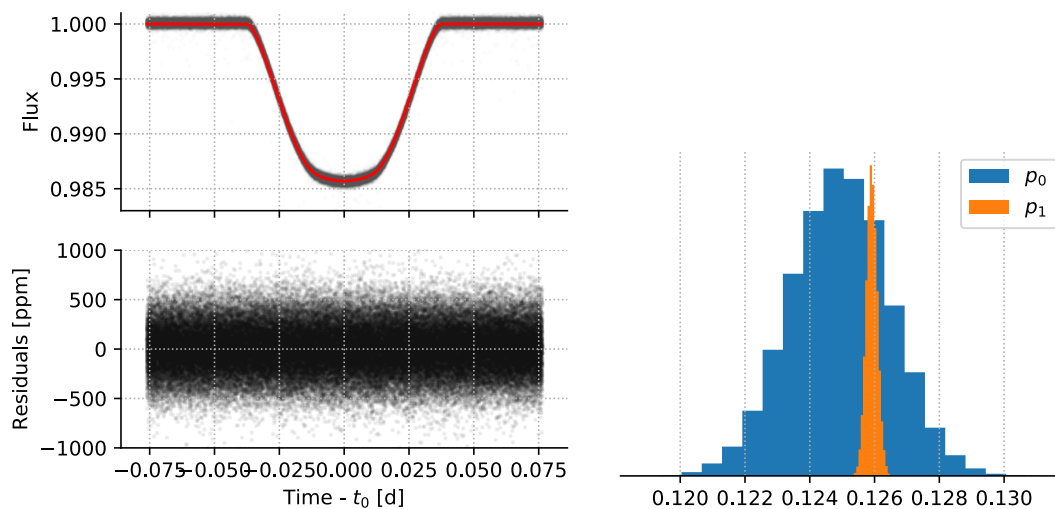


Figure 11.7: *Left*: maximum-likelihood transit model for TrES-2 b (red) compared with *Kepler* short cadence observations (black). *Right*: posterior distributions verifying that $p_0 \approx p_1$. In other words, we do not detect large-scale surface brightness variations on TrES-2.

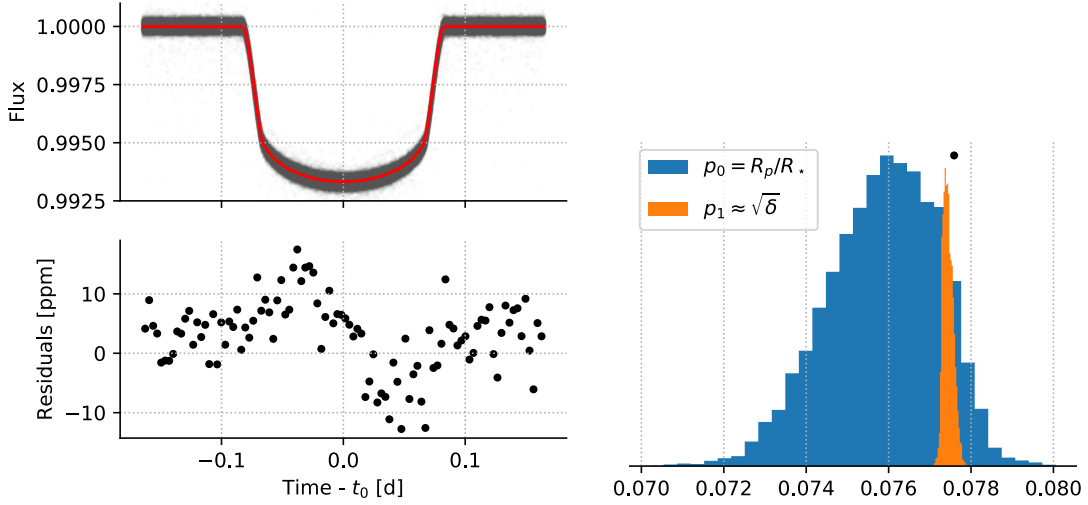


Figure 11.8: *Left*: maximum-likelihood transit model for HAT-P-7 b (red) compared with *Kepler* short cadence observations (black), and binned residuals which show evidence for gravity darkening. *Right*: posterior distributions for p_0 and p_1 . Note that $p_0 \approx p_1$, indicating that the stellar intensity in the transit chord is generally representative of the star on the whole, despite gravity darkening known to affect this star.

darkening parameters fixed at $u_1, u_2 = 0.39256, 0.29064$ (Magic et al., 2015). The posterior distributions of p_0 and p_1 are overlapping, indicating that the planet radius inferred from the transit depth is consistent with the radius inferred from the ingress and egress durations (see Figure 11.7). This measurement aligns with our expectation for a middle-aged, solar-like star such as TrES-2, since sunspots typically cover $\sim 0.03\%$ of the solar surface (Howard et al., 1984). We note that the quadratic limb-darkening parameters of (Magic et al., 2015) appear to be sufficient for describing the transit of this G0 star even at extremely high S/N. Table 11.1 reports the results from this analysis.

HAT-P-7 (Kepler-2)

HAT-P-7 is a slightly evolved F6 star, orbited by a highly misaligned hot-Jupiter (Pál et al., 2008; Winn et al., 2009a). Asteroseismology indicates that the star is likely in a pole-on configuration (Benomar et al., 2014; Lund et al., 2014). Several authors have noted that there is a ~ 20 ppm positive residual bump in the transit light curve between ingress and mid-transit, which may be attributed to stellar gravity darkening (Masuda, 2015; Morris et al., 2013; Van Eylen et al., 2012).

We fit the phase-folded *Kepler* light curve of HAT-P-7 for $p_0, p_1, a/R_\star, i_o, t_0$ and the four nonlinear limb-darkening parameters. We put a Gaussian prior on $a/R_\star$ with the value inferred from asteroseismology by (Lund et al., 2014), $\langle \rho_\star \rangle = 0.266 \pm 0.008 \text{ g cm}^{-3}$ or $a/R_\star = 4.090 \pm 0.044$. The results are shown in Figure 11.8. We find that $p_0 \approx p_1$, indicating that the transit chord of the planet is representative of the typical intensity of the star, despite the gravity-darkening signal evident in the transit residuals. This would appear to be a result of the stellar orientation, with its bright pole being occulted between mid-transit and egress, and its dimmer low latitudes being occulted between ingress and mid-transit. The net effect of the gravity darkening on the light curve residuals appears to cancel out since p_0 is consistent with p_1 .

HAT-P-11 (Kepler-3)

HAT-P-11 is a benchmark system for studying stellar activity with planetary transits. It is a $0.8M_\odot$ star with a rotation period similar to the sun ($P_{\text{rot}} = 29 \text{ d}$) (Bakos et al., 2010; Deming et al., 2011; Sanchis-Ojeda & Winn, 2011; Southworth, 2011). In Morris et al. (2018g, 2017b,c) we establish qualitative similarities between the Sun and HAT-P-11's starspot distributions and activity cycles.

We fit the phase-folded *Kepler* light curve of HAT-P-11 for $p_0, p_1, a/R_\star, i_o, t_0$ and quadratic limb-darkening parameters. We place a Gaussian prior on $a/R_\star$ with the value inferred from asteroseismology by Christensen-Dalsgaard et al. (2010), $\langle \rho_\star \rangle = 2.5127 \pm 0.0009 \text{ g}$

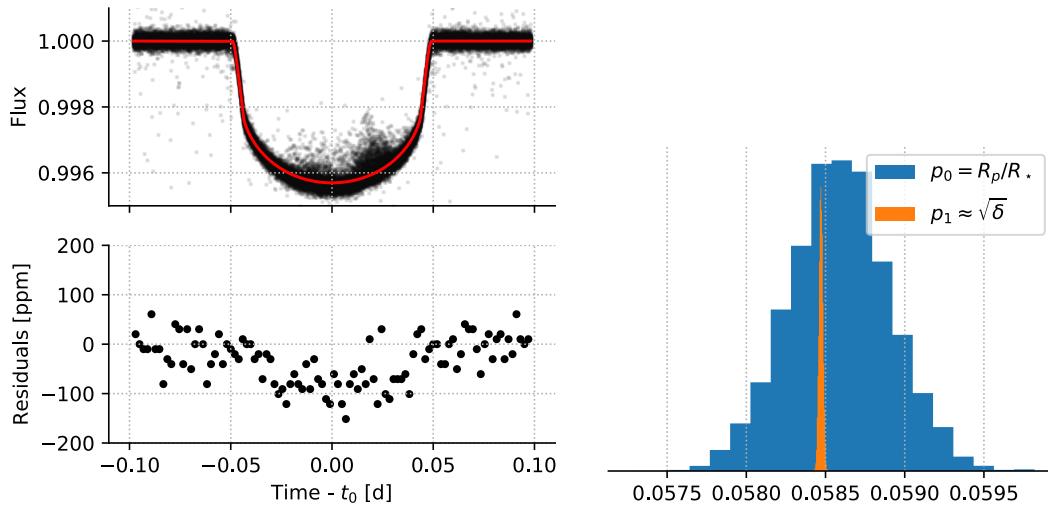


Figure 11.9: *Left*: maximum-likelihood transit model for HAT-P-11 b (red) compared with *Kepler* short cadence observations (black), and binned residuals of the model within each bin. *Right*: posterior distributions for p_0 and p_1 . Note that $p_0 \approx p_1$ despite the spots known to be present on HAT-P-11. It would appear that the small spot covering fraction ($f_S \sim 3\%$ from Morris et al. 2017b) is insufficient to be measured from the *Kepler* photometry with this technique.

$\text{cm}^{-3} \Rightarrow a/R_\star = 14.6950 \pm 0.0017$, and fix the eccentricity and argument of periastron to the measurements of Winn et al. (2010). The results are shown in Figure 11.9. We find $p_0 \approx p_1$, indicating that the spot covering fraction is relatively small.

It is interesting to compare the spot covering fractions measured in- and out-of-transit for HAT-P-11 from Morris et al. (2017b). The *Kepler* light curve shows $\sim 3\%$ rotational modulation each quarter. If we assume the starspots have contrast similar to sunspots, we can use Equations 9-14 of Morris et al. (2017b) to estimate the spot covering fraction within the transit chord from p_0 and p_1 by noticing that the depth of transit will be diluted by starspots with contrast c (where $c = 1$ means spots with the same intensity as the photosphere and $c = 0$ means spots that are perfectly dark), and covering fraction f_S ,

$$p_1^2 \approx p_0^2(1 - f_{S,\text{transit}}(1 - c)). \quad (11.22)$$

For example, if the transit chord is completely covered ($f_S = 1$) by perfectly dark spots ($c = 0$), then the transit depth goes to zero. If the transit chord has sun-like spots with $c = 0.7$, then we can solve for the spot covering fraction given p_0 and p_1 ,

$$f_{S,\text{transit}} \approx \frac{1}{1 - c} \left(1 - \left(\frac{p_1}{p_0} \right)^2 \right). \quad (11.23)$$

For HAT-P-11, this yields the spot covering fraction in the transit chord $f_{S,\text{transit}} \approx 0.01 \pm 0.03$. We can compare the in-transit spot coverage to the spot covering fraction that one would estimate from the flux deficit method (Morris et al., 2017b), which estimates the asymmetric component of the spot covering fraction on the whole star via

$$f_{S,\text{asym}} \gtrsim (1 - \min(f))/(1 - c), \quad (11.24)$$

or $f_{S,\text{asym}} \gtrsim 0.03_{-0.01}^{+0.06}$ for HAT-P-11. Detailed spot occultation modeling from Morris et al. (2017b) yields spot covering fractions of 0-10% within the chord of any given transit, broadly consistent with the small covering fraction measured with the self-contamination technique.

We note that due to the significant obliquity of the orbit of the planet relative to the spin of the star, the time-averaged surface brightness contrast of the transit chord may match

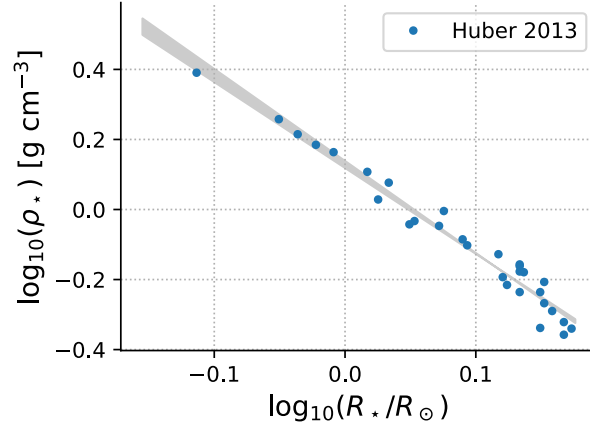


Figure 11.10: Asteroseismic stellar densities and model stellar radii from Huber et al. (2013) yield constraints on the stellar density for main sequence stars of a given radius. When fitting the following transit light curves, we fix a Gaussian prior on the stellar radii from Berger et al. (2018) via *Gaia* DR2 observations, and a prior on the stellar density via the relation above and in Equation 11.25.

the stellar disk as the spots traverse about the same fraction of the stellar disk as they do of the transit chord. Consequently, the lack of detection in this case may be hampered by this geometry.

Estimating stellar densities in the absence of asteroseismology

When a star lacks an asteroseismic density measurement, the three-way degeneracy between p_0 , the limb-darkening parameters, and the impact parameter (or equivalently a/R_* or ρ_*) must be broken in order to produce meaningful constraints on p_0 . For the following three planetary systems, Kepler-17, -39 and -412, no asteroseismic density is available in the literature.

We can estimate the stellar densities for stars without asteroseismic measurements by noting the tight correlation between stellar radius and density found in the asteroseismic

sample of Huber et al. (2013) – see Figure 11.10. For bright *Kepler* targets, Huber et al. (2013) used asteroseismology to calculate stellar densities, and isochrone models to predict stellar radii and masses. We fit a power-law to the measured stellar densities as a function of radius, and find

$$\log_{10}(\rho_{\star}[\text{g cm}^{-3}]) = (-2.540 \pm 0.087) \log_{10}(R_{\star}/R_{\odot}) + (0.12 \pm 0.001), \quad (11.25)$$

with fractional scatter in $\rho_{\star}$ of 0.083. Then for each star, we use the *Gaia* DR2 (Gaia Collaboration et al., 2018b) stellar radius measurements from Berger et al. (2018) in combination with Equation 11.25 to predict the stellar density.

At each step in our Markov chains for Kepler-17, -39 and -412, we sample for the parameters $M_{\star}$ and $R_{\star}$, placing a Gaussian prior on $R_{\star}$ with the value and uncertainty from *Gaia* (Berger et al., 2018) ($R_{\star} = 1.01R, 1.23R, 1.35R$ for Kepler-17, -36 and -412, respectively), and placing a Gaussian prior on the stellar density following Equation 11.25 with fractional uncertainty 0.083 g cm^{-3} .

Kepler-17

Kepler-17 is an active G2V star with $T_{\text{eff}} = 5630 \pm 100 \text{ K}$ and age $3 \pm 1.6 \text{ Gyr}$, with a hot Jupiter companion that produces starspot occultations in nearly every transit studied by Désert et al. (2011) and Davenport (2015a). Thus Kepler-17’s geometry is similar to the toy model in Section 11.4.1, where a planet occults an active latitude with many starspots, diluting the transit depth, and in which the stellar spin axis is aligned (in this case, to within 15°).

We fit the phase-folded *Kepler* light curve of Kepler-17 for $p_0, p_1, b, t_0, T_{14}, M_{\star}, R_{\star}$, and quadratic limb-darkening parameters. We place priors on $M_{\star}$ and $R_{\star}$ as described in Section 11.5.1. The results shown in Figure 11.11 indicate $p_0 > p_1$ at 93% confidence ($\sim 2\sigma$), in agreement with our expectation that starspot occultations dilute the apparent transit depth. We measure $p_0 = R_p/R_{\star} = 0.1354^{+0.0010}_{-0.0014}$, which is significantly larger than the Désert et al.

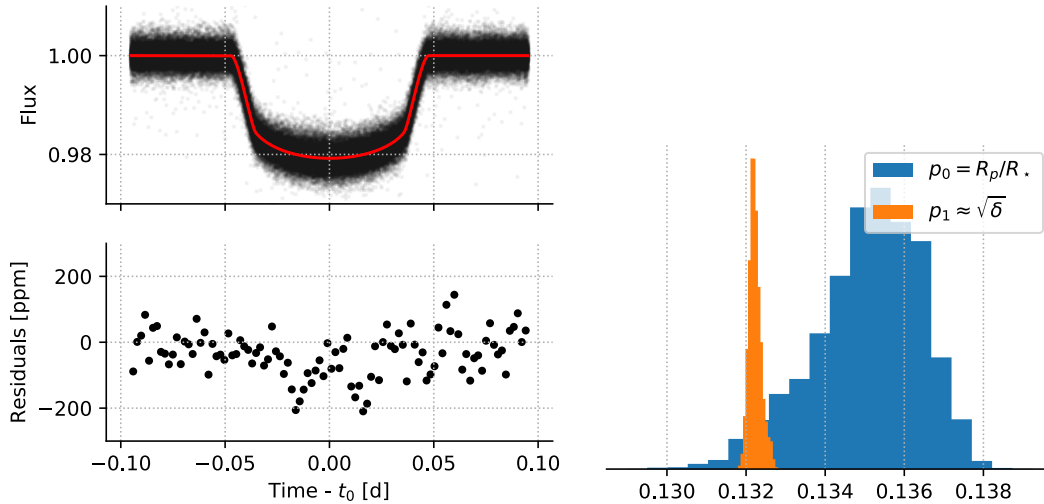


Figure 11.11: *Left*: maximum-likelihood transit model for Kepler-17 b (red) compared with *Kepler* short cadence observations (black). *Right*: Posterior histograms for p_0, p_1 . For this system we find weak evidence for $p_0 > p_1$, consistent with an occultation of a dark region of the stellar surface. This is consistent with the detailed analyses of Désert et al. (2011) and Davenport (2015a), which suggest that Kepler-17 occults an active latitude near the stellar equator.

(2011) estimate ($R_p/R_* = 0.13031^{+0.00022}_{-0.00018}$).

As we did for HAT-P-11 in Section 11.5.1, we can compare the spot covering fractions measured in- and out-of-transit for Kepler-17. The *Kepler* light curve shows $\sim 4\%$ rotational modulation each quarter. If we assume the starspots have contrast similar to sunspots, as in Davenport (2015a), we can use Equation 11.23 to estimate the spot covering fraction within the transit chord and find $f_{S,\text{transit}} \approx 0.27^{+0.12}_{-0.18}$. We can compare the in-transit spot coverage to the spot covering fraction that one would estimate from the flux deficit method, $f_{S,\text{asym}} \gtrsim 0.13$. These two measurements are consistent, and perhaps suggest that the transit chord may be more spotted than the mean photosphere, consistent with the apparent equatorial active latitude deduced from detailed spot modeling by Davenport (2015a).

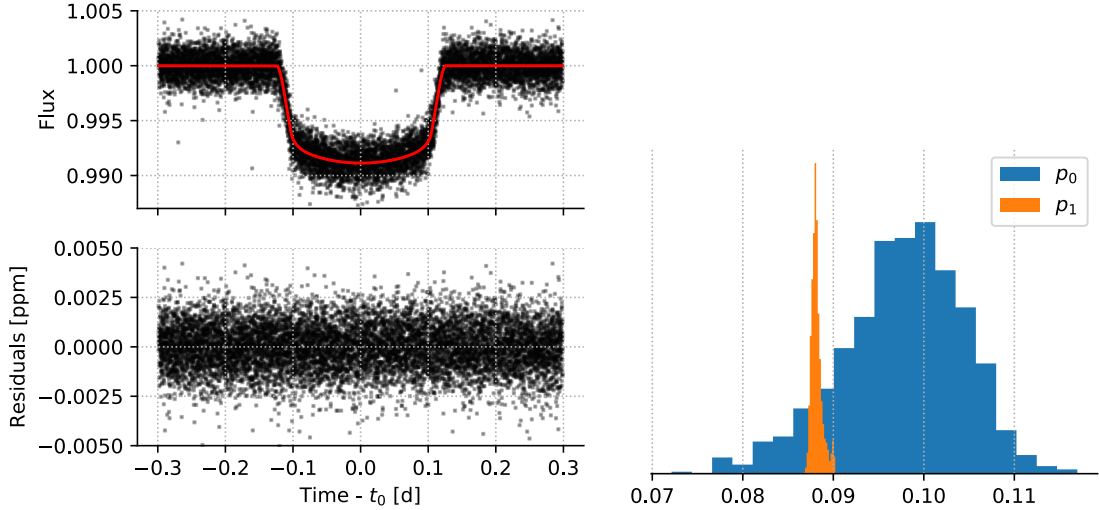


Figure 11.12: *Left*: maximum-likelihood transit model for Kepler-39 b (red) compared with *Kepler* short cadence observations (black). *Right*: Posterior histograms for p_0, p_1 . For this system we detect weak evidence for $p_0 > p_1$, consistent with either (1) an occultation of a dark region of the stellar surface; or (2) oblateness of the planetary companion $f = 0.25^{+0.13}_{-0.06}$. The out-of-transit rotational modulation due to starspots confirms that there are starspots present, see Figure 11.13, while others in the literature interpret the signal as planetary oblateness (Zhu et al., 2014).

Kepler-39

Kepler-39 is a young F7V host star with $T_{\text{eff}} = 6350 \pm 100$ K, and age $0.7^{+0.9}_{-0.3}$ Gyr (Bonomo et al., 2015; Mamajek & Hillenbrand, 2008). Zhu et al. (2014) claim its $20 M_J$ companion has nonzero oblateness $f = 0.22^{+0.11}_{-0.11}$.

We fit the phase-folded *Kepler* light curve of Kepler-39 for $p_0, p_1, b, t_0, T_{14}, M_\star, R_\star$, and quadratic limb-darkening parameters. We place priors on $M_\star$ and $R_\star$ as described in Section 11.5.1. The results are shown in Figure 11.12. Zhu et al. (2014) measure $R_p/R_\star = 0.0889 \pm 0.0006$ with their oblate planet model, consistent with our maximum likelihood $p_0 = R_p/R_\star = 0.090 \pm 0.010$. We find that $p_0 > p_1$ with 90% confidence, suggesting weak

evidence for either starspot occultations in the transit light curve, or the degenerate signal of planetary oblateness. We find $f = 0.25^{+0.13}_{-0.06}$, consistent with the oblateness reported by Zhu et al. (2014).

However, we caution that the *Kepler* light curve shows rotational modulation of the star consistent with starspot coverage (see Figure 11.13), albeit several times smaller than for Kepler-17. We can estimate the minimum spot covering fraction from the amplitude of the rotational modulation, which gives us a constraint on the asymmetry of the spot distribution as the star rotates, $f_{S,\min} \geq (1 - \text{min flux})/(1 - c)$ where $c = 0.7$ is the spot contrast for sunspots (Solanki, 2003). Thus assuming spots with the contrast of sunspots, $f_{S,\min} \geq 2\%$ – a factor of $\gtrsim 100$ greater than the typical sunspot area coverage, comparable to the spot coverage of HAT-P-11 (Morris et al., 2017b). It is possible that the marginal detection of $p_0 > p_1$ is attributable to either or both planetary oblateness and occulted starspots.

Kepler-412

Kepler-412 is a G3V host to a hot Jupiter with $M_p = 0.939 \pm 0.085 M_J$, and an apparently inflated radius of $1.325 \pm 0.043 R_J$ (Deleuil et al., 2014).

We fit the phase-folded *Kepler* light curve of Kepler-412 for $p_0, p_1, b, t_0, T_{14}, M_\star, R_\star$, and quadratic limb-darkening parameters. We place priors on $M_\star$ and $R_\star$ as described in Section 11.5.1. The results are shown in Figure 11.14; we find $p_0 = R_p/R_\star = 0.0926^{+0.0095}_{-0.0089}$ corresponding to $R_p = 1.16 \pm 0.11 R_J$ – consistent with the literature value ($R_p/R_\star = 0.1058 \pm 0.0023$, Deleuil et al. 2014). We measure $p_0 \approx p_1$.

As with Kepler-39 in Section 11.5.1, $p_0 \lesssim p_1$ could be interpreted as insignificant evidence ($\sim 1\sigma$) for dark starspots on the stellar photosphere outside of the transit chord; however, without the ability to further refine the uncertainty on p_0 , we cannot strengthen this claim. The *Kepler* light curve shows small variations in the stellar intensity that may be rotational modulation due to unocculted starspots (see Figure 11.13).

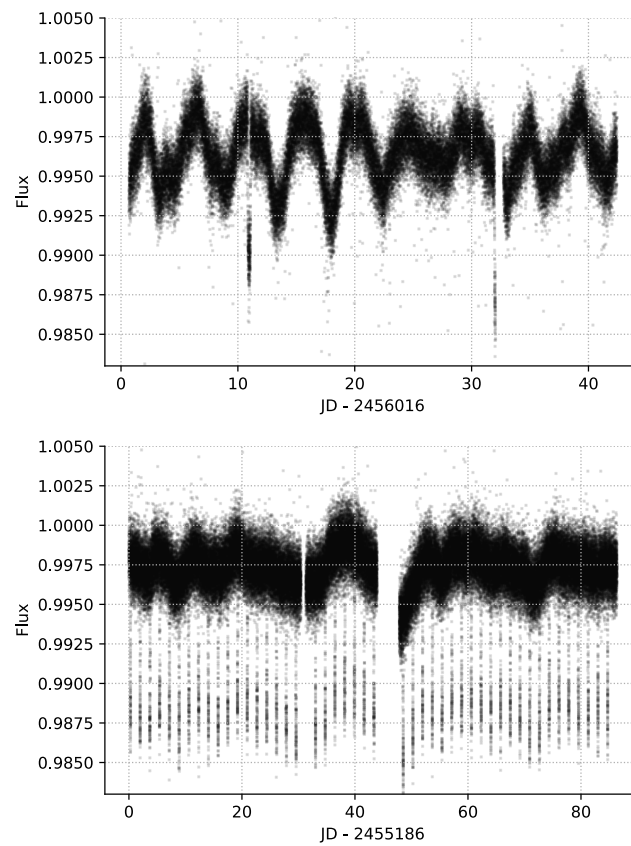


Figure 11.13: Rotational modulation of Kepler-39 (left) and Kepler-412 (right) showing evidence for starspot coverage, despite the lack of starspot crossings in the transit photometry.

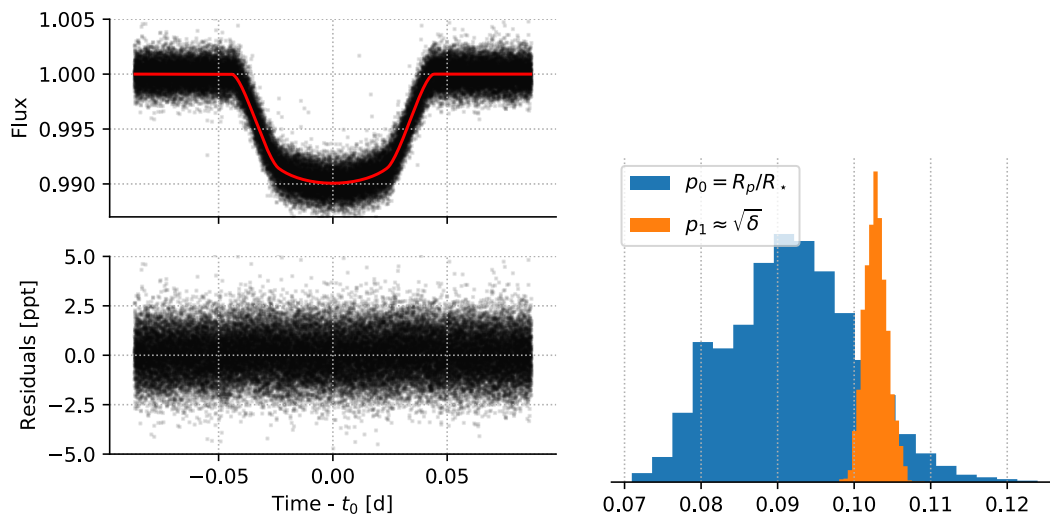


Figure 11.14: *Left*: maximum-likelihood transit model for Kepler-412 b (red) compared with *Kepler* short cadence observations (black). *Right*: Posterior distributions for p_0, p_1 and R_p/R_* (equivalent to fixing $p_0 = p_1$). There is insignificant evidence for $p_0 < p_1$. See Figure 11.13 for the out-of-transit rotational modulation of Kepler-412.

11.5.2 K2 Observations of TRAPPIST-1

TRAPPIST-1 is an M8V host to seven Earth-sized planets (Delrez et al., 2018a; Gillon et al., 2016, 2017; Luger et al., 2017b). Its spots seem to evolve on a timescale similar to the apparent rotation period (Roettenbacher & Kane, 2017), the spot and faculae covering fractions might be quite high (Rackham et al., 2018; Zhang et al., 2018), and bright spots might be required to explain the apparent rotational modulation of TRAPPIST-1 (Morris et al., 2018b). Here we analyze the K2/EVEREST short-cadence TRAPPIST-1 light curves of the two innermost TRAPPIST-1 planets for evidence of photospheric inhomogeneities (Luger, 2017; Luger et al., 2016).

We fit the transit light curves of TRAPPIST-1 b and c for p_0, p_1, T_{14} and the quadratic limb darkening coefficients u_1 and u_2 , see Figures 11.15 and 11.16. We place Gaussian priors on the impact parameter based on the joint light curve analysis by (Luger et al., 2017b), with impact parameters for planets b and c: $b_b = 0.093^{+0.011}_{-0.015}$ and $b_c = 0.128^{+0.015}_{-0.020}$.

We find $p_0 \approx p_1$ for both planets, indicating insufficient evidence for a difference in spot coverage inside compared to outside of the overlapping transit chords of planets b and c. Combined with the lack of observed spot occultations, the indication that the star may not be highly spotted is somewhat at odds with the spot covering fraction estimates from Rackham et al. (2018); Zhang et al. (2018), who find a potentially large spot covering fraction, $f_S = 8^{+18}_{-7}\%$.

As best we can tell from Doppler imaging, fully-convective stars are likely highly spotted, and their spots may be randomly distributed, arranged into active latitudes, or concentrated at the poles (Barnes & Collier Cameron, 2001; Donati et al., 2003; Morin et al., 2008). If we continue to measure $p_0 \approx p_1$ with further transit observations of TRAPPIST-1, that may suggest that active regions on the star are small, low contrast, and/or uniformly distributed. It will be especially interesting to search for differences between p_0 and p_1 for the outer planets, which span a range of impact parameters, and thus a range of stellar latitudes. Upcoming *Spitzer* and JWST observations may improve this measurement, as the degeneracy

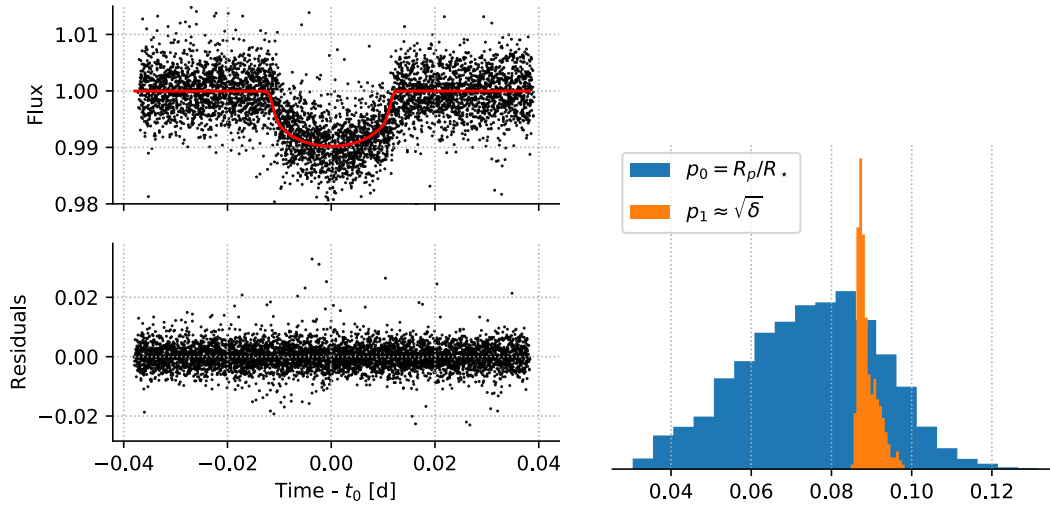


Figure 11.15: *Left*: maximum-likelihood transit model for TRAPPIST-1 b (red) compared with *Kepler*/K2 short cadence observations (black). *Right*: posterior distributions for p_0 and p_1 . p_0 is consistent with p_1 , suggesting the occulted stellar surface is generally similar in brightness to the rest of the surface.

between p_0 and the limb darkening is substantially diminished in the infrared, although the spot contrast is also diminished at longer wavelengths.

11.5.3 Spitzer Light Curves

We analyze two *Spitzer* light curves of interest. One is the transit of HD 80606 b, which is remarkable – among other reasons – for having a twelve hour transit observed at a very short cadence, providing us with exceptionally well-sampled transit ingress and egress. The other is GJ 1214 – an M dwarf host to a transiting super-Earth.

HD 80606

HD 80606/HD 80607 is a wide, solar-type binary system with a massive Jovian planet orbiting the brighter component in an extremely eccentric ($e = 0.93$), misaligned orbit (Moutou et al.,

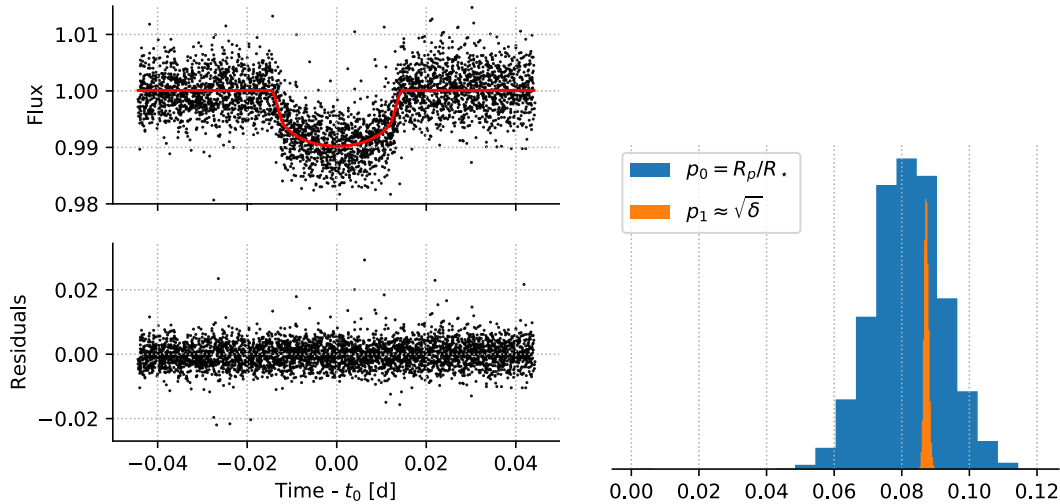


Figure 11.16: *Left*: maximum-likelihood transit model for TRAPPIST-1 c (red) compared with *Kepler*/K2 short cadence observations (black). *Right*: posterior distributions for p_0 and p_1 . See Figure 11.15 for further interpretation.

2009; Naef et al., 2001; Winn et al., 2009b). We re-analyze warm *Spitzer* photometry of the ~ 12 hour-long transit observed at $4.5 \mu\text{m}$ by Hébrard et al. (2010) (see Figure 11.17).

We fit the *Spitzer* transit light curve of HD 80606 b for p_0, p_1, b, t_0 and T_{14} , fixing the quadratic limb-darkening parameters $u_1, u_2 = 0.0866, 0.1071$ (Claret et al., 2013). We find $p_0 < p_1$ with 96% confidence, suggesting that either the planet may be occulting a relatively bright region of the stellar surface, or that we have to place a constraint upon the impact parameter. The transit light curve of HD 80606 shows evidence of at least one starspot occultation; perhaps unocculted starspots are responsible for the tension between p_0 and p_1 (see Figure 11.17).

The maximum likelihood $p_0 = R_p/R_* = 0.053^{+0.025}_{-0.017}$ in combination with the stellar radius from Hébrard et al. (2010) of $1.007 \pm 0.024 R_\odot$ yields the planetary radius $R_p = 0.51^{+0.26}_{-0.16} R_J$, 2σ smaller than proposed by Hébrard et al. (2010) ($R = 0.981 R_J$); they also measure a smaller impact parameter, $b = 0.808 \pm 0.007$, than we measure, which accounts for this

discrepancy.

The density of the star inferred by Hébrard et al. (2010) is $\rho_* = 1.39 \pm 0.07$ g/cc, which is consistent with the value we infer from the Huber et al. (2013) relation that we derived above of $\rho_{*,Huber} = 1.29 \pm 0.11$ g/cc. We conclude that if we had placed this density constraint as a prior on the stellar density, we would have obtained a smaller impact parameter, and hence a larger value of p_0 (see Figure 11.3) consistent with Hébrard et al. (2010).

GJ 1214

GJ 1214 is an M4.5 host to a transiting super-Earth (Charbonneau et al., 2009). The stellar activity of GJ 1214 has been studied extensively for its effect on the transmission spectrum of this potentially water-rich world (Fraine et al., 2013). Rotational modulation of the stellar flux is very limited, suggesting that either the star has either few or small spots, or more likely that the spots are arranged in a nearly-axisymmetric distribution (Berta et al., 2011; Narita et al., 2013). We re-analyze warm *Spitzer* 4.5 μm photometry of 13 transits of GJ 1214 b by Gillon et al. (2014) to verify that the spot distribution inside the transit chord is similar to the rest of the stellar surface.

We fit the *Spitzer* transit light curve of GJ 1214 for p_0, p_1, b, T_{14} and fit for the quadratic limb darkening parameters q_1 and q_2 (Kipping, 2013), see Figure 11.18. The resulting constraint on p_0 is very weak and is consistent with p_1 , suggesting an isotropic spot distribution, consistent with the conclusions of Berta et al. (2011) and Narita et al. (2013).

11.6 Discussion

We have investigated the prospects for robust measurement the radius ratios of planets using the ratio of the ingress duration to total transit duration, which should be less affected by contamination by starspots than the transit depth measurements. We have then applied this to a sample of ten stars to look for differences between the radius ratio measured from ingress (p_0) versus that measured from transit depth (p_1).

Given the probability measurements of $p_0 < p_1$ for the ten stars in our study, we can

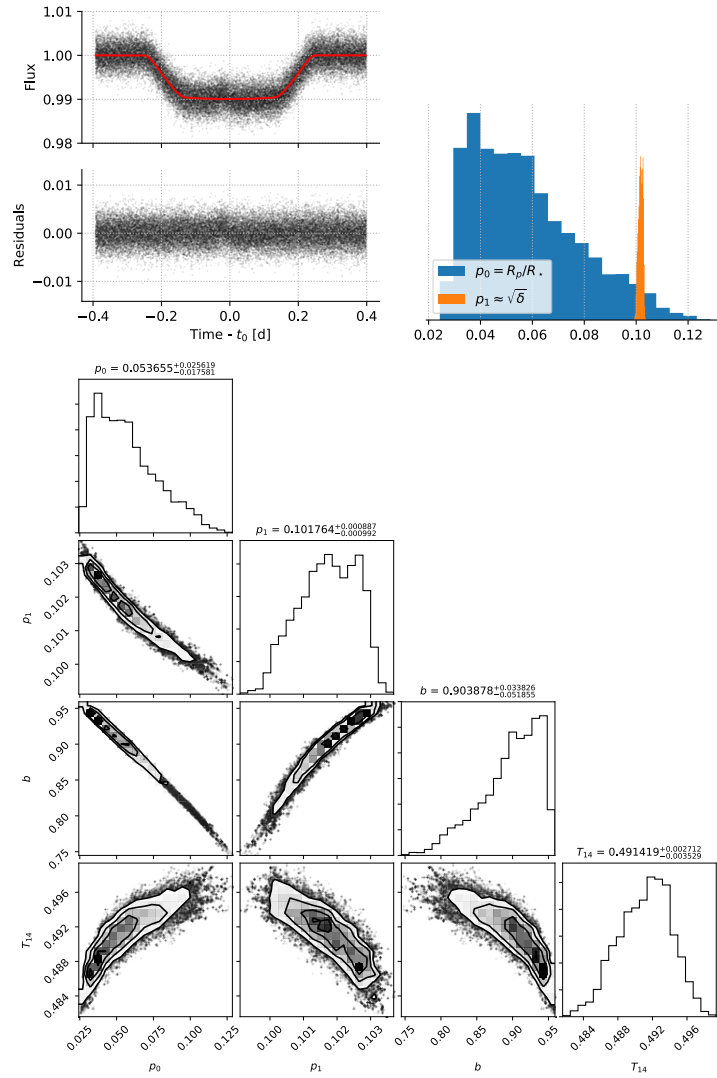


Figure 11.17: *Upper left:* maximum-likelihood transit model for HD 80606 b (red) compared with the *Spitzer* observations at 4.5 μm from Hébrard et al. (2010) (black), and binned residuals. *Upper right:* *Right:* Posterior distributions for p_0, p_1 and R_p/R_* (equivalent to fixing $p_0 = p_1$). The modest difference in p_0 and p_1 may indicate that there is stellar activity and the transit chord is an unusually bright portion of the stellar surface (see Section 11.4.2). *Lower:* Posterior distributions for all parameters in the fit to the transit light curve of HD 80606 b.

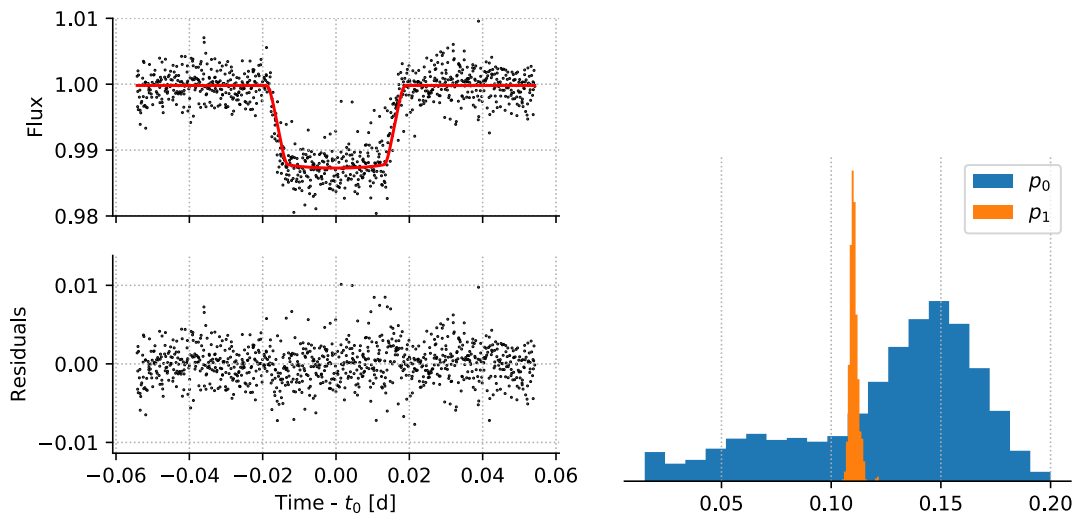


Figure 11.18: *Left*: maximum-likelihood transit model for GJ 1214 b (red) compared with the *Spitzer* observations at $4.5\ \mu\text{m}$ from Gillon et al. (2014) (black). *Right*: posterior distributions for p_0 and p_1 . Consistent values for both parameters indicates that the intensity distribution in the transit chord is consistent with the rest of the stellar surface.

Target	$p_0 = R_p/R_\star$	$p_1 \approx \sqrt{\delta}$	ϵ	Condition	CI
TrES-2	$0.1250^{+0.0015}_{-0.0014}$	$0.12590^{+0.000168}_{-0.00017}$	$-0.013^{+0.027}_{-0.027}$	$p_0 < p_1$	71%
HAT-P-7	$0.0758^{+0.0015}_{-0.0016}$	$0.07744^{+0.00015}_{-0.00013}$	$-0.042^{+0.044}_{-0.050}$	$p_0 < p_1$	85%
HAT-P-11	$0.05859^{+0.00033}_{-0.00031}$	$0.058471^{+0.000012}_{-0.000012}$	$0.004^{+0.011}_{-0.010}$	$p_0 > p_1$	66%
Kepler-17	$0.1348^{+0.0013}_{-0.0017}$	$0.13224^{+0.00024}_{-0.00015}$	$0.039^{+0.019}_{-0.029}$	$p_0 > p_1$	93%
Kepler-39	$0.0984^{+0.0059}_{-0.0074}$	$0.08813^{+0.00062}_{-0.00041}$	$0.20^{+0.08}_{-0.15}$	$p_0 > p_1$	90%
Kepler-412	$0.0909^{+0.0083}_{-0.0065}$	$0.1028^{+0.0015}_{-0.0013}$	$-0.28^{+0.22}_{-0.22}$	$p_0 < p_1$	90%
GJ 1214	$0.136^{+0.028}_{-0.059}$	$0.1101^{+0.0021}_{-0.0015}$	$0.3^{+0.1}_{-1.4}$	$p_0 > p_1$	71%
HD 80606	$0.053^{+0.029}_{-0.019}$	$0.1017^{+0.0010}_{-0.0010}$	$-2.6^{+2.1}_{-5.8}$	$p_0 < p_1$	96%
TRAPPIST-1 b	$0.074^{+0.017}_{-0.015}$	$0.0859^{+0.0006}_{-0.0007}$	$-0.18^{+0.29}_{-0.70}$	$p_0 < p_1$	74%
TRAPPIST-1 c	$0.0824^{+0.0089}_{-0.0095}$	$0.08709^{+0.00057}_{-0.00058}$	$-0.11^{+0.20}_{-0.31}$	$p_0 < p_1$	70%

Table 11.1: Maximum-likelihood parameters for p_0, p_1 , the self-contamination parameter $\epsilon = 1 - (p_1/p_0)^2$, and the confidence interval (CI) for each detection of p_0 relative to p_1 .

ask the question of whether there is evidence that the probability sample is drawn from a uniform probability distribution. We sort the probabilities of $p_0 < p_1$ for the ten stars in our study, and plot these versus a uniform probability distribution. Figure 11.19 shows the cumulative probability distribution of the sample versus the measured probabilities. If the distributions of p_0 and p_1 are statistically consistent for the entire sample, then we expect that ten measured probabilities of $p_0 < p_1$ will be consistent with being drawn from a uniform probability distribution. We apply the K-S test to the sample, finding a maximum distance of -0.2 for a sample size of 10, giving a probability that this is drawn from a uniform distribution of 28%. We view this as indicating that the distribution of $p_0 < p_1$ probabilities is likely drawn from a uniform distribution; i.e. that the sample as a whole is consistent with $p_0 = p_1$ for all planets.

Similar analyses have been conducted for the single systems CoRoT-2 (Bruno et al., 2016) and CoRoT-7 (Barros et al., 2014), and more general discussions appear in Oshagh et al.

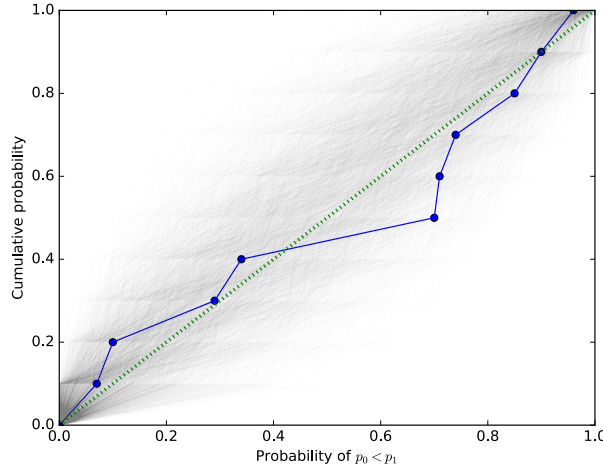


Figure 11.19: Cumulative probability distribution for the probability that $p_0 < p_1$ for the ten stars in our sample (blue points). The light grey lines show 3000 Monte Carlo simulations of probabilities drawn from a uniform distribution between zero and one. The green curve shows a uniform probability distribution.

(2013) and Csizmadia et al. (2013). The main differences between this work and others is that we explicitly use the ingress and egress durations to measure the true planet radii in the presence of bright or dark regions on the stellar surface.

This work echoes Csizmadia et al. (2013) – in particular, we found that fixing the limb-darkening parameters to their theoretical values for several systems introduced artificial constraints on the impact parameter and p_1 , occasionally producing apparent discrepancies where $p_0 \neq p_1$, which become consistent once the limb-darkening parameters are allowed to float. We encourage users of this light curve parameterization to fit for the limb-darkening parameters whenever possible, though we note the exceptionally good fit to TrES-2 using the quadratic limb-darkening parameters of (Magic et al., 2015).

We also note the importance of asteroseismic constraints on the orbital parameters for several systems. The asteroseismic stellar density provides us with an independent measurement of $a/R_\star$, which is otherwise degenerate with i_o, p_0 and the limb-darkening parameters.

Bright TESS targets may also be amenable to asteroseismic density measurements, and therefore good candidates for this self-contamination analysis. Alternatively the stellar density can be measured to high precision in multi-planet systems from the planet periods and transit durations, which will be valuable for dim stars like TRAPPIST-1.

Diminished limb-darkening in the infrared promises that *Spitzer* and JWST observations of transiting exoplanets will be interesting subjects for analysis with the self-contamination analysis. Ground-based follow-up may also be a fruitful means of detecting the affects of stellar activity on transiting exoplanet light curves, especially with the high precision and time resolution enabled by holographic diffusers (see e.g. Morris et al., 2018g; Stefansson et al., 2017).

11.7 Conclusions

We have presented a reparameterization of the transit light curve of Mandel & Agol (2002) which splits the original “ p ” parameter into two parameters: $p_0 = R_p/R_\star$ which defines the planet radius, and $p_1 \approx \sqrt{\delta}$ which defines the transit depth. This parameterization allows the transit model to account for significant contamination by bright or dark active regions on the stellar surface, or significant planetary oblateness in the planet’s direction of motion. The resulting constraint on $p_0 = R_p/R_\star$ is more accurate in the presence of stellar activity (and usually less precise).

We fit the light curves of several transiting planets to study the photospheric inhomogeneities of their host stars, see Table 11.1. We report $p_0 \approx p_1$ (no significant detection of self-contamination) for *Kepler* light curves of TrES-2, HAT-P-7, TRAPPIST-1 and *Spitzer* observations of GJ 1214. We find that the uncertainties on p_0 are typically an order of magnitude larger than p_1 , consistent with estimates of the noise (Appendix C). We find little evidence for transit depth dilution due to occulted starspots ($p_0 > p_1$) for the well-studied spotted pair of host stars HAT-P-11 and Kepler-17, and we find weak evidence that the transiting planets of Kepler-412 and HD 80606 likely occult relatively bright regions of the stellar photosphere ($p_0 < p_1$). We can recover the reported oblateness of Kepler-39 b using

this parameterization, though its detection is not statistically significant. We note that in general the oblateness is likely degenerate with self-contamination – so the unusually large inferred oblateness may have an alternate explanation as being due to an inhomogeneous photosphere.

In the best cases we have studied in this paper, HAT-P-11b, Kepler-17b, and TrES-2b, we obtain sensitivity to self-contamination, ϵ at the 1-3% level (Table 11.1), which is close enough to the expected levels of contamination that we were unable to achieve a definitive detection. This ratio of precisions on p_0 range from 5–25 times the uncertainties on p_1 (Table 11.1) The main advantage, then, in measuring p_0 is to obtain the radius ratio of the planet to the star when the unknown contamination of the stellar flux is significant. The other circumstance which may favor measuring p_0 is when there is significant red noise which has a larger amplitude on the timescale of the transit than on the timescale of ingress/egress. Granulation noise tends to be strongly red, and thus will affect the measurement of the transit depth more strongly than the measurement of the ingress/egress duration.

With the James Webb Space Telescope (JWST) we expect to obtain much higher precision on p_0 due to the larger collecting area. As an example, the Trappist-1 system has ingress/egress durations of $\approx 2 - 5$ minutes, and when observed with NIRSPEC, we expect precisions of 2 – 5 seconds for the precision of these measurements. This will enable a measurement of p_0 comparable to the current precisions obtained with Spitzer for which multiple transits have been observed for each planet. Thus, we expect that JWST will yield constraints upon p_0 which will give accurate radius ratios for these planets to diagnose the contamination by starspots. We find our simulations with extremely high signal-to-noise (§11.4) demonstrate that the radius-ratio of the planet measured from p_0 can be recovered more accurately than the radius ratio measured from p_1 in the presence of star spot contamination, since p_1 is biased by the presence of star spots (although p_1 is measured more precisely).

We have shown that p_0 is degenerate with the limb-darkening parameters. As a result, this technique will work better at red wavelengths, where limb-darkening is less severe, than

in the blue. However, the contrast of starspots against the stellar photosphere diminishes as one observes at longer wavelengths as well, so this technique might be best-suited to observations in the red optical, where the spot contrast may be significant but the limb-darkening is weaker.

This technique is complementary to other starspot measurement techniques – it is sensitive to time-independent spots, though it provides a weaker signal than techniques like the flux deficit. The flux deficit technique – which measures variations in flux as a star rotates – has been applied to vast numbers of *Kepler* stars (Mathur et al., 2014; Notsu et al., 2013; Walkowicz & Basri, 2013). Or alternatively, spot distributions can be revealed by detailed modeling of individual spots throughout rotational modulation (Davenport et al., 2015), or via observations of spot occultations by transiting exoplanets (for example: Dai et al., 2018; Davenport, 2015a; Morris et al., 2017b; Sanchis-Ojeda & Winn, 2011; Wolter et al., 2009).

11.A Planet radius from the duration of ingress/egress

For a transiting exoplanet in a circular orbit, the transit duration from first through fourth contact is

$$T_{14} = \frac{P}{\pi} \sin^{-1} \left[\frac{R_{\star}}{a} \frac{\sqrt{(1+p_0)^2 - b^2}}{\sin i} \right], \quad (11.26)$$

and the duration from second through third contact is

$$T_{23} = \frac{P}{\pi} \sin^{-1} \left[\frac{R_{\star}}{a} \frac{\sqrt{(1-p_0)^2 - b^2}}{\sin i} \right], \quad (11.27)$$

where $p_0 = R_p/R_{\star}$, P is the orbital period, b is the impact parameter, i is the planet's orbital inclination, and $a/R_{\star}$ is the scaled orbital semi-major axis (Winn, 2010c). We can invert these relations to find the planet-to-stellar radius ratio as a function of the transit durations,

$$\frac{R_p}{R_{\star}} = \frac{1}{2} \left(\left[\left[\frac{a}{R_{\star}} \sin \frac{\pi T_{14}}{P} \sin i \right]^2 + b^2 \right]^{1/2} - \left[\left[\frac{a}{R_{\star}} \sin \frac{\pi T_{23}}{P} \sin i \right]^2 + b^2 \right]^{1/2} \right). \quad (11.28)$$

We can get a sense for the scaling of the terms in this equation by simplifying to the case where $i = 90^\circ$, $b = 0$ and $T_{14}, T_{23} \ll P$ using the small angle approximation,

$$\frac{R_p}{R_\star} \sim \frac{\pi}{2P} \frac{a}{R_\star} (T_{14} - T_{23}). \quad (11.29)$$

The constraint on the planetary radius ($p_0 = R_p/R_\star$ in our reparameterization) primarily comes from the difference between the durations of first-through-fourth contact and second-through-third contact.

11.B Limiting cases: Extreme spot distributions

In Sections 11.4.1 and 11.4.2 we assumed that the starspots had the same contrast as sunspots, $c = 0.7$. In this section, we revisit those toy-model analyses with more extreme spot contrasts, by setting the contrast to that of sunspot umbrae, $c = 0.2$.

First we simulate a dense band of spots with contrast $c = 0.2$ centered on the stellar equator – see Figure 11.20. The self-contamination parameter $\epsilon = 1 - (p_1/p_0)^2 = -0.598^{+0.014}_{-0.032}$ in this limiting case.

Next we simulate a pair of polar spots that extend almost all the way from the pole to the edge of the transit chord, with contrast $c = 0.2$ – see Figure 11.21. The self-contamination parameter $\epsilon = 0.419^{+0.011}_{-0.015}$ in this case.

Thus one might expect ϵ to vary roughly on $-0.5 \lesssim \epsilon \lesssim 0.5$ for extreme self-contamination due to occulted or unocculted starspots.

11.C Uncertainties

Using the estimates by Carter et al. (2008) for the uncertainties on the ingress and total duration given Fisher information analysis of a piecewise-linear transit model, we can estimate the uncertainties on p_0 and p_1 . For flux observations with independent Gaussian uncertainties σ , for a transit with depth δ , ingress duration τ , mid-ingress to mid-egress duration T ,

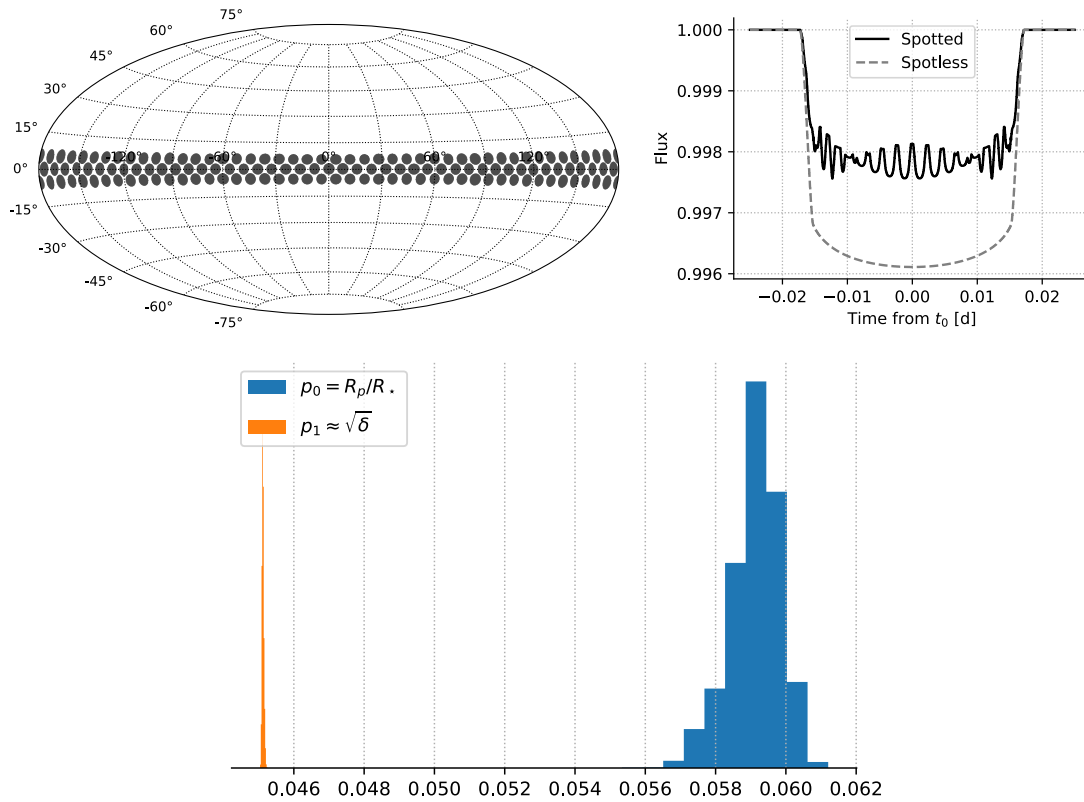


Figure 11.20: *Left*: Hypothetical spot map for a dense band of spots in an active latitude at the stellar equator, with contrast $c = 0.2$. *Right*: Transit of a small planet across the star with the spot map on the left, with $i_o = 90^\circ$ and $\lambda = 0^\circ$ and other parameters set to those of TRAPPIST-1 g (black curve), compared with the transit of the same system without spots (gray dashed curve). At lower S/N, or for different spot geometries, the bottom of the spotted transit might simply appear flat and relatively shallow, but the ingress and egress durations are the same for both light curves, allowing us to recover the true planet radius from timing, independent of the transit depth which is affected by starspots.

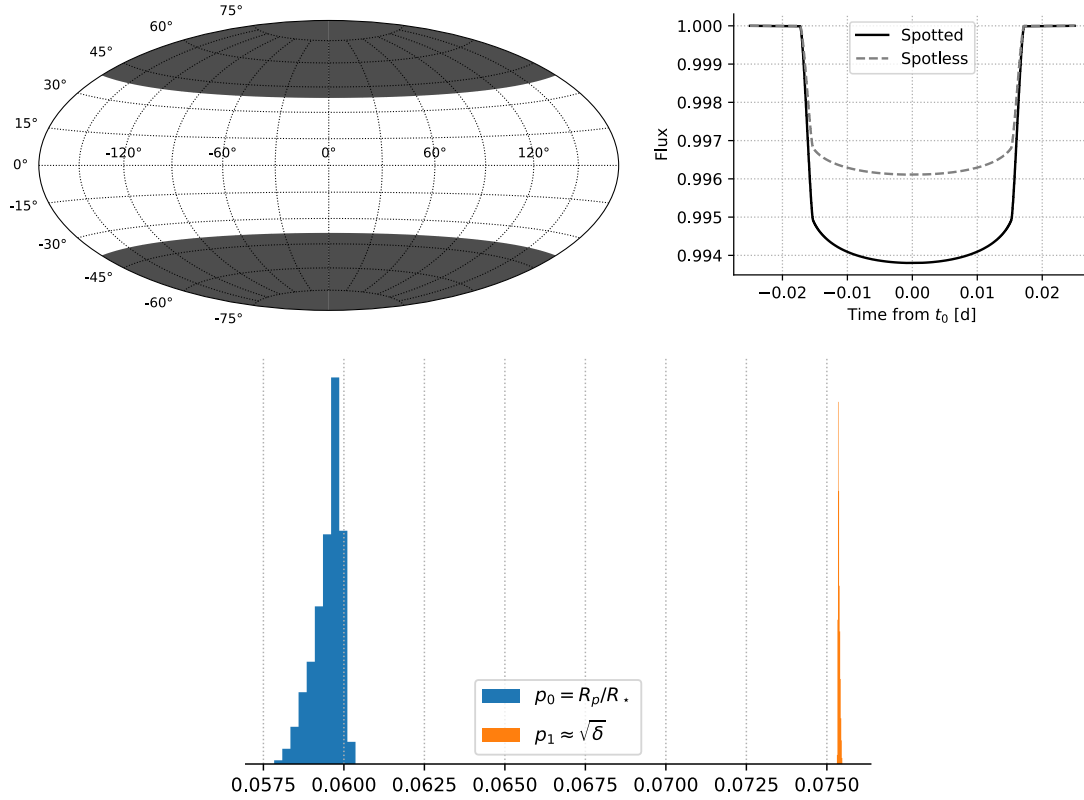


Figure 11.21: *Left*: Hypothetical spot map for dark polar spots that cover much of the star except the transit chord, with contrast $c = 0.2$. *Right*: Transit of a small planet across the star with the spot map on the left, with $i_o = 90^\circ$ and $\lambda = 0^\circ$ and other parameters set to those of TRAPPIST-1 g (black curve), compared with the transit of the same system without spots (gray dashed curve). At lower S/N, or for different spot geometries, the bottom of the spotted transit might simply appear flat and relatively shallow, but the ingress and egress durations are the same for both light curves, allowing us to recover the true planet radius from timing, independent of the transit depth which is affected by starspots.

defined as

$$T \equiv 2\tau_0\sqrt{1-b^2} \quad (11.30)$$

$$\tau \equiv 2\tau_0 \frac{p_0}{\sqrt{1-b^2}} \quad (11.31)$$

$$(11.32)$$

where τ_0 is

$$\tau_0 = \frac{P}{2\pi} \frac{R_\star}{a}, \quad (11.33)$$

with uncertainties on τ and T given by

$$\sigma_\tau \approx \frac{\sigma}{\delta T} \sqrt{\frac{6\tau}{\Gamma}}, \quad (11.34)$$

$$\sigma_T \approx \frac{\sigma}{\delta T} \sqrt{\frac{2\tau}{\Gamma}}, \quad (11.35)$$

where Γ is the sampling rate (if N photometric measurements are taken uniformly over a total observing time T_0 , then $\Gamma = N/T_0$), so Γ^{-1} is the time between the start of successive exposures. Rearranging, we find

$$p_0 = \frac{\tau T}{4\tau_0^2}, \quad (11.36)$$

and therefore the uncertainty, σ_{p_0} , is given by

$$\left(\frac{\sigma_{p_0}}{p_0}\right)^2 = \frac{T}{Q^2} \left[\frac{6+\eta}{\tau}\right] + \left(\frac{\sigma_{\tau_0}}{\tau_0}\right)^2 \quad (11.37)$$

in the limit of $\tau \ll T$, where $\eta = T/(T_0 - T - \tau)$ is the ratio of the duration of photometric measurements in-transit to out-of-transit ($\eta \rightarrow 0$ for perfectly known out-of-transit flux). From this equation we see conclusions we discussed elsewhere in this work, for example, if τ_0 is known imprecisely by lack of prior constraints on the stellar density or transit impact parameter, then p_0 will have large uncertainties.

If we know the stellar density/impact parameter well ($\sigma_{\tau_0} \rightarrow 0$) and measure the out-of-transit flux well ($\eta \rightarrow 0$), then

$$\frac{\sigma_{p_0}}{p_0} = \frac{\sigma 6^{1/2}}{p_1^2 (\Gamma \tau)^{1/2}} \propto \frac{(1-b^2)^{1/4}}{p_0^{1/2}}, \quad (11.38)$$

i.e., we obtain higher precision on p_0 for systems with higher impact parameters, for which the ingress/egress durations are longer.

The uncertainty on p_1 can be computed from σ_δ given $p_1^2 \approx \delta$, so

$$\sigma_{p_1} = \frac{\sigma_{p_1^2}}{2p_1} \quad (11.39)$$

thus

$$\frac{\sigma_{p_1}}{p_1} = \frac{\sigma}{2p_1^2(\Gamma T)^{1/2}}. \quad (11.40)$$

Comparing the fractional uncertainties on p_0 (eqn 11.38) and p_1 (eqn 11.40), we find:

$$\frac{\sigma_{p_0}}{p_0} \left(\frac{\sigma_{p_1}}{p_1} \right)^{-1} = 24^{1/2} \left(\frac{T}{\tau} \right)^{1/2} = 15.5(1 - b^2)^{1/2}(p_0/0.1)^{-1/2}. \quad (11.41)$$

Consequently, the fractional uncertainty on p_0 tends to be $\approx$ an order of magnitude larger than p_1 ; this can be exacerbated further by strong limb-darkening which causes the depth of transit at ingress and egress to be shallower than the mean transit depth.

The foregoing equations assume uncorrelated, time-independent white noise, which will not be the case for high precision measurements at which point the uncertainties will be dominated by stellar granulation variability.

Chapter 12

ROBUST TRANSITING EXOPLANET RADII: REVISITING TRAPPIST-1

In the previous chapter we developed and applied the “self-contamination” technique used to analyze transit light curves of planets which occult spotted stars. The self-contamination simply modifies the Mandel & Agol (2002) transit light curve equation such that the transit depth is disconnected from the ratio of planet to stellar radii. The depths of transit light curves may be contaminated by the presence of starspots, bright or dark, occulted or unocculted, without affecting the radius determination.

In this chapter, we apply the self-contamination technique to a star we have already visited with great interest in this dissertation: TRAPPIST-1. As we explored in Chapter 9, bright spots may be required to explain the *Kepler* and *Spitzer* photometry of TRAPPIST-1. Knowing the true properties of the stellar activity of TRAPPIST-1 is key to understanding the transmission spectra of its exoplanets. Thus in this chapter, we use recent *Spitzer* transit observations of several TRAPPIST-1 exoplanets to probe the stellar surface inhomogeneities of TRAPPIST-1 with the self-contamination technique.

This chapter was first published in the *Astrophysical Journal Letters* (Morris et al., 2018h).

12.1 Introduction

TRAPPIST-1 is a system of seven approximately Earth-sized planets orbiting an M8V star (Delrez et al., 2018a; Gillon et al., 2016, 2017; Luger et al., 2017b). It is the subject of much hope for characterization with the James Webb Space Telescope (Barstow & Irwin, 2016; Batalha et al., 2018; Gillon et al., 2016; Morley et al., 2017), though stellar activity may

complicate efforts to characterize the exoplanets (Rackham et al., 2018).

The photosphere of TRAPPIST-1 may be described as a mixture of several photospheric components with different temperatures, according to Hubble Space Telescope (HST) spectra in the analysis by Zhang et al. (2018). Roettenbacher & Kane (2017) showed that the spots evolve on the apparent rotation timescale, and comparison of *Kepler* and *Spitzer* time-dependent modulation independently suggests that there are bright (hot) spots in the photosphere (Morris et al., 2018b). These hot spots appear to be correlated with strong flares in the K2 light curve, which calls into question the association of spot variability with stellar rotation. Recent analysis of the broadband transmission spectra of the TRAPPIST-1 planets yields a non-detection of spectral contamination by stellar activity (upper limit of 200 – 300 ppm in the spectra of planets b and d Ducrot et al., 2018).

In this work, we analyze the *Spitzer* transit light curves of TRAPPIST-1 with the “self-contamination” technique of Morris et al. (2018h). The self-contamination method fits the transit light curves of planets orbiting spotted stars, allowing the host star to be a source of contaminating positive or negative flux which influences the transit depths. Accounting for the contamination potentially allows for robust inference of the exoplanet radii from the transit ingress and egress durations, even in the presence of extreme starspot distributions, like those predicted for TRAPPIST-1 by some (Rackham et al., 2018; Zhang et al., 2018). Crucially, unlike spot occultation observations (see e.g. Morris et al., 2017b; Sanchis-Ojeda & Winn, 2011), the self-contamination technique can detect nearly-homogeneous distributions of spots throughout the transit chord of an exoplanet, or surrounding the transit chord of an exoplanet, so long as the transit chord has a different mean intensity than the rest of the photosphere (Morris et al., 2018h).

12.2 Observations

We analyze new, 2018 *Spitzer* observations of the TRAPPIST-1 planets including 29, 28, 16, 9, 8, 6, and 5 transits of planets b, c, d, e, f, g, and h; in *Spitzer* Channel 1 ($3.6\mu\text{m}$) for planet b and Channel 2 ($4.5\mu\text{m}$) for the others. Further detailed analysis of these data will

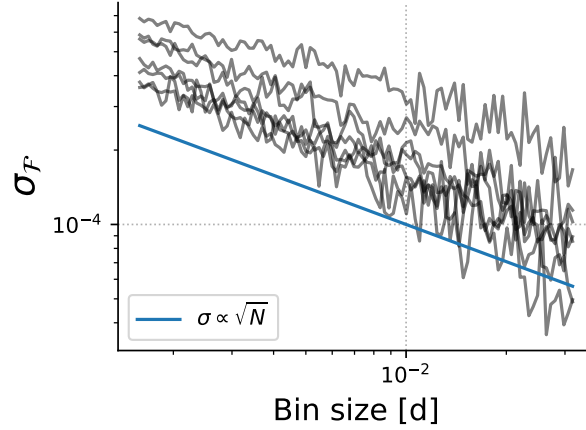


Figure 12.1: Lack of correlated noise in the detrended light curves of each planet (black) compared with the expectation for Gaussian, uncorrelated errors (blue).

be presented in Ducrot et al. (2018, in prep.).

We detrend each transit light curve with a linear combination of: (1) the stellar FWHM in the $\hat{x}$ and $\hat{y}$ directions; (2) the x and y pixel coordinates of the stellar centroid; (3) the maximum-likelihood transit model of Delrez et al. (2018a) using most of their orbital parameters but allowing the mid-transit times to float; and (4) a Matérn-3/2 kernel Gaussian process (Foreman-Mackey et al., 2017). We vary the weights each of these observational basis vectors and fit for the mid-transit time with Markov Chain Monte Carlo (MCMC) to produce detrended light curves (Foreman-Mackey et al., 2013). The mid-transit times must be allowed to float to account for transit timing variations.

The correlated noise in the final light curve residuals is negligible after removing the Gaussian process. We verify that the noise bins down as $\propto N^{-1/2}$ by binning the noise into successively larger time bins and measuring the standard deviation of the residual flux in each bin. We find that the photometric scatter bins down to the power of -0.55 ± 0.08 , consistent with uncorrelated Gaussian noise, see Figure 12.1. This is a weak independent confirmation that there are no significant departures from independent Gaussian uncertainties on the

residual fluxes after our detrending and transit model analysis, implying a lack of occultations of bright or dark regions in the *Spitzer* transit light curves. In addition, we performed Anderson-Darling tests of the residuals of the *Spitzer* transit light curves and find that the residuals are consistent with normally distributed noise.

We then use the maximum-likelihood mid-transit times to produce phase-folded light curves of each of the planets, with the planet orbital periods from Delrez et al. (2018a). We fit the phase-folded light curve with the Morris et al. (2018h) transit light curve parameterization, which allows for significant contamination by dark starspots or regions inside or outside of the transit chord. We fit for the $p_0 = R_p/R_\star$ (the true planet radius), $p_1 \approx \sqrt{\delta}$ (where the observed transit depth is δ), quadratic limb-darkening parameters, orbital inclination, mid-transit time, and semimajor axis.

We place Gaussian priors on the semi-major axis based on the simultaneous analysis of all transits from Ducrot et al. 2018 (in prep.), which yield $\rho_\star = 50.7 \pm 2.2\rho_\odot$ (which is related to the semi-major axis of each planet by Kepler’s law), and we place Gaussian priors on the limb-darkening parameters from the global analysis which assume interpolated limb-darkening parameters from Claret et al. (2013): $(u_1, u_2) = (0.171 \pm 0.019, 0.24 \pm 0.02)$ in *Spitzer* Channel 1 (3.6 μm) and $(u_1, u_2) = (0.147 \pm 0.019, 0.20 \pm 0.02)$ in Channel 2 (4.5 μm). For each planet, we also place a prior on the radius of the planet p_0 such that when combined with the maximum-likelihood planet mass derived by Grimm et al. (2018), the bulk density of the planet is less than or equal to the density of iron. This last prior only informed the posterior distributions of p_0 for planets g and h.

12.3 Results

The results of self-contamination analysis involve comparison of the $p_0 = R_p/R_\star$ – the true radius of the planet – and $p_1 \approx \sqrt{\delta}$ – the apparent transit depth (Morris et al., 2018h). Finding $p_0 < p_1$ may suggest that a relatively bright chord of the star is being occulted, while $p_0 > p_1$ may suggest that a dark chord is being occulted, or that the planet is oblate.

In Figures 12.2 and 12.3 we show the maximum-likelihood transit models, and the poste-

rior distributions for p_0 and p_1 for each planet. For all planets, we find insignificant evidence for $p_0 \neq p_1$. The most significant discrepancy is for planet g, which is still $2\text{-}\sigma$ consistent with the null hypothesis ($p_0 = p_1$). For planet b, the planet with the most-sampled light curve, we measure self-contamination $\epsilon = 1 - (p_1/p_0)^2 = 0.22 \pm 0.10$.

Planet g has $p_0 < p_1$ at 94% confidence for a contamination parameter $\epsilon = 1 - (p_1/p_0)^2 = -0.35 \pm 0.15$, though the improvement in the fit compared to one where $p_0 = p_1$ is only $\Delta\chi \approx 5$, providing insignificant evidence for occultation of TRAPPIST-1 g by a bright latitude. If more data confirm that $p_0 < p_1$, the radius of the planet (from, for example, Delrez et al., 2018a) may be somewhat overestimated in the literature. The posterior distribution for p_0 has a mode near $p_0 = R_p/R_\star = 0.07$, which corresponds to the limit where the planet would require the bulk density of iron. We emphasize that this result is statistically insignificant, and more observations by *Spitzer* or with JWST are needed to confirm or falsify the apparently small radius of planet g.

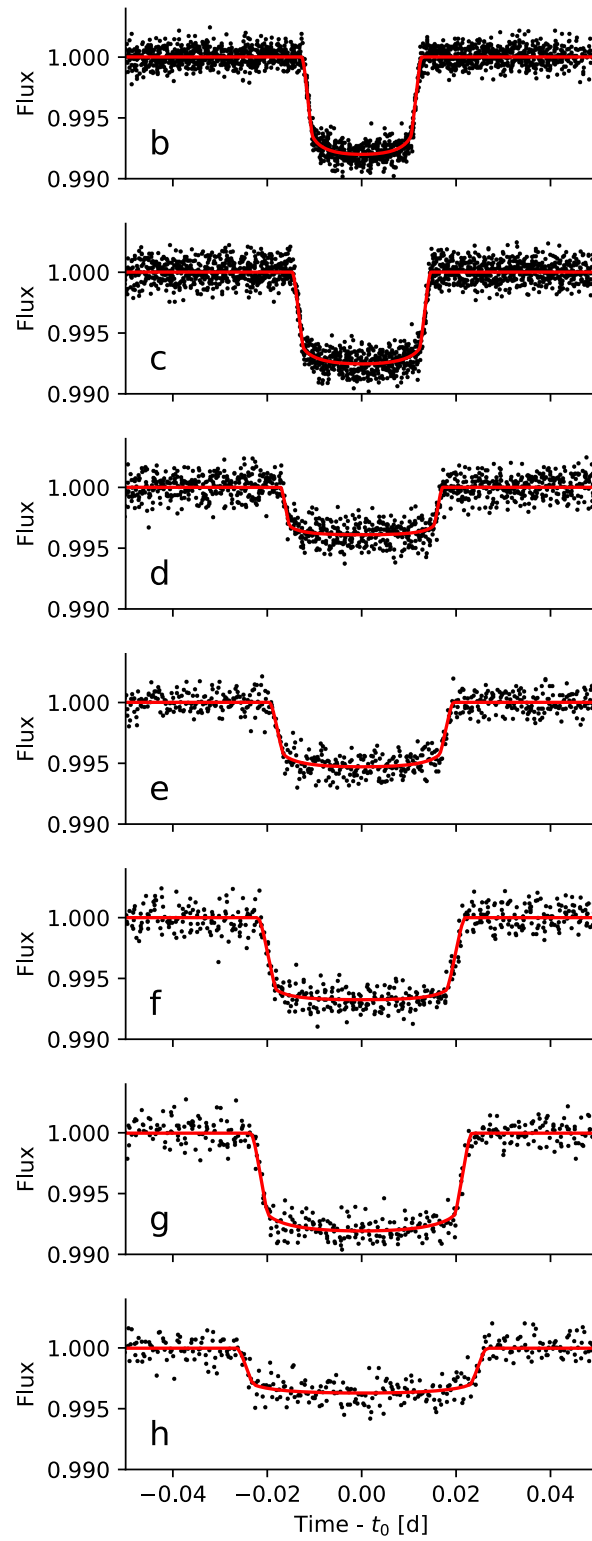


Figure 12.2: Maximum-likelihood transit models and detrended *Spitzer* light curves for each of the TRAPPIST-1 planets.

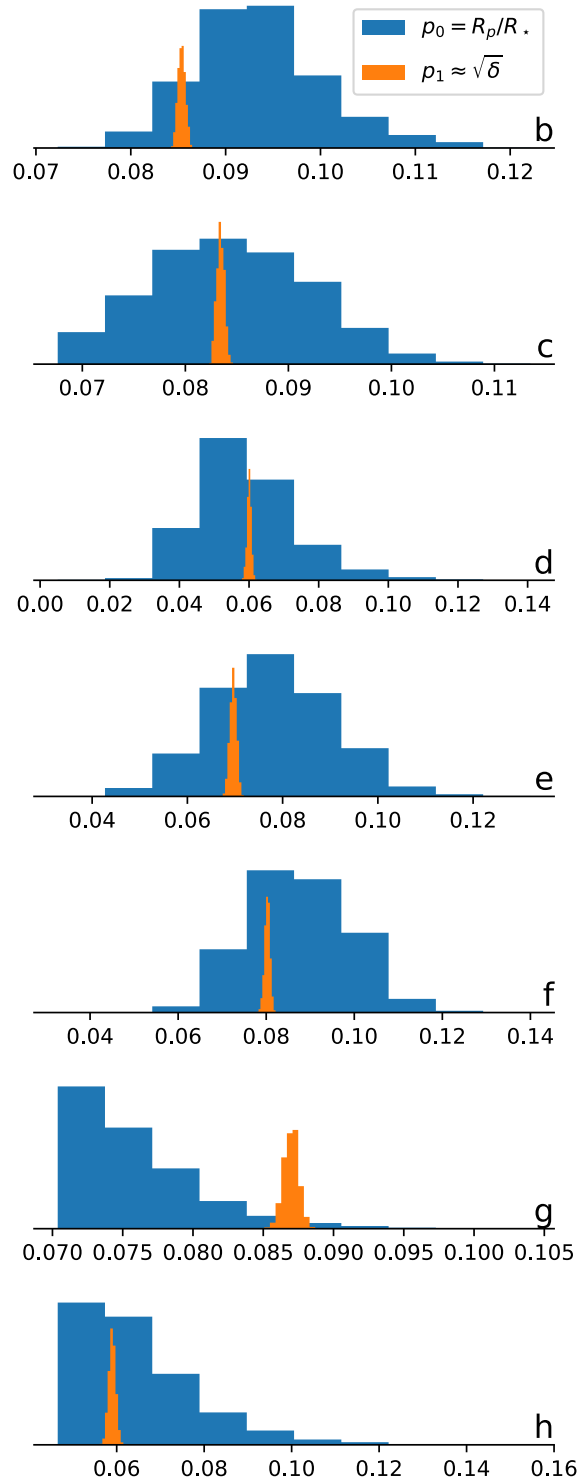


Figure 12.3: Posterior distributions for p_0 and p_1 for planets b through h. All of the planets present $p_0 \approx p_1$, suggesting that the photospheric intensity within transit chords of the planets is roughly representative of the rest of the stellar photosphere.

At present the observational uncertainties are too large to place robust constraints on whether or not significant spot distributions contaminate the *Spitzer* transit light curves using the self-contamination technique. This result is in agreement with the recent analysis by Ducrot et al. (2018), who find insufficient evidence for strong contamination of the broad-band spectrum of the TRAPPIST-1 planets by stellar activity. The lack of apparent spot contamination is at odds with the large spot coverage upper-limits inferred by Rackham et al. (2018); Zhang et al. (2018). Short-cadence JWST/NIRSpec observations of the TRAPPIST-1 planets will be ideal for placing more informative constraints on possible self-contamination by stellar activity on TRAPPIST-1 (Batalha et al., 2018).

Perhaps an even stronger non-detection of spots than the lack of self-contamination is the lack of active region occultations, implying an apparently facula/spot-free surface of TRAPPIST-1 within the transit chords. This spot-free region in the photosphere may seem to be at odds with the literature, which suggests that most late type M dwarfs are chromospherically active, e.g., when observed via $H\alpha$ emission (West et al., 2008, 2015). However, $H\alpha$ observations of TRAPPIST-1 in particular show $\log L_{H\alpha}/L_{\text{bol}} = -4.70$ (Reiners et al., 2018), making this star appear relatively inactive even among late M dwarfs (see for example Figure 7 of West et al. 2015). We note that chromospheric activity, which influences the FUV and Ly- α environments of these potentially habitable worlds, is not constrained by these observations – we are only probing the near-IR spot coverage with the self-contamination technique.

If we assume that we are viewing TRAPPIST-1 equator-on and that the orbits are aligned with the stellar spin axis ($i_{\star} = 90^{\circ}$ and $\lambda = 0^{\circ}$), then the planets should occult latitudes from the equator up to 30° in one hemisphere – which is perhaps a surprisingly small portion of the stellar hemisphere, see Table 12.1 for the range of latitudes occulted by each planet. Active latitudes on young M dwarfs have been observed via Doppler imaging of HK Aqr and RE 1816 +541 (Barnes & Collier Cameron, 2001). HK Aqr’s spot distribution peaks near 30° latitude and most spots on RE 1816 +541 were found at latitudes $> 30^{\circ}$ – making most of those observed spots just out-of-reach of the transit chords of the TRAPPIST-1 planets.

However, these stars are much younger and hotter than the inferred age and temperature for TRAPPIST-1 (Burgasser et al., 2015), and may not be fully convective, making it unclear if it is sensible to compare them with TRAPPIST-1.

Perhaps one way to place spots on the star without affecting the transit light curves is to place the spots at or near the poles – it is also possible that there is a spot at one rotational pole which is hidden from view due to stellar inclination. We expect polar magnetic active regions on late M stars as they have been observed widely with Doppler imaging (see e.g. Morin et al., 2010, 2008; Strassmeier, 2002). Such polar spots may be long lived; for example, the observed polar spot on the fully convective dwarf V374 Peg is stable on one-year timescales (Morin et al., 2008). However, these will lead to rotational variability, which is constrained by the K2 dataset. If the correlation between flares and spot brightening in the K2 data is confirmed (Morris et al., 2018b), then this may suggest that spots are not responsible for the quasi-periodic brightening.

Finally, we confirm the non-detection of spot occultations in the transit light curve by modelling the light curve of TRAPPIST-1 b with STSP (Hebb et al. 2018¹), assuming the temperature contrast of Rackham et al. (2018) ($T_{\text{phot}} = 2500$ K, $T_{\text{spot}} = 2064$ K; Spitzer IRAC-1 contrast $c = 0.75$). We vary the radius of the spot to place an upper-limit on the plausible size of occulted spots that may go undetected in the transit photometry – see Figure 12.4. We find that spots with radii $R_{\text{spot}}/R_{\star} < 0.04$ induce spot occultations with amplitudes $\lesssim 3\sigma$ discrepant with the observed *Spitzer* light curve of TRAPPIST-1 b. This implies that spots within the transit chord should have physical radii of $\lesssim 3.3$ Mm. For comparison with the Sun, the smallest sunspots are roughly 1.75 Mm in radius (Solanki, 2003). Thus it is still possible that very small-scale magnetic activity is occurring within the transit chords, to which we are still insensitive with *Spitzer*’s photometric precision.

¹ Open source, available online: <https://github.com/lesliehebb/stsp>

Planet	Lower [°]	Upper [°]
b	4 ± 4	14 ± 4
c	4 ± 5	13 ± 5
d	1 ± 6	8 ± 6
e	10 ± 3	18 ± 3
f	15 ± 2	25 ± 3
g	19 ± 2	30 ± 2
h	19 ± 2	27 ± 3

Table 12.1: Stellar latitude ranges occulted by each planet, assuming the stellar inclination is $i_\star = 90^\circ$ and the projected spin-orbit angle is $\lambda = 0^\circ$, given the impact parameters and planetary radii from Delrez et al. (2018a).

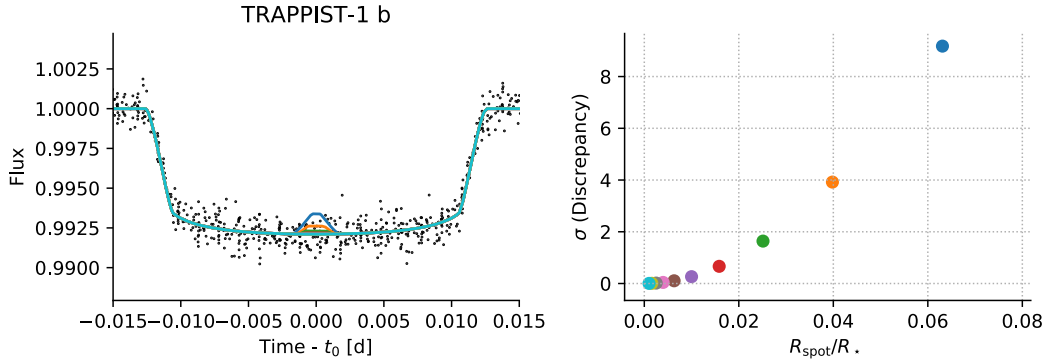


Figure 12.4: *Left*: STSP model light curves occulting spots of various radii and the *Spitzer* photometry of TRAPPIST-1 b. *Right*: The corresponding discrepancy between the data and the STSP model for each radius. We find that the photometry is insensitive to spots smaller than $R_{\text{spot}}/R_\star < 0.04$, which is similar in size to the smallest sunspots – so small-scale magnetic activity may still be lurking undetected within the transit chords.

12.4 Conclusions

We present a self-contamination analysis of the *Spitzer* transit light curves of the TRAPPIST-1 planets, using the transit light curve parameterization of Morris et al. (2018h). We find insufficient evidence for contamination by bright or dark spots inside or outside of the transit chord using the self-contamination technique of Morris et al. (2018h), measuring contamination $\epsilon = 0.22 \pm 0.10$ for planet b. This is a tighter constraint on the contamination than measured with *Kepler* photometry in Morris et al. (2018h). This analysis suggests that the mean photosphere is similar to the photosphere occulted by the TRAPPIST-1 planets. However, we cannot exclude the possibility that small-scale magnetic activity analogous in size to the smallest sunspots may be occurring within (or outside) of the transit chords given the photometric precision of the *Spitzer* observations.

Chapter 13

THE LIMITS OF TRANSIT CHARACTERIZATION WITH JWST/NIRSPEC DUE TO STELLAR VARIABILITY: THE CASES OF TRAPPIST-1, KEPLER-296 AND KEPLER-62

In the previous Parts, we built an array of tools for understanding stellar magnetic activity, and variability due to granulation and oscillations. In the previous two Chapters (11-12), we introduced and implemented a novel technique for measuring the radii of transiting exoplanets in the presence of stellar activity. In this Chapter, we synthesize all of the efforts cataloged in this thesis towards one goal: characterizing a small sample of potentially habitable exoplanets with active host stars.

The James Webb Space Telescope stands to revolutionize observations of transiting exoplanets, with nearly a factor of seven more photon-collecting area than the Hubble Space Telescope. Its high throughput observing modes, such as the NIRSpec detector with the Prism, promise tremendous photon fluxes enabling precision studies of transiting exoplanets. However, one major obstacle looms over the fantastic feats we hope to achieve with James Webb: the time-dependent and chromatic variations in brightness of the host stars. In this Chapter, we present case studies of three systems with potentially habitable worlds, and examine the limits of exoplanet characterization imposed by their host stars.

This chapter is in preparation for submission to the *Astronomical Journal*.

13.1 Introduction

The James Webb Space Telescope (JWST) will offer an early chance to characterize small worlds, through measurements of their bulk densities, and transmission spectroscopy of their atmospheres. The integration times required to produce transmission spectra will be highly

expensive, so it's likely that only a handful of small planets will be observed in transmission by JWST with sufficient signal-to-noise to characterize their atmospheres and densities (Cowan et al., 2015).

We can measure densities of some transiting worlds in multiplanet systems with transit timing variations (TTVs) (Agol et al., 2005; Holman & Murray, 2005). This technique allows us to measure the masses of planets in multi-planet systems by via their gravitational influence on each other, causing some transits to appear earlier than expected, and others later. The variations in transit times are related to the masses and eccentricities of each planet, enabling us to measure exoplanet masses, relative to their star, with photometry alone. TTVs are especially promising for measuring the masses of small, potentially habitable worlds which are too small and far from their stars to impart measurable radial velocities on their host stars. Recent work by Agol & Deck (2016a,b); Deck et al. (2014) makes forward-modeling of TTVs computationally efficient enough to sample for planet masses and eccentricities with Monte Carlo techniques.

We can measure the atmospheric compositions of exoplanets with transmission spectroscopy. At wavelengths where an exoplanet's atmosphere is opaque, the planet will appear larger in transit than at wavelengths where the atmosphere is transparent, allowing us to measure an absorption spectrum of the planet's atmosphere from measurements of the wavelength-dependent transit depth. JWST will be the first telescope capable of measuring transmission spectra of small, rocky exoplanet atmospheres. Fortunately, transit timing measurements can be derived from any transit observations, including transmission spectroscopy, for example.

In this work, we focus on the potential for characterization of three pairs of planets: TRAPPIST-1 b and c, Kepler-62 e and f, and Kepler-296 e and f. TRAPPIST-1 is an M8 dwarf with at least three habitable, Earth-sized planets (Delrez et al., 2018a; Gillon et al., 2016, 2017). Kepler-62 is a K2 dwarf with $\sim$ one habitable, Earth-sized planet (Borucki et al., 2013), and Kepler-296 is an M1 star with five planets and an M4 companion (Barclay et al., 2015).

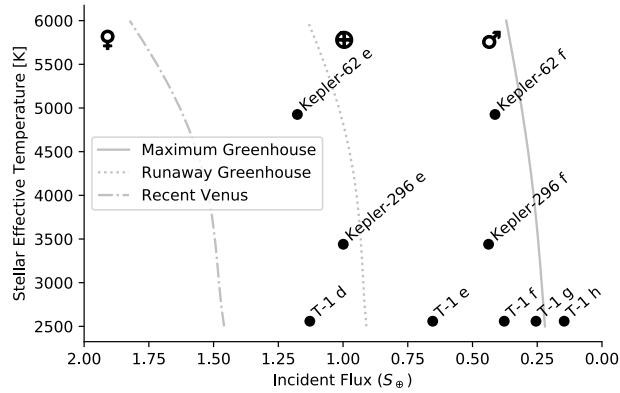


Figure 13.1: Habitable zone planets under consideration for mass measurements with TTVs from JWST (Borucki et al., 2013; Delrez et al., 2018a). We also mark the limits of the habitable zone defined by Kopparapu et al. (2013).

Stellar atmospheres introduce a variety of challenges to transit characterization (Rackham et al., 2018; Zhang et al., 2018). Rotational variability due to starspots and “microvariability” as observed on TRAPPIST-1 by Delrez et al. (2018a) are sources of astrophysical noise with amplitudes greater than or similar to the photon-noise on each target. Any analysis of the transit times and transmission spectra of the planets of these stars must account for the time- and wavelength-dependent variability of heterogeneous stellar atmospheres.

13.2 Targets

13.2.1 TRAPPIST-1

TRAPPIST-1 is a M8V host to seven small planets in a resonant chain (Delrez et al., 2018a; Gillon et al., 2016, 2017; Luger et al., 2017b). Dynamical simulations show that most of the planets are consistent with Earth-like masses (Quarles et al., 2017). The habitability of the worlds in the TRAPPIST-1 system is up for debate – the inner planets suffer from dessication when the star is young and hot (Bolmont et al., 2017; Luger et al., 2015). The star is active, and its flares and UV activity may be hazardous to life on the planets (Davenport, 2017;

Roettenbacher & Kane, 2017; Vida et al., 2017).

Characterization of the rotation period and stellar activity of TRAPPIST-1 has proven beguiling (Morris et al., 2018b; Rackham et al., 2018; Roettenbacher & Kane, 2017; Zhang et al., 2018), though its age is well constrained (7.6 ± 2.2 Gyr) (Burgasser & Mamajek, 2017).

13.2.2 Kepler-296

Kepler-296 is a M1V host to five transiting planets, and it is also orbited by a M4V companion (Barclay et al., 2015; Lissauer et al., 2014; Torres et al., 2015).

13.2.3 Kepler-62

Kepler-62 is a K2V host to five transiting planets (Borucki et al., 2013). Planets e and f are potentially habitable. Kaltenegger et al. (2013) proposed these could be water planets. Shields et al. (2016) ran global climate models to show what atmospheric chemistry and orbital dynamics are necessary to maintain habitability for planet f. Tides are important to consider for habitability (Bolmont et al., 2014, 2015).

Unlike the TRAPPIST-1 planets, Kepler-62 f is far enough from its host to avoid desiccation in the hot, pre-main sequence phase, and could retain liquid water (Luger et al., 2015).

13.3 Simulated Observations

13.3.1 JWST Observing Mode: NIRSpec/Prism BOTS

JWST’s NIRSpec infrared spectrograph has a Bright Object Time Series (BOTS) observing mode, with the $1.6 \times 1.6''$ S1600A1 aperture and the prism/clear filter to collect spectra with resolution $R \sim 100$. The SUB512 subarray yields spectra with 512×32 pixels. The frame time, or the duration of an individual sample up-the-ramp, is 0.226 s.

Even with this short frame time, some pixels will be saturated by TRAPPIST-1 ($J=11.354$) for $N_{\text{group}} > 2$, where N_{group} is the number of frames per “group”. However, we should be

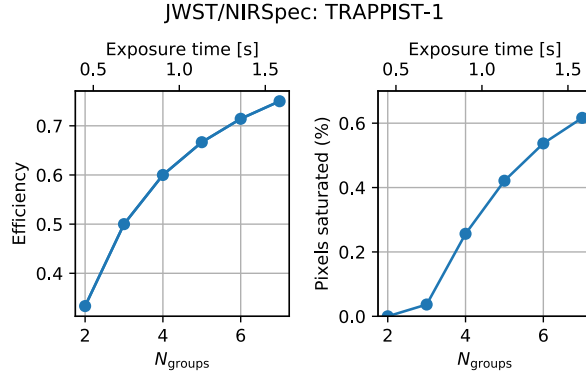


Figure 13.2: Observing efficiency for different NIRSpec configurations using the SUB512 subarray on TRAPPIST-1 ($J=11.354$).

able to measure the flux in those pixels with first 2-3 samples up-the-ramp of each group (see also Batalha et al., 2018). We therefore choose to simulate observations of TRAPPIST-1 with $N_{\text{group}} = 6$, which saturates $< 1\%$ of pixels, centered near $1.75 \mu\text{m}$. This observing strategy yields the on-sky observing efficiency 71.4%.

For the slightly dimmer Kepler-62 ($J=12.256$), we also choose to observe with $N_{\text{group}} = 6$, which is dim enough to avoid saturation. For the significantly dimmer Kepler-296 ($J=13.391$), we can manage to observe $N_{\text{group}} = 18$ without saturating the detector for observing efficiency of 90%.

13.3.2 IRTF Spectral Templates

We represent the host-star spectra with flux-calibrated infrared template spectra collected by Cushing et al. (2005) and Rayner et al. (2009) on the SpeX instrument on the NASA Infrared Telescope Facility (IRTF) (Rayner et al., 2003).

We can compute the number of photons received by JWST from the flux-calibrated IRTF spectra, f_{λ} , with units $\text{W m}^{-2} \mu\text{m}^{-1}$. For a telescope with aperture area A , with spectroscopic resolution elements of width $\Delta\lambda$, and exposure time Δt , the flux measured

Target	T_{eff}	Spectral	IRTF
	[K]	Type	Template
Kepler-296	3526	M2V	HD 95735
TRAPPIST-1	2511	M8V	Gl 752B
Kepler-62	4926	K2V	HD 3765

Table 13.1: Target stars for TTV observations with JWST, and NASA IRTF Spectral Library template stars that we use as their spectral analogs.

within each resolution element is:

$$f_{\lambda} = \frac{hc}{\lambda} \frac{N_{\text{template}}}{\Delta t A \Delta \lambda} \quad (13.1)$$

where N_{template} is the number of photons received from the template star. Solving for N_{template} ,

$$N_{\text{template}} = \frac{\lambda}{hc} \Delta t A \Delta \lambda f_{\lambda}. \quad (13.2)$$

The templates are observations of real stars with magnitude J_{template} , and we are interested in the counts received from a source with magnitude J_{target} , so the number of photons received from the target star N_{target} is

$$N_{\text{target}} = N_{\text{template}} 10^{\Delta J/2.5} \quad (13.3)$$

where $\Delta J = J_{\text{template}} - J_{\text{target}}$. The measured detector gain of the NIRSpec detectors is close to unity, so N_{target} describes the number of counts registered by the detector.

13.3.3 Starspots

The spot covering fraction of TRAPPIST-1 is an area of rapidly evolving literature, at present (Morris et al., 2018b; Rackham et al., 2018; Wakeford et al., 2019; Zhang et al., 2018). The stellar photosphere contains several temperature components, possibly including both dark and bright regions. We adopt the hypothetical scenario presented in Morris et al. (2018b),

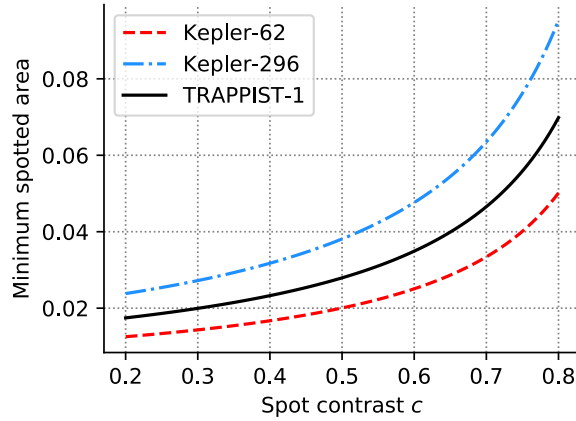


Figure 13.3: Approximate minimum spotted areas, approximated by the rotational modulation of each star in the *Kepler* or K2 light curves.

where there are a few bright (hot) spots. This model reproduces the apparent rotational variability in the *Kepler* band, and lack of corresponding variability in the *Spitzer* band. It is possible that in fact the star does not have bright spots and a rotation period of 3.3 d, in which case adopting the Morris et al. (2018b) model will produce the most conservative estimates in the uncertainties on the transit depths and times. We assume spots have the spectrum of the IRTF template K0V star HD 145675, and a surface distribution consistent with the spot positions and radii of Morris et al. (2018b).

The spot distribution of Kepler-62 is also unconstrained by the available observations. Given its similarities to the Sun in rotation period and spectral type, we assume a spot distribution like the Sun’s is appropriate for Kepler-62. Given its long apparent rotation period (36 days, Borucki et al. 2013), and the small total flux variations imparted by sunspots, we thus ignore the rotational modulation of spots on Kepler-62.

Covering fraction lower limit: Flux deficit

We measure the minimum spotted area on each of the three stars using the flux deficit technique (see e.g. Morris et al., 2017b). The minimum spotted area f_S on the observer-facing hemisphere is

$$f_S = (1 - \min(\mathcal{F}))(1 - c) \quad (13.4)$$

where $\mathcal{F}$ is the set of observed fluxes normalized to the maximum flux in the light curve, and c is the spot intensity contrast, such that spots with $c = 0$ are perfectly dark, and spots with $c = 1$ have the same intensity as the photosphere. f_S is a lower bound on the spotted area, because in the limit of many spots distributed isotropically about the stellar surface, each spot that rotates out of view is replaced by another spot rotating into view, and the rotational modulation is small.

It is presently unclear if there are trends in spot contrast with stellar effective temperature (Mancini et al., 2017), so we consider the minimum spotted area for each star over a range of plausible spot contrasts in Figure 13.3. For comparison, the sunspot umbral contrast is $c \sim 0.2$ and penumbral contrast is $c \sim 0.8$ (Solanki, 2003).

The flux deficit technique indicates that in the worst case – where spots have $c = 0.8$ – each star must have at least 5% of its observable hemisphere covered in stars. The flux deficit does not provide an upper limit on the spot covering fraction.

We compute the spotted area on the observable hemisphere of the star using the spot modulation algorithm in Morris et al. (2018a). The spot model assumes circular spots and quadratic limb-darkening, and uses affine invariant MCMC to fit the light curve for spot radii, positions, and a global spot contrast parameter (Foreman-Mackey et al., 2013). Figure 13.4 shows a portion of the *Kepler* light curve of Kepler-296, and draws from the posterior distributions from the model fit. The corresponding maximum-likelihood spot temperature is ~ 3300 K, in good agreement with measured spot temperatures of similar M dwarfs (Berdyugina, 2005).

When we generate realizations of the star with its spots, we draw from the posterior

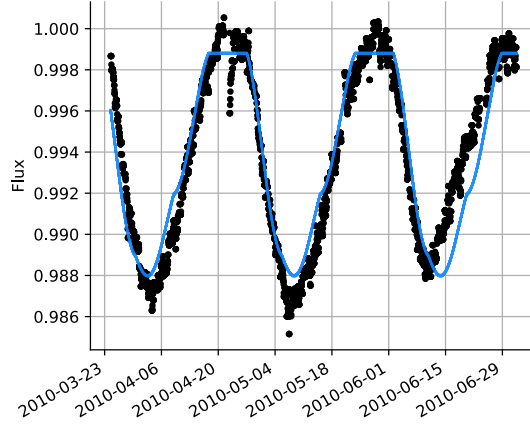


Figure 13.4: Draws from the MCMC posterior samples of spot model fits (blue curves) to a two-rotation segment of the median-filtered Kepler-296 light curve (black circles). Assuming there are two circular spots responsible for the rotation, the spots have characteristic sizes of $0.1 < R_{\text{spot}}/R_{\star} < 0.2$, and contrasts of $0.4 < c < 0.6$.

distributions of the spot radii, contrasts and positions to place spots on the star. For Kepler-296, the long rotation period $P_{\text{rot}} \sim 36$ d ensures that stellar rotational modulation does not cause significant variability on transit timescales.

We approximate the rotational modulation’s effect on the stellar spectrum by modeling the stellar spectrum as a linear combination of spectra with the effective temperatures of the photosphere and spots. We choose the nearest IRTF spectral template to the spot temperatures found for each star.

13.3.4 Flares

The K2 EVEREST light curve of TRAPPIST-1 reveals several flare events (Luger, 2017). We remove the stellar rotation and instrumental systematics by dividing the light curve by itself smoothed with a 31 cadence kernel median-filter. We fit the positive outliers with the Davenport et al. (2014) empirical flare model to solve for the typical flare peak flux and

duration of 11 significant flares in the K2 light curve. In simulated light curves, we sample flares from a Poisson process with a rate of 11 events per 78 days, and draw the peak-flux and duration parameters for each simulated flare from the fits to the observed K2 light curves. We assign the spectrum of a 10,000 K blackbody to each flare (Kowalski et al., 2015).

Kepler-62 had few significant flare events over the four years of *Kepler* observations, suggesting that the probability of a flare event occurring during a transit is negligible.

Kepler-296 had ~ 4 significant flare events over the four years of *Kepler* observations, suggesting that the probability of a flare event occurring during a transit is negligible.

13.3.5 “Microvariability” of TRAPPIST-1 at $4.5 \mu\text{m}$

An unidentified source of variability was observed in the *Spitzer* $4.5 \mu\text{m}$ light curve of TRAPPIST-1 of Delrez et al. (2018a) after removing transits and flares. We detect a periodic signal in the autocorrelation function and the Lomb-Scargle periodogram of the light curve near 0.5 days. It is not clear whether or not the variability observed with *Spitzer* is due to stellar granulation or something else.

We model the quasi-periodic oscillations with Gaussian process regression using an exponential kernel (Foreman-Mackey et al., 2017). We include this variability observed at $4.5 \mu\text{m}$ in the light curve simulations, assuming there is no wavelength dependence.

13.3.6 Scaling the Kepler-band variability of Kepler-62 and Kepler-296

For Kepler-62 and Kepler-296, lacking empirical observations of the stellar variability in the near infrared, we must approximate the amplitude and functional form of the microvariability. We measure the microvariability directly by fitting a Gaussian process with an exponential kernel to the *Kepler* short-cadence light curve at short timescales. Then we must extrapolate the amplitude observed in the *Kepler* band to the NIRSpec bandpass. We assume that the microvariability is due to stellar granulation (Ludwig et al., 2002; Trampedach et al., 2017; Tremblay et al., 2013). In this section, we outline an approximation for estimating the

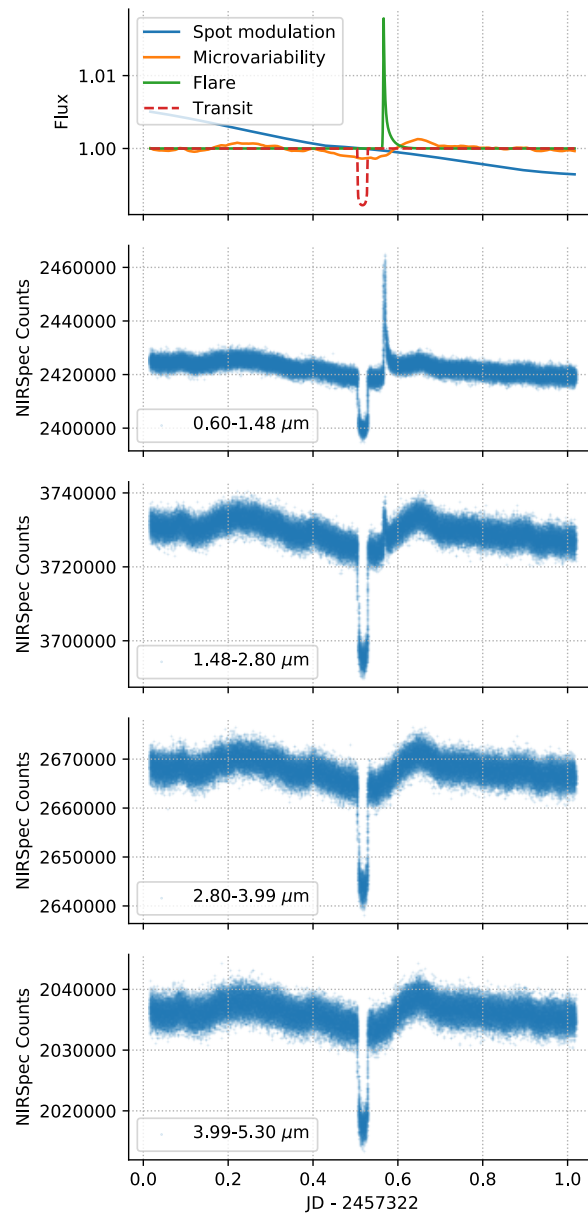


Figure 13.5: Simulated spectrophotometric observations of TRAPPIST-1 with JWST/NIRSpec, with $N_{\text{groups}} = 6$, assuming the starspot distribution of Morris et al. (2018b). The top-most panel shows the input components into the model, including the transit of TRAPPIST-1 b, rotational spot modulation, microvariability as observed in the Spitzer $4.5 \mu\text{m}$ band, a flare following the morphology of Davenport et al. (2014).

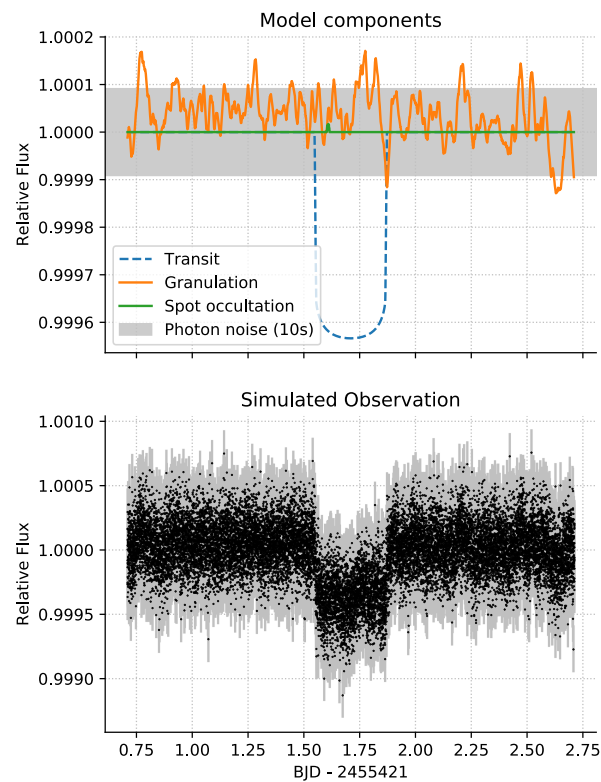


Figure 13.6: Scale of the microvariability (orange) compared to the photon noise (gray) and a band-integrated transit of Kepler-62 f (blue). We also show what a typical spot occultation might look like assuming Kepler-62 has a Sun-like spot distribution (green), which is significantly smaller than the microvariability and the photon noise.

amplitude of microvariability due to granulation in the NIRSpec band, given a measurement of the granulation amplitude in the *Kepler* band.

Ignoring limb-darkening, let's say a fraction $f_c \ll 1$ of the star is covered by the cool portion of granules with temperature T_c , while the remainder of the star we take as having a constant temperature, T_s . Then, the flux from the star is given by:

$$F_\nu = \Omega [f_c I_\nu(T_c) + (1 - f_c) I_\nu(T_s)] \quad (13.5)$$

we will assume the granule temperature is constant, so the only way that the flux can vary in the *Kepler* band is via a variation in f_c . The specific intensity is $I_\nu(T)$ for an atmosphere at temperature T , while Ω is the solid angle of the star.

Then, integrating over the *Kepler* (subscript K) and JWST/NIRSpec Prism (subscript P) bands:

$$\dot{N}_K = \int d\nu \frac{F_\nu}{h\nu} T_{K,\nu} \quad (13.6)$$

$$\dot{N}_P = \int d\nu \frac{F_\nu}{h\nu} T_{N,\nu} \quad (13.7)$$

where $T_{K,\nu}$ is the *Kepler* throughput at frequency ν , and $\dot{N}_K$ is the photon count rate ($\text{cm}^2 \text{s}^{-1}$).

When F_ν varies, this causes variation in $\dot{N}_K$ and $\dot{N}_P$, but both of these just depend on f_c . Since the amplitude of variation is small, we Taylor expand:

$$\dot{N}_K = \dot{N}_K|_{f_{c,0}} \left[1 + (f_c - f_{c,0}) \frac{d\dot{N}_K}{df_c} \frac{1}{\dot{N}_K|_{f_{c,0}}} \right] \quad (13.8)$$

Now,

$$\begin{aligned} \frac{d\dot{N}_K}{df_c} \frac{1}{\dot{N}_K|_{f_{c,0}}} &= \\ &= \frac{\int d\nu [I_\nu(T_c) - I_\nu(T_s)] \nu^{-1} T_{K,\nu}}{\int d\nu [f_c I_\nu(T_c) + (1 - f_c) I_\nu(T_s)] \nu^{-1} T_{K,\nu}} \\ &\approx \frac{\int d\nu [I_\nu(T_c) - I_\nu(T_s)] \nu^{-1} T_{K,\nu}}{\int d\nu I_\nu(T_s) \nu^{-1} T_{K,\nu}} \end{aligned} \quad (13.9)$$

where the approximation assumes $f_c \ll 1$. A similar relation holds for NIRSpec/Prism. Thus, the ratio of the fractional amplitude of variation in NIRSpec/Prism to that in *Kepler*, α , is given by:

$$\alpha \equiv \left(\frac{d\dot{N}}{df_c} \frac{1}{\dot{N}_P|f_{c,0}} \right) \left(\frac{d\dot{N}_K}{df_c} \frac{1}{\dot{N}_K|f_{c,0}} \right)^{-1} \approx \frac{\int d\nu [I_\nu(T_c) - I_\nu(T_s)] \nu^{-1} T_{P,\nu}}{\int d\nu [I_\nu(T_c) - I_\nu(T_s)] \nu^{-1} T_{K,\nu}} \frac{\int d\nu I_\nu(T_s) \nu^{-1} T_{K,\nu}}{\int d\nu I_\nu(T_s) \nu^{-1} T_{P,\nu}} \quad (13.10)$$

Trampedach et al. (2013) estimates that for a star like Kepler-62, the intensity contrast due to granulation $I_{\text{rms}}/\langle I \rangle = 0.12$ (see their “simulation 33”), which implies $\alpha \approx 0.8$. For Kepler-296 with $I_{\text{rms}}/\langle I \rangle = 0.07$ (“simulation 36”) we find $\alpha \approx 0.85$.

13.3.7 Transits

We inject Mandel & Agol (2002) transits $\mathcal{T}(t)$ into the simulated spectrophotometry of TRAPPIST-1 assuming spots are unocculted by the planets,

$$\mathcal{F}_\lambda(t) = (\mathcal{T}(t) - f_S(t))F_{\lambda,\text{photo}} + f_S(t)F_{\lambda,\text{spot}}, \quad (13.11)$$

where $f_S(t)$ is the spotted area as a function of time, $F_{\lambda,\text{photo}}$ is the spectrum of the photosphere, and $F_{\lambda,\text{spot}}$ is the spectrum of a starspot.

Kepler-296 is a binary system with a faint companion M star, so we modify the above equation accordingly:

$$\mathcal{F}_\lambda(t) = \epsilon((\mathcal{T}(t) - f_S(t))F_{\lambda,\text{photo,primary}} + f_S(t)F_{\lambda,\text{spot}}) + (1 - \epsilon)F_{\lambda,\text{photo,secondary}}, \quad (13.12)$$

where $\epsilon = 0.785 \pm 0.012$ is the flux dilution factor (Barclay et al., 2015), and $F_{\lambda,\text{photo,secondary}}$ is the spectrum of the secondary star. We assume that the amplitude of the secondary star’s rotational variability is small compared to the primary star.

13.3.8 Injected transmission spectra

We generate transmission spectra by placing a wavelength-dependence on the simulated transit depth. We adopt high-resolution simulated transmission spectra from Lincowski et al.

(2018), which are generated using a line-by-line, multi-stream, multi-scattering radiative transfer model (SMART; Meadows & Crisp, 1996) that has been validated for a wide variety of terrestrial atmospheres, including Earth (Robinson et al., 2011), Mars (Tinetti et al., 2005), and Venus (Arney et al., 2014; Meadows & Crisp, 1996). The temperature profiles for the simulated spectra were generated by Lincowski et al. (2018) using a new 1D radiative-convective-equilibrium climate model, VPL Climate (Lincowski et al., 2018; Robinson & Crisp, 2018), which uses SMART as its core for radiative transfer, and has been validated for Earth, Mars, and Venus (Robinson & Crisp, 2018). The simulated cloudy Venus-like atmospheres included the vertically-resolved radiative effects of aerosols. To generate the climate states and spectra for the oxygen-dominated, post-runaway greenhouse atmospheres posited by Luger & Barnes (2015), Lincowski et al. (2018) coupled VPL Climate to a terrestrial-based photochemistry model, to self-consistently include the effects of the M dwarf host star spectrum on abundances of atmospheric trace gases, and hence spectral signatures that might be observed by JWST.

13.4 Analysis of synthetic observations

13.4.1 Gaussian-process regression

We fit each band-integrated transit with a Mandel & Agol (2002) transit model. Ideally, we would like to detrend the transit observations against a set of observational basis vectors including: the spotted area of the star over time, and microvariability flux of the star over time, while modeling and removing any flares that occur during the observations. We anticipate lacking such supporting observations, and thus we model the correlated stellar noise with a Gaussian process (GP) (Foreman-Mackey et al., 2017). The flexible GP models allow us to sample accurate parameter uncertainties for the mid-transit times and depths without specifying the exact functional form of the variability.

We model the out-of-transit variability with a simple-harmonic oscillator (SHO) kernel, rather than the true input exponential kernel, since in practice we will not know the appro-

priate kernel function *a priori*. We’re likely to use a kernel like the SHO kernel because SHO kernels have desirable properties for smoothly varying observations of stellar variability – they are periodic but damped, with small but finite power at high frequencies.

13.4.2 Transit Timing Precision

TRAPPIST-1

We now compute the mass uncertainties on the planets TRAPPIST-1 b and c. First, we compute the expected transit times during the JWST mission, conditioned on the observed transits reported in Grimm et al. (2018). We use **TTVFast** to solve for the masses, orbital periods, eccentricities, and mean anomalies and their uncertainties for planets e and f simultaneously using MCMC.

We keep the eccentricities of planets b and c fixed at zero, as analysis by Luger et al. (2017b) showed that eccentricities of b and c are tidally damped below $e < 0.01$. We also put Gaussian priors on the masses of each planet with the maximum-likelihood values and standard deviations reported by Grimm et al. (2018).

By conditioning our TTV fits on the transits of Grimm et al. (2018), we recover masses for b and c of $M_b = 1.12 \pm 0.17 M_\oplus$ and $M_c = 1.10 \pm 0.15 M_\oplus$ (consistent with the mass prior). Next we project 10 transit times of each planet (consistent with the proposed transmission spectroscopy observations proposed in Section 13.4.4), and recover the masses with **TTVFast**. The additional ten transits of each planet do little to add to the mass constraints – the posterior mass distributions for each planet are consistent with the prior from Grimm et al. (2018), indicating that transit timing variations of planets b and c from JWST are unlikely to yield much more information on the planet masses.

Kepler-62

We now compute the mass uncertainties on the planets Kepler-62 e and f using transit timing variations observed in our simulated transits. First, we must compute the expected transit

times of planets e and f during the JWST mission, conditioned on the observed transits of each planet with *Kepler* and the Hubble Space Telescope (HST, cite Burke). We use **TTVFast** to solve for the masses, orbital periods, eccentricities, and mean anomalies and their uncertainties for planets e and f simultaneously using MCMC.

Priors are critical to attaining convergence in our **TTVFast** fits. We place a uniform prior on eccentricity $e < 0.32$ consistent with dynamical modeling by Shields et al. (2016). We compute the most-likely masses for Kepler-62 e and f using Chen & Kipping (2017) **forecaster** tool, which predicts masses for a given radius, assuming the planetary radii from Berger et al. (2018), yielding probabilistic masses $M_e = 4.45^{+3.18}_{-1.68} M_{\oplus}$ and $M_f = 3.26^{+2.10}_{-1.15} M_{\oplus}$ – and place Gaussian priors on the mass of each planet, centered on the maximum-likelihood mass and taking the maximum of the two-sided errorbars for the standard deviation. We also enforce the Hill stability criterion of Gladman (1993) at each step in the MCMC chains.

Next we select the maximum-likelihood iteration of the MCMC chains to predict future transit times of the Kepler-62 system, shown in Figure 13.7. One interesting feature of the maximum-likelihood solution are occasional 20 minute excursions from the expected midtransit time of a system without TTVs, which would be excellent times for observing the system to verify or falsify the maximum-likelihood combination of masses and orbital parameters.

Typical timing precisions for the simulated transits of Kepler-62 e and f are 25 and 41 seconds, respectively. It is critical that we observe Kepler-62 e and f for as long as possible, and not just during ingress and egress – the portions of the light curve which constrain the midtransit time. The stellar variability is similar in amplitude and timescale to the ingress and egress, and so integrating over a long time baseline is necessary to properly measure and marginalize over the stellar variability with Gaussian process regression.

We next test an optimistic scenario, assuming that JWST observes every transit of Kepler-62 e and f during its nominal five year mission (this isn’t actually possible since the target is not in the continuous viewing zone). This amounts to 15 transits of e and 6 transits of f. The mass posteriors for this “all-in” every-transit campaign are shown in Figure 13.8. We

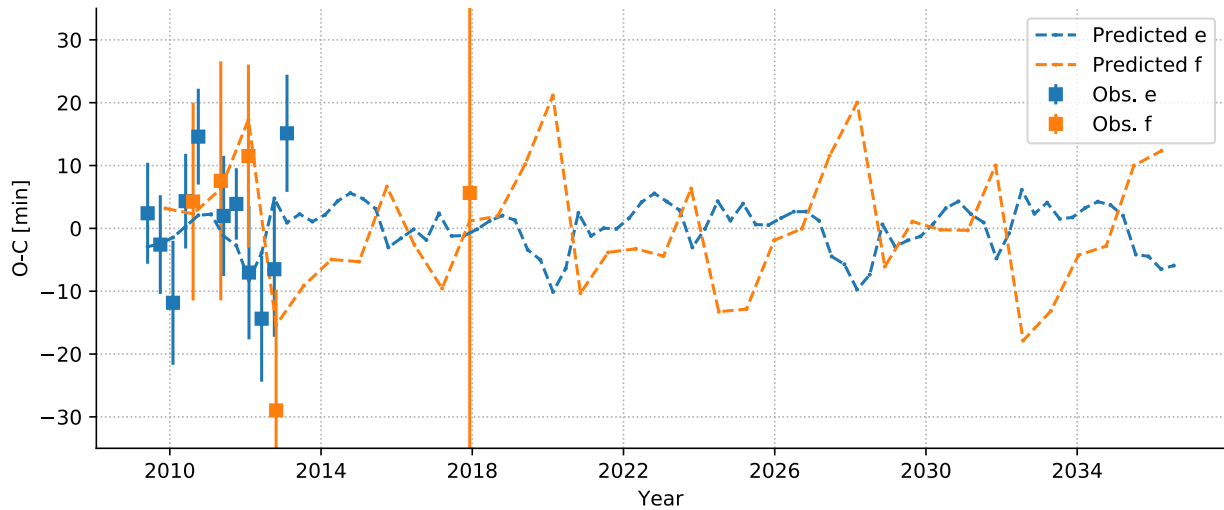


Figure 13.7: Predicted transit times using TTVFast to predict the transit timing variations of Kepler-62 e and f.

can measure the masses of each terrestrial planet accurately and to 10% precision. We note that this remarkable feat is not possible with modern radial velocity techniques – the only way to measure habitable terrestrial planet masses for a Sun-like star such as Kepler-62 is with this type of resource-intensive photometric TTV campaign.

If we instead calculate the mass precisions from TTV measurements accounting for the finite observability of Kepler-62 from JWST using the most recent version of APT, we find that there will be seven observable transits of planet e and four transits of planet f. Typical mass precisions retrieved from these transits have 10% precision for planet f, and 20% precision for planet e.

13.4.3 Bulk Density Precision

Taking the realistic mass precisions from the previous section accounting for the finite observability of Kepler-62 from JWST, we now estimate the bulk density precision feasible with NIRSpec/Prism given the uncertainties on $R_p/R_\star$ and M_p for Kepler-62 e and f. Figure 13.10

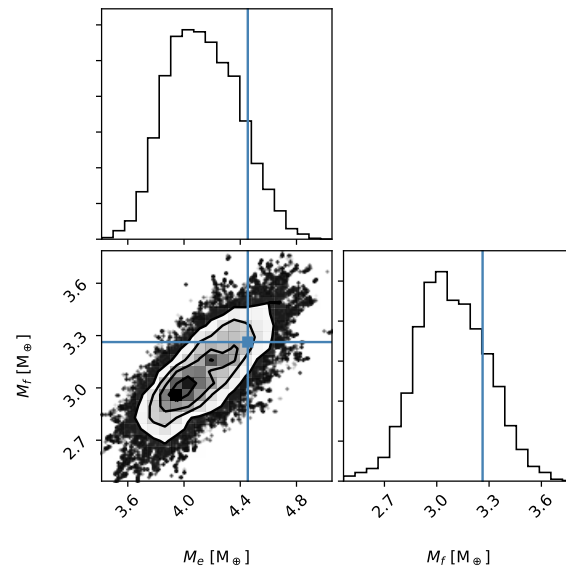


Figure 13.8: Posterior distributions for the masses of Kepler-62 e and f, assuming JWST observes every transit of each planet over its five year nominal mission. We achieve mass precisions of order 10% for both terrestrial planets. The input parameters to the simulated observations are shown in blue, confirming that the TTVs recover the correct masses within 1σ .

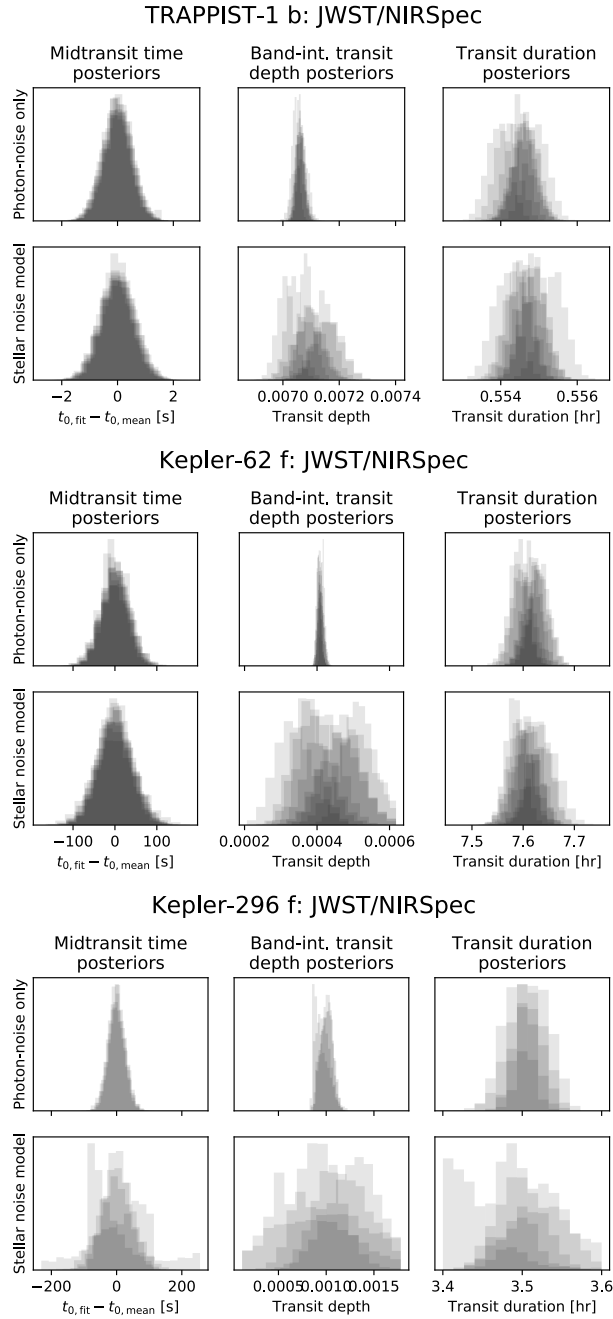


Figure 13.9: Posterior distributions on the mid-transit times and depths given a photon-noise only model, compared with the full stellar activity model. The stellar activity model does little to change the uncertainty on the transit times but significantly increases the uncertainty on the absolute, band-integrated transit depth for Kepler-62, while the uncertainties in all parameters increase for Kepler-296.

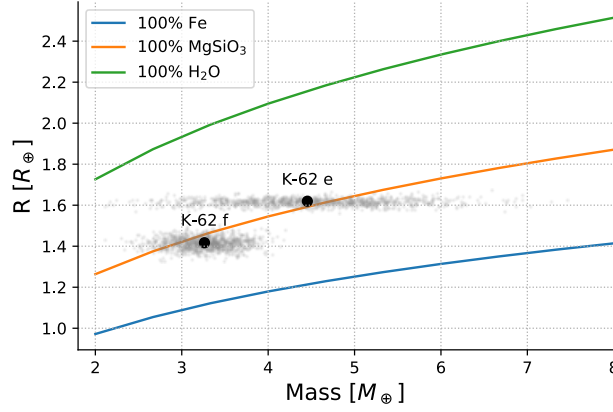


Figure 13.10: Mass/radius measurements attainable with a 5 year campaign for Kepler-62 e and f, with seven and four transits respectively, given the transit timing and planet radius precision predicted by our model. Black circles are the input masses and radii, the cloud surrounding them are the recovered posterior distributions in mass and radius. The curves show mass-radius relationships for solid exoplanets by Seager et al. (2007).

shows the positions and uncertainties for planets e and f on the mass-radius diagram. The black circles represent the input radii, and masses which were predicted by **forecaster** and recovered by **TTVFast** (see previous section). Overplotted are curves for the mass-radius relations for solid exoplanets from Seager et al. (2007). In this analysis, we have assumed that the mass and radius of the host star are known with great precision, and the uncertainty in the exoplanet radii and masses are dominated by uncertainties in the transit timing analysis and transit depth. In reality, the mass and radius of Kepler-62 is known to $\sim 3\%$, so there will in fact be noticeable correlations between the mass and radius posterior solutions in Figure 13.10.

13.4.4 Transmission spectroscopy

We measure transmission spectra by: (1) fitting the band-integrated light curve with a Gaussian process with an SHO kernel, masking out interloping transits of other planets,

and (2) linearizing the combined Gaussian process and transit model, and fitting only for the transit depth as a function of wavelength at the native instrument resolution. This has the advantage of being computationally efficient, as the linear model is trivial to optimize, while avoiding any binning of the spectrum, which contains spectroscopic information at each wavelength.

Validation against PandExo

We compare our stellar variability noise model to the open-source and publicly available PandExo JWST noise model (Batalha et al., 2017). PandExo leverages the STScI’s pixel-based signal-to-noise calculator, Pandeia (Pontoppidan et al., 2016), which forms the backbone of the official JWST exposure time calculator (ETC). We refer the reader to Batalha et al. (2017) and Pontoppidan et al. (2016) for a thorough description of PandExo and Pandeia, respectively. Briefly, for each calculation Pandeia simulates a spectral data cube at the pixel level which accounts for background noise, the point-spread-functions, instrument specific throughput and optical paths, pixel saturation levels, ramp noise, correlated read noise, flat field errors, and data extraction. Notably, it does not account to any time-dependent noise sources such as spacecraft drift and jitter or stellar variability. PandExo builds upon Pandeia to calculate transmission spectra of transiting exoplanets by considering in- and out- of transit wavelength dependent fluxes. PandExo does not simulate time-series spectro-photometry, but rather assumes a homogeneous stellar disk such that all in-transit time is equally viable observing time. This neglects the effects of stellar limb darkening and heterogeneous photospheres.

Figure 13.12 compares the model we developed in the paper with PandExo for a single transit of TRAPPIST-1 b with the JWST/NIRSpec Prism. For this test, we assume that TRAPPIST-1 b possesses a CO₂ dominated cloud-free atmosphere (Lincowski et al., 2018). Both model simulations use the NIRSpec Prism with the SUB512 subarray with 6 groups per integration. The number of groups per integration results in 50 saturated pixels at the end of a ramp, however this allows for an observational efficiency of 71.4%, compared

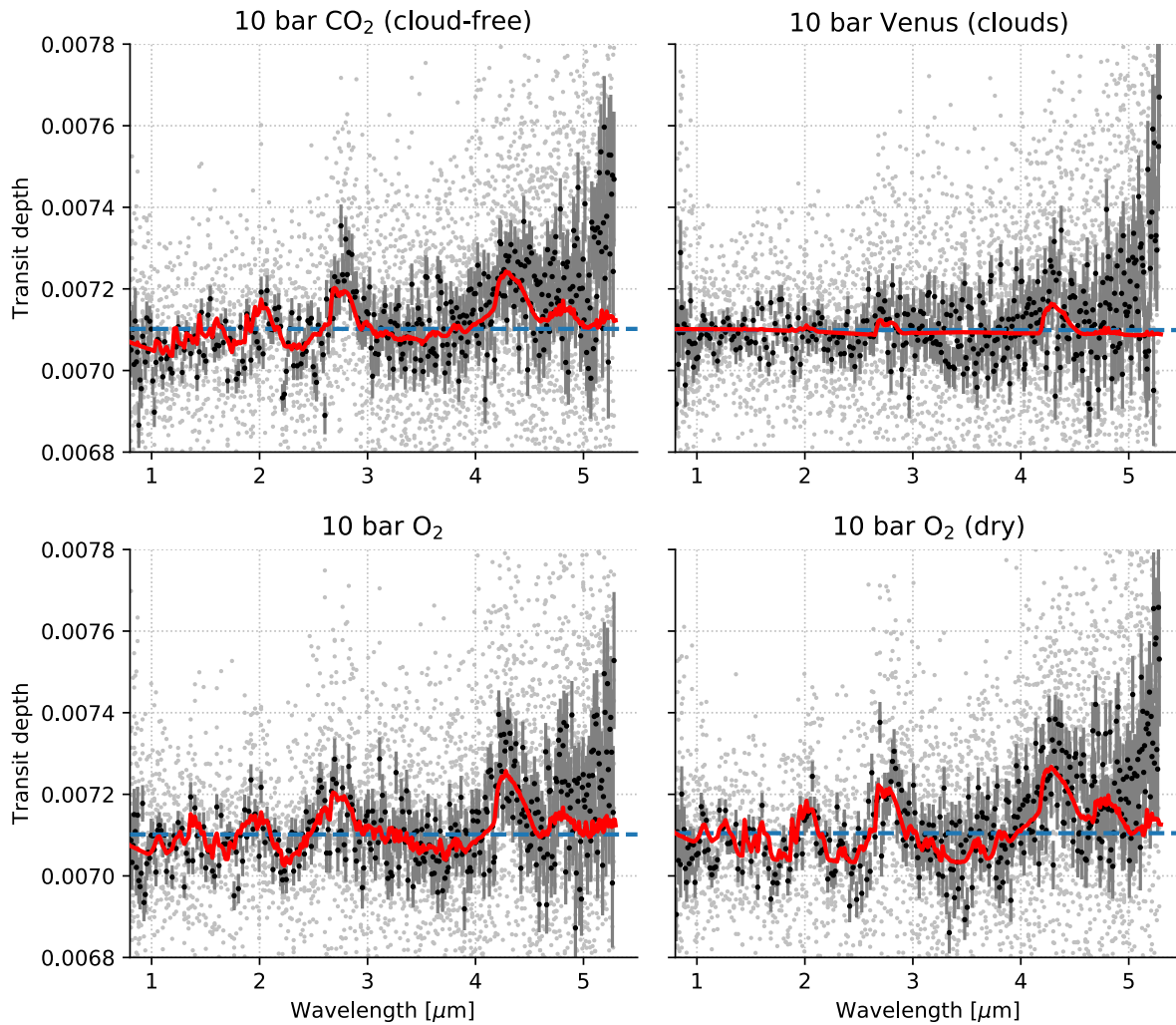


Figure 13.11: Simulated JWST/NIRSpec Prism transmission spectra of TRAPPIST-1 b with 10 transits. The red curve shows the input model spectrum, the gray points show the unbinned transmission spectrum of TRAPPIST-1 b at the native instrument resolution. The black points show the binned spectrum of TRAPPIST-1 b.

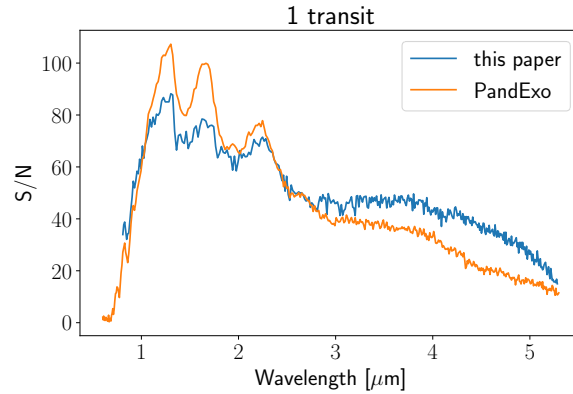


Figure 13.12: Signal-to-noise ratio on the transit depth for one transit of TRAPPIST-1 b with the JWST/NIRSpec Prism comparing PandExo (orange line) and the model developed in this paper (blue line).

to 33.3% with no saturation when only 2 groups per integration are used. We find good agreement between our model and PandExo, with subtle and interesting deviations. Between $1 - 2.5 \mu\text{m}$, near the peak of the stellar SED, our model predicts lower S/N transmission spectra than PandExo by up to $\sim 25\%$. Beyond $2.5 \mu\text{m}$ our model predicts higher S/N than PandExo by $\sim 50\%$. We can reconcile these differences by considering that stellar photon noise dominates the transmission spectrum noise budget, so that when we account for the realistic time-dependence of the stellar spectrum we get less optimistic and more realistic noise estimates. Thus we conclude that the transmission spectrum S/N estimates of our simulated observations are consistent with PandExo.

13.5 Discussion

13.5.1 Are the innermost planets of TRAPPIST-1 the best possible NIRSpec targets?

Given that the JWST budget is approaching \$10 billion and the mission has a nominal lifetime of 5 years, the cost of observations to the taxpayer is roughly \$63 per second. With that price tag, robust justification must be made to invest in the long observing programs

required to characterize exoplanets, and target lists must be carefully culled.

Of the three targets we discuss in this paper, we note that TRAPPIST-1 b, c and d are perhaps *the most optimal targets possible for characterization with JWST/NIRSpec* from several perspectives. Any target brighter than TRAPPIST-1 would either saturate the detector significantly for medium-duration exposures, or require very short exposures – incurring a steep penalty in the observing efficiency. To date, there are no known exoplanet host stars smaller than TRAPPIST-1, maximizing the available transit depths for rocky planets. To the best of our knowledge, both planets b and c are probably rocky (Fulton et al., 2017; Marcy et al., 2014; Rogers, 2015; Weiss & Marcy, 2014). The short orbital periods of the planets also ensure that each transit is short (about ~ 80 minutes) compared with transits of habitable zone planets orbiting Sun-like stars (~ 7.5 hours). It would seem, by nearly every metric, it will be difficult to find terrestrial planets more amenable to follow-up with JWST/NIRSpec than TRAPPIST-1 b, c and d.

It is presently unknown if TRAPPIST-1 b, c and d have atmospheres. If they have clear skies, we should be able to detect molecular absorption features with 10 transits or less. If they are cloudy or have no atmospheres, we will converge on flat transmission spectra by 10 transits. To distinguish between a Venus-like, cloudy planet and a rocky world with no atmosphere, additional instruments and observing techniques will be necessary – planet-planet occultations, for example, are especially promising in this area (Luger et al., 2017a).

Should we be fortunate enough to observe clear skies on TRAPPIST-1 b/c/d and the molecular absorption features have high enough S/N to discriminate between the different climate outcomes of Lincowski et al. (2018), we may be able to say something about the atmospheric composition of a rocky exoplanet for the first time.

13.6 Conclusions

1. JWST/NIRSpec is a high-throughput instrument with great potential to study exoplanets in the BOTS mode, provided it can be allowed to saturate for the brightest targets

2. With transit timing variations, we are unlikely to better constrain the masses of TRAPPIST-1 b or c; though we can measure the masses of Kepler-62 e and f to 20 and 10% respectively
3. With the band-integrated transit depths and masses from TTVs, we can measure the bulk density of Kepler-62 e and f to 20%
4. Transmission spectroscopy of TRAPPIST-1 b and c may distinguish between the climate scenarios in Lincowski et al. (2018) with as little as 10 transits
5. The innermost TRAPPIST-1 planets may be the most optimal observing targets for JWST/NIRSpec BOTS mode.

Part IV
CONCLUSIONS

*When I heard the learn'd astronomer,
When the proofs, the figures, were ranged in columns before me,
When I was shown the charts and diagrams, to add, divide, and measure them,
When I sitting heard the astronomer where he lectured with much applause in the
lecture-room,
How soon unaccountable I became tired and sick,
Till rising and gliding out I wander'd off by myself,
In the mystical moist night-air, and from time to time,
Look'd up in perfect silence at the stars.*

— Walt Whitman

Chapter 14

CONCLUSIONS

14.1 *Summary*

In Part I we studied the magnetic activity of the Sun, and its impact on observations of Earth-like exoplanets orbiting Sun-like stars. In Chapter 2 we reconstructed the rotational modulation of the Sun over 68 years of observations using archival sunspot records. In Chapter 3 we found that stellar oscillations and granulation are a significant source of astrophysical noise in measuring exoplanet radii with precision, with applications to observations by the PLATO mission. In Chapter 4 we exploited a numerical technique for efficiently generating long-term light curves of Sun-like oscillators including the effects of p -mode oscillations, granulation and supergranulation. In conclusion, Part I built a foundational understanding of solar magnetic activity and variability, setting the stage for studies of distant stellar surfaces.

In Part II we presented detailed studies of the magnetic activity of HAT-P-11, a K4V with a transiting hot-Neptune in a fortuitous orbit. The planet transits from near the south pole of the star to the north pole, which allowed us to resolve starspots as a function of latitude on the stellar surface in Chapter 5. The spots reveal that the star likely has a Sun-like dynamo, producing spots with a similar latitudinal distribution, though the spot coverage is two orders of magnitude larger. In Chapter 6 we studied the long-term chromospheric activity of HAT-P-11 and found that the star likely has a $\gtrsim 11$ year activity cycle similar to the Sun's, and we provide evidence that the close-in planet could induce the enhanced stellar activity that we observed.

In Chapter 7 we investigated whether plages regions are spatially associated with dark starspots on a young G star and two K stars, and find evidence for a Sun-like association

between starspots and plages for the G star, but no such evidence for the K stars, which seem to have global chromospheric activity not closely associated with the dark starspots driving rotational modulation. We measured the stellar temperatures, surface gravities, and spot covering fractions for a sample of bright stars in Chapter 8, and find that chromospheric activity weakly correlates with spot covering fraction, and that high precision color priors are crucial to measuring sensible spot coverages.

We turned our attention to the magnetic activity of the very lowest mass planet-hosting star, TRAPPIST-1, in Chapter 9. Using *Kepler* and *Spitzer* photometry, we reasoned that TRAPPIST-1 likely has bright regions driving the stellar variability observed at optical wavelengths but not observed in the near infrared. We also found evidence that the presence of the bright regions seems to be associated with flare occurrence, perhaps indicating that the apparent rotational modulation observed at optical wavelengths may not be rotational modulation after all. Finally, we looked to astrometry for a novel measurement of extreme stellar magnetic activity by its influence on stellar astrometric centroids in Chapter 10.

In Part III we brought together our knowledge of stellar magnetic activity and exoplanet characterization to prepare for observations of planets orbiting active host stars. In Chapter 11 we considered a “worst-case scenario” where starspots affect our measurements of exoplanet radii, and found that robust exoplanet radii can still be recovered measuring the durations of ingress and egress. In Chapter 12 we applied this technique to new *Spitzer* observations of TRAPPIST-1 and found no evidence for significant contamination of the transit chords of the TRAPPIST-1 planets by stellar activity. Lastly, in Chapter 13 we prepared for observations of the systems of potentially habitable planets of TRAPPIST-1, Kepler-62 and Kepler-296 with the James Webb Space Telescope (JWST) using NIRSpec’s in Prism mode. We determined that TRAPPIST-1 may be one of the best known systems for follow-up with James Webb due largely to its brightness and the small size of its host star. We outlined a plan for measuring the mass of the potentially habitable planet Kepler-62 f with precision as good as 10%, and showed that transmission spectroscopy of the TRAPPIST-1 planets can discriminate between different climates in the absence of clouds.

14.2 *Concluding Thoughts*

In this dissertation we have used a variety of observational techniques to constrain the heterogeneity of stellar surfaces due to magnetic activity. Looking towards the coming decade, efforts to precisely characterize stellar surface inhomogeneities will become increasingly important as we invest significant resources in collecting spectra of small exoplanet atmospheres. Cowan et al. (2015), for example, suggested that perhaps the most efficient way to allocate JWST observation time towards the study of exoplanet atmospheres is to perform a “narrow and deep” survey, limiting our observations to only a handful of exoplanets studied over a long period of time. A similar strategy may be carried out by extremely large telescopes (ELTs) on the ground. Accurate interpretation of these expensive spectra must be built upon a comprehensive understanding of the stellar surfaces which illuminate each exoplanet, as a function of wavelength and time. We have summarized these recommendations in the 2020 decadal white paper by Rackham et al. (2019).

14.2.1 *The Sun as a Star*

We are quite certain that the efforts in Part I to characterize the Sun as a star, and to predict the effects of Sun-like magnetic activity and variability on exoplanet characterization, are only parts of a prologue to a much longer story written for the exoplanet community about the only easily-resolved star from Earth. The Sun will always be the best-studied star in the sky, and for the foreseeable future, it will remain the only known host star to an inhabited exoplanet. As such, the Sun and the heliophysics it enables should always hold a special place in the minds of exoplaneteers as we study distant stars.

14.2.2 *Magnetic activity of Sun-like Stars*

Often in studies of exoplanets and habitability, many stars are lumped together under the term “Sun-like stars”, generally encompassing spectral types F through K. In this dissertation, we have presented evidence that G and K main-sequence stars may in fact exhibit

similar magnetic activity to the Sun’s. In Chapter 5 we showed that the latitude and radius distributions of starspots on the K4 dwarf HAT-P-11 are consistent with the Sun’s at solar maximum, though the spot coverage is two orders of magnitude greater than solar. In Chapter 6 we showed that the activity cycle duration of HAT-P-11 may be similar to the Sun’s. In Chapter 7 we showed that the bright faculae and starspots of a young G star may be physically associated with dark starspots, as they are on the Sun. From the perspective of stellar magnetic activity, it appears that the catch-all term “Sun-like stars” is justified for both G and K type main-sequence stars, with the important caveat that the quantity of starspots likely increases with later spectral type. This may be an important justification for observations in the coming decades as more planets are discovered orbiting G and K stars by TESS and PLATO, and since some have advocated that K dwarfs may be the ideal candidate host stars for searches for biosignatures in exoplanet atmospheres (see, for example, Arney, 2019).

14.2.3 HAT-P-11 as a Benchmark for Active Stars

Rarely have starspot analyses focused as much effort on characterizing the spots of a single star as we have spent on HAT-P-11 (with one glaring exception being the Sun). Most of the tests developed in this dissertation have been applied to that fortuitous system, which is perhaps triply lucky given its relative brightness ($V = 9.5$), its highly-inclined exoplanet orbit, and its ample spot coverage. It is our sincerest hope that HAT-P-11 can act as a benchmark star, against which other active G and K stars can be compared. Should we be lucky enough to discover a habitable planet orbiting a nearby mid-K star, we will be able to analyze spectroscopy of that planet’s atmosphere with informative prior expectations for the stellar activity of its host thanks to HAT-P-11.

14.2.4 Photometric variability of TRAPPIST-1

The magnetic activity of TRAPPIST-1 will continue to beguile astronomers after this dissertation has concluded. We presented one of the first multi-color photometric analyses

of the stellar variability of TRAPPIST-1 in Chapter 9, with an additional (inconclusive) supporting analysis in Chapter 12, which illuminated several interesting properties of this important exoplanet host star. The variability observed at optical wavelengths and the lack of variability in the near-infrared can be described by a few bright, hot regions on the stellar surface. We note an intriguing correlation between the emergence of bright regions and the occurrence of flare events, which perhaps suggests that the variability of the star is due to the emergence and decay of active regions temporally associated with the flares, rather than rotational modulation. This may also explain the apparently discrepant rotation periods of the star in the literature (Gillon et al., 2016; Luger et al., 2017b).

14.2.5 Prospects for future applications of the methods presented

We have developed and refined a number of techniques in this dissertation which allow observers to make the most of the information contained in transit light curves of exoplanets, particularly with respect to characterizing the stellar magnetic activity of exoplanet host stars. One useful way of discussing the utility of the techniques presented here, popularized by Michael Gully-Santiago, is in terms of the “scalability” of the method, i.e. how widely we can hope to apply each method, and the “fidelity” of the method, i.e. how informative and quantitative are the results produced by each method. For example, the spot occultation modeling technique applied to HAT-P-11 in Chapter 5 allowed us to resolve small starspots and to identify their positions on the stellar surface, so it may be said that these observations were “medium-fidelity”. However the MCMC inference technique was computationally expensive, and the ability to map the latitude distribution of starspots is applicable only to transiting exoplanets with highly-inclined orbits, so the spot occultation technique has “low-scalability.” We are optimistic that analogs of HAT-P-11 and Kepler-17 will be discovered in TESS and PLATO observations, which will enable us to apply this method to a handful of stars. While the number of spot-occultation targets will be small, the unique ability of spot occultations to test predictions of stellar magnetic dynamo theory (see, for example, Gilman, 2018) promises that future efforts to expand upon Chapter 5 will be worthwhile.

Our experiment with the TiO absorption technique presented in Chapter 8 showed that precise characterization of starspots requires telescopes with larger apertures and/or spectrographs with higher resolutions than the $R = 31,500$ ARC Echelle Spectrograph on the ARC 3.5 m Telescope at APO, even for bright stars; thus we deem the TiO absorption method medium-fidelity and low-scalability. However, we note that it is already common practice to collect high resolution, high signal-to-noise spectra of exoplanet host stars, and thus it may be possible to mine the wealth of spectra of exoplanet host stars already obtained for starspot analyses.

The two-color photometric analysis of TRAPPIST-1 in Chapter 9, along with searches for correlations between stellar flux and flare occurrence, must be repeated for more M8V stars to understand TRAPPIST-1's purported magnetic activity. Some spectroscopic evidence is accruing that the bright spots we hypothesized in Chapter 9 may be real (see, for example, Ducrot et al., 2018; Wakeford et al., 2019), but the conflicting reports for TRAPPIST-1's rotation period remain unresolved in the literature. Since TESS is likely to discover the best exoplanets amenable to characterization with JWST, and TESS observes in the optical while JWST observes in the infrared, we will likely have access to photometry in two colors for the most promising exoplanet hosts. Thus we note that the spot modulation analysis of Chapter 9 has high-scalability and low-fidelity.

The self-contamination technique in Chapters 11 and 12 is applicable to all transiting exoplanet observations, though it is most informative when applied to short-cadence photometry, such as photometry from the PLATO mission (with 45-second cadence). However, the inferences it makes about the properties of starspots are qualitative, ranking the technique: high-scalability and low-fidelity.

This brief survey of the starspot analysis methods presented in this dissertation demonstrates that each individual technique is incapable of answering our many questions about the starspots of a given star. Perhaps our greatest hope is to combine all of the above techniques to construct the most detailed picture of the stellar magnetic activity of a star. In addition to our multi-pronged approach to uncovering the starspots of HAT-P-11, another

comprehensive analysis of note was carried out for the star LkCa 4 by Gully-Santiago et al. (2017). We hope to see the establishment of more benchmark active stars like HAT-P-11 and LkCa 4 discovered and characterized in the near future.

14.3 Future Work

Moving forward, there are several questions that will define the scope of my future research, including:

1. Do TESS two-minute cadence observations provide any constraints on the radii of the smallest exoplanets through the durations of ingress and egress?
2. Are there HAT-P-11-like systems with large amplitude spot occultations in TESS two-minute cadence observations? Can we make inferences about stellar dynamos as a function of stellar mass using spot occultations? Can we follow-up these targets using ground-based observations?
3. What newly discovered small exoplanets may take the lead as the most promising candidates for atmospheric and mass characterization with JWST?
4. What existing and future spectroscopic observations can be taken to constrain the spot coverages of planet-hosting stars?
5. Can we make use of future data releases of ESA Gaia astrometry to detect the photometric centroid offsets of stars due to their magnetic activity?
6. Is the photometric variability of TRAPPIST-1 driven by rotational modulation, or something else?

In the sections that follow, we expand upon each of these questions and provide strategies for answering them.

14.3.1 *Exoplanet detection and characterization with TESS and ground-based follow-up*

The Transiting Exoplanet Survey Satellite (TESS) will observe 200,000 stars at 2 minute cadence, providing a *Kepler*-like photometric database for the brightest stars distributed throughout the entire sky. Unlike *Kepler*, most TESS stars will be observed for only 27 consecutive days, compared to the four years of *Kepler* photometry. As a result of these short observing windows, when it comes to characterizing exoplanet host star magnetic activity, we will have to make more with less space-based photometry, and lean more heavily on ground-based follow-up observations. For TESS targets to be amenable to follow-up characterization with JWST, they must have either little or well-characterized stellar activity. I am prepared to provide a multi-pronged approach to characterizing the activity of exoplanet host stars observed with TESS, in preparation for characterization by JWST. I will achieve this goal with TESS photometry, and ground-based follow-up observations.

The deepest insights into stellar magnetic activity of exoplanet host stars come from the transit light curves of exoplanets. There are two primary techniques that I plan to use to measure the activity of exoplanet host stars using the publicly available TESS photometry: the “self-contamination” technique, and spot occultation mapping.

Robust radii for small exoplanets via the self-contamination technique

We usually measure the radii of transiting exoplanets from the transit depth, which are given by the ratio of cross-sectional areas of the planet and star. However, if a star has dark starspots distributed throughout the transit chord, the transit depth will be biased toward smaller values, and thus the inferred planet radius will appear smaller if these spots are unaccounted for. In Morris et al. (2018f,h) we reparameterize the transit light curve to account for self-contamination by photospheric inhomogeneities by splitting the parameter $R_p/R_\star$ into two parameters: one for the radius ratio, which controls the duration of ingress and egress, and another which measures the possibly contaminated transit depth. The radius recovered from measurement of the ingress/egress duration can recover the true radii

of planets transiting spotted stars with axisymmetric spot distributions, especially when asteroseismic observations are available. This will be critical for measuring robust radii of small exoplanets orbiting the brightest stars, which are the focus of the TESS mission, using the publicly available TESS photometry alone.

Spot occultation mapping for precision dynamo studies

The clearest window into small-scale magnetic activity of exoplanet host stars to date is spot occultation mapping, which reveals the positions and sizes of starspots as exoplanets occult them during transits (Sanchis-Ojeda & Winn, 2011). When coupled with Rossiter-McLaughlin observations which constrain the spin-orbit alignment of an exoplanet system, spot occultations can reveal the latitudes and longitudes of spots on the stellar surface, allowing for direct comparison with solar activity (Morris et al., 2017b; Winn et al., 2010, see Chapter 5). I will search the TESS photometry of exoplanet host stars for every spot occultation observed during by TESS mission. For a subset of the stars with Rossiter-McLaughlin observations, I will reconstruct the latitude/longitude distributions of the spots, enabling precision comparisons between stellar and solar activity, as I did in Chapter 5.

Holographic diffusers enable high precision photometry from the ground (Morris et al., 2018c; Stefansson et al., 2017, 2018) – diffuser photometry may be a key asset for follow-up of TESS targets. The diffuser transforms the point-spread function of a star from a nearly Gaussian distribution with a tight radial spread of only a few pixels to a broad top-hat shaped distribution covering an area of thousands of pixels. For bright stars, spreading the light out over many pixels is advantageous for several reasons: (1) it enables longer exposures, which can become long enough to average over atmospheric scintillation noise; (2) it makes the photometry less sensitive to fine pointing errors and intra-pixel sensitivity variations, which are significant when most of the stellar flux is landing on only a handful of pixels; and (3) the photometry is also less sensitive to inter-pixel sensitivity variations (or flat-field precision), since the flux is spread roughly evenly over many pixels. This last point is one of the key advantages in favor of diffuser photometry over defocused photometry, where the

flux is often concentrated unevenly onto a few pixels.

Stellar activity of TESS host stars

Since TESS will observe many more late K and M type stars than *Kepler* (Muirhead et al., 2018), the mission will enable us to construct spot occultation maps for more stars across the low-mass end of the main sequence, allowing us to probe the behavior of stellar dynamos as a function of stellar mass. At present, small-scale spot maps are only available for a handful of stars, such as Kepler-17, Kepler-63, HAT-P-11 and the Sun (Davenport, 2015b; Morris et al., 2017b; Sanchis-Ojeda et al., 2013; Solanki, 2003). TESS may open a window into the dynamos of low-mass stars, allowing us to determine how magnetic activity changes with rotation period, tachocline depth, Rossby number, or other fundamental stellar parameters which are thought to influence stellar dynamos (Berdyugina, 2005; Gilman, 2018).

Diffuser photometry is not only useful for measuring transits and transit timing variations, but the uniquely high precision diffuser photometry is well-suited to measuring spot occultations from the ground (Morris et al., 2018g). Should more stars be discovered like HAT-P-11 which show frequent spot occultations, ground-based diffuser photometry may allow us to measure properties stellar magnetically active regions over very long baselines, for example, throughout stellar activity cycles. Also exciting is the possibility of expanding upon the monochromatic photometry of TESS by observing spot occultations from the ground in a different bandpass. For example, we can collect ground-based photometry of HAT-P-11 in the SDSS *u* band while TESS observes in its redder bandpass, allowing us to use the simultaneous observations to roughly estimate the color, and therefore the temperature, of starspots on HAT-P-11 (or other stars).

14.3.2 Exoplanet characterization with JWST

The TESS planet yield, in addition to ground-based surveys like SPECULOOS (Delrez et al., 2018b) and SAINT-Ex, should produce a handful of planets which are ideal for characterization with the James Webb Space Telescope (JWST). JWST may provide some of the clearest

views into exoplanet atmospheres and their masses to date using transmission spectroscopy and transit timing variations (TTVs), as we discussed in Chapter 13.

While stellar magnetic activity, granulation and oscillations will enforce fundamental noise floors on the precision of JWST observations of exoplanets, we are optimistic that some targets may be bright and quiet enough to measure the masses of potentially habitable (cool) planets via TTVs, and to measure the presence or lack of an atmosphere for some close-in (hot) rocky planets.

If we are lucky enough to have a system where both techniques can be applied to the same planet, in principle, we can measure the bulk density of the planet, *and* the atomic and molecular constituents of its atmosphere. For the first time, we may be able to say something about the bulk chemistry of an exoplanet’s interior as well as basic properties of its atmosphere like the presence or lack of clouds. In the case of a cloud-free atmosphere, we might also be able to discern between different climates on the planet via its atmospheric chemistry.

14.3.3 Ground-based Spectroscopic Follow-up of Exoplanet Hosts

In Chapter 8, we showed that the resolution and signal-to-noise of ARCES spectra from the ARC 3.5 m Telescope at Apache Point Observatory are insufficient to detect starspot coverages $\lesssim 10\%$. We can improve upon this effort in the future, for example, by turning to archival observations from W.M. Keck Observatory. There is a valuable database of high resolution, high signal-to-noise spectra for 1305 Kepler Objects of Interest collected by the California-Kepler Survey (CKS: Johnson et al., 2017; Petigura et al., 2017). This treasure-trove of spectra may contain evidence for starspot coverage due to absorption by TiO on exoplanet host stars, for example, at 7054 and 7125 Å which are covered by the CKS archival spectra.

14.3.4 *Gaia Observations of Stellar Magnetic Activity*

In Chapter 10 we described a technique for observing stellar activity through photometric centroid offsets using the exquisite photometric precision afforded by ESA’s Gaia mission. In the near future, Gaia data releases will provide constraints on the “excess astrometric noise” detected for each bright, nearby target. This excess noise will be used to probe stellar multiplicity and the presence of exoplanets, but it can also be used to search for extreme activity for some of the nearest stars. I will lead efforts to measure excess astrometric noise due to stellar magnetic activity on the nearby, bright stars that we suggested as high priority targets in Chapter 10.

14.3.5 *The Activity of TRAPPIST-1*

Since the publication of Chapter 9, observations have led other groups to also conclude that there are likely bright, hot regions on the surface of TRAPPIST-1 (Ducrot et al., 2018; Wakeford et al., 2019). With upcoming observations of late-M stars like those of SPECULOOS and SAINT-Ex, it may be possible to determine whether or not these apparently bright regions are common, or if they are particular to TRAPPIST-1. It may also be possible to mine these observational databases of other stars for evidence of the flux-flare correlation described in Chapter 9. We are optimistic that by studying populations of late-M stars, it may be possible to identify which aspects of TRAPPIST-1’s activity are due to bright spots, which are due dark spots, and whether or not the apparent rotational modulation of TRAPPIST-1 is in fact due to rotation rather than the evolution of active regions. We also note that observations with very high resolution spectrographs, like PEPSI at $R = 270,000$, may make it possible to measure the stellar $v \sin i$ and thus the rotation period, even on a very late M dwarf (Strassmeier et al., 2015). With these observations we might hope to overcome the degenerate interpretations of the optical light curve of TRAPPIST-1, which may be the result of rotational modulation, or the evolution of active regions.

14.3.6 Outlook for astrobiology

The aforementioned observations are the primary ingredients that go into determining the true habitability of an exoplanet. It is possible that JWST will usher us into a new era in the study of exoplanet habitability, leaving behind the rough definition of habitability based on the instellation, by using the moist and maximum greenhouse effects as boundaries of the habitable zone, and moving onward to identifying whether or not the observed surface and climate properties of a specific planet are consistent with a habitable planet or not. With careful consideration given to the properties of the host stars, we are poised to ask one of the paramount questions of astrobiology: where are the conditions for life met in the local Universe?

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In the previous Parts, repositories of software were written to facilitate each scientific effort, all of which are available on GitHub¹. In the appendices, we highlight two open source, open development coding efforts which may be of use to the broader community. In Appendix A we introduce **astroplan**, an astropy-affiliated package for observation planning and scheduling in Python. In Appendix B we introduce **aesop**, a Python package for analysis of echelle spectra collected with the ARC Echelle Spectrograph (ARCES) at Apache Point Observatory (APO). In Appendix C we introduce **arcesetc**, a Python exposure time calculator package for the ARCES at APO.

¹ <http://github.com/bmorris3>

Appendix A

ASTROPLAN: AN OPEN SOURCE OBSERVATION PLANNING PACKAGE IN PYTHON

This chapter was first published in the *Astronomical Journal* (Morris et al., 2018i).

A.1 Introduction

The Astropy Project is a community effort to develop a common core package for astronomy in Python, and to foster an ecosystem of interoperable astronomy packages. The `astropy` core package contains all of the machinery necessary for computing whether or not a given object is observable from a location on the Earth at specified times. It defines an object-oriented framework for specifying times, and coordinates on the sky and Earth. In this paper, we assume that the reader has some familiarity with the tools available in `astropy`, see Astropy Collaboration et al. (2013) or the online documentation¹.

There are several practical algorithms useful for observation planning that are not included in `astropy`. Some questions that users may seek to answer using `astropy` would require substantial effort, such as: “is this star currently above 30° altitude from the Apache Point Observatory?” or “what time is astronomical twilight this evening on Mauna Kea?”

`astroplan` is an Astropy affiliated package for ground-based observation planning and scheduling, which provides functionality for answering these questions. It is a pure-Python package that provides an efficient application programming interface (API) for quick access to common observational calculations, while using the full accuracy and precision of `astropy` under-the-hood to handle the sky and time coordinate transformations.

The most similar existing Python software that can be used to plan observations is

¹ <http://docs.astropy.org>

`pyephem` (Rhodes, 2011). `astroplan` is different from `pyephem` in a few fundamental ways. `astroplan` provides support for computing the positions of the Sun, Moon, stars, and major planets. It uses `astropy`'s modern and more accurate IAU2000/2006 methods and NASA's DE430 planetary ephemeris. `astroplan` is built around the `astropy` objects which specify times and coordinates. `astroplan` users can use the extensively documented and constantly improving `astropy` framework for specifying times and coordinates. `pyephem` uses package-specific implementations of times and coordinates that are not cross-compatible with packages in the Astropy Project ecosystem. `pyephem` supports the Sun, Moon, stars, major planets, asteroids and comets, and uses the older IAU1976/1980 precession/nutation methods, and VSOP87 planetary ephemerides.

Here we briefly outline some key features of `astroplan` version 0.4, and the design decisions that went into making them. In Section A.2 we outline the `astroplan` API, and in Section A.3 we direct the reader to the online documentation, and resources for teaching and learning `astroplan`.

A.2 API

A.2.1 Basic operations

We begin by defining the `Observer` object, which specifies the location of an observer on the Earth. Most of the major observatories included in IRAF (National Optical Astronomy Observatories, 1999) are accessible by name in `astroplan` via the `at_site` class method:

Example A.1: Define a common observer

```
>>> from astroplan import Observer
>>> keck = Observer.at_site("Keck")
>>> apo = Observer.at_site("Apache Point")
>>> print(apo)
<Observer: name='Apache Point',
      location (lon, lat, el)=(-105.822 deg, 32.78 deg, 2798 m),
```

```
timezone=<UTC>>
```

An observer can be located anywhere on the Earth with use of `astropy`'s `EarthLocation` object.

Example A.2: Define a custom observer

```
>>> from astropy.coordinates import EarthLocation
>>> import astropy.units as u

>>> longitude = '-155d28m48.900s'
>>> latitude = '+19d49m42.600s'
>>> elevation = 4163 * u.meter
>>> location = EarthLocation.from_geodetic(longitude, latitude, elevation)
>>> observer = Observer(name='Subaru', location=location)
```

In order to account for atmospheric refraction in different environments, several atmospheric parameters can be described on the `Observer` object, including the atmospheric pressure, temperature and relative humidity.

Targets with fixed celestial coordinates are described by `FixedTarget` objects, which contain their coordinate and name:

Example A.3: Define a fixed celestial target

```
>>> from astroplan import FixedTarget
>>> from astropy.coordinates import SkyCoord

>>> sirius = FixedTarget.from_name("Sirius")
>>> vega_coord = SkyCoord(ra="18h36m56s", dec="+38d47m01s")
>>> vega = FixedTarget(coord=vega_coord, name="Vega")
```

The `from_name` class method uses tools from `astropy.coordinates` to query Simbad, NED,

and VizieR for target coordinates by name through the Sesame Name Resolver (Schaaff, 2004). Non-fixed targets apart from the Sun and Moon are not implemented in `astroplan` at the time of writing, and community contributions for supporting minor bodies are welcome.

Rise and set times are the cornerstone computations of observation planning. `astroplan` computes the rise and set times of an object by transforming the sky coordinates of the object (e.g. ICRS, galactic, etc.) into a grid of altitude-azimuth coordinates for that target as seen by an observer at a specific location on the Earth, at 10 minute intervals over a 24 hour period. The rise or set time is then computed by linear interpolation between the two coordinates nearest to zero. The meridian/anti-meridian transit time is computed similarly; it takes a numerical derivative of the altitudes before searching for the appropriate zero crossing. The user can also define a rise or set horizon other than 0° altitude, which is useful for observatories with non-zero altitude limits.

We chose to compute rise and set times with a grid-search to maximize accuracy, rather than speed. In particular, we sought to preserve the `astropy` altitude-azimuth coordinate transformation which accounts for atmospheric refraction.

Convenience methods are included to compute the altitude-azimuth coordinates of a target at a given time, and the times of rise, set, meridian and anti-meridian transit:

Example A.4: Find target altitude/azimuth and rise time

```
>>> from astropy.time import Time
>>> observing_time = Time("2017-01-01 05:23:45", scale="utc")
>>> apo.altaz(observing_time, sirius)
<SkyCoord ...: (az, alt) in deg
    ( 150.06353683, 34.88938344)>
>>> apo.target_rise_time(observing_time, sirius)
<Time object: scale='utc' format='jd' value=2457754.5765391565>
```

Times can be defined in a variety of scales using `astropy Time` objects, including UTC, TAI, TCB, TCG, TDB, TT, UT1.

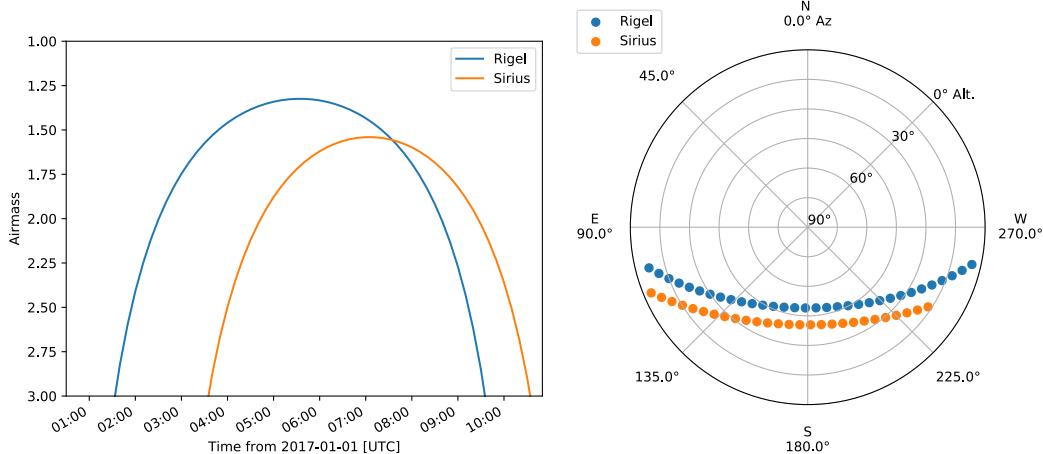


Figure A.1: An airmass plot and a sky chart for observing Sirius and Rigel from Apache Point Observatory, made with the `astroplan.plots` methods `plot_airmass` and `plot_sky`. The underlying altitude/azimuth calculation powered by `astropy.coordinates` includes atmospheric refraction.

The sky coordinates of the major Solar System bodies are computed using the `jplephem` package, which provides an API for querying JPL’s Satellite Planet Kernel files. The methods for querying the positions of Solar System bodies were originally developed for `astroplan`, and have since been moved into the `astropy.coordinates` package.

Common plots are accessible through the `astroplan.plots` module – see Figure A.1 for a few examples. There are many more example plots, and the source code that generates them, available in the online documentation².

A.2.2 Observing Constraints

Planning astronomical observations often requires an observer to determine whether or not a celestial object is observable given a list of observing constraints. `astroplan` contains a generic framework for defining observing constraints, and computing the “observability” of

² <https://astroplan.readthedocs.io/en/stable/tutorials/plots.html>

a list of targets given those constraints.

For example, suppose an observer is planning to observe low-mass stars in Praesepe in the optical and infrared from the W.M. Keck Observatory. The constraints imposed by the telescope and science case require all observations to occur: (i) between astronomical twilights; (ii) while the Moon is separated from Praesepe by at least 45° ; and (iii) while Praesepe is above the lower elevation limit of Keck I, about 33° . These observing constraints can be specified with the `AtNightConstraint`, `MoonSeparationConstraint`, and `AltitudeConstraint` objects.

Other built-in constraints allow users to specify acceptable ranges of: Moon illuminations, airmass, Sun separations (e.g., for non-optical observations), and local times. The observing constraint classes take as input: targets, times and an observer; and the constraints return boolean matrices indicating whether or not those targets are observable at each time.

The constraints framework is modular and written to be extensible. Users can implement their own constraints for a particular observatory or science case by following a tutorial in the online documentation³ to produce constraint objects which are compatible with the `astroplan` scheduling framework.

A.2.3 Transiting exoplanets and eclipsing binaries

The `astroplan.periodic` module contains a framework for defining systems with periodic events, such as exoplanets and binaries. There are specialized classes for eclipsing systems, such as eclipsing binaries (EBs) and transiting exoplanets. The module makes use of the generic terms “primary eclipse” and “secondary eclipse”, where the primary eclipse is a “transit” in the case of exoplanets. There are convenience functions for computing the next primary or secondary eclipses of an exoplanet or EB, or as well as computing ingress and egress times of the next primary or secondary eclipse.

³ <https://astroplan.readthedocs.io/en/stable/tutorials/constraints.html#user-defined-constraints>

Example A.5: Find upcoming exoplanet transit times

```
>>> from astropy.time import Time
>>> import astropy.units as u
>>> from astroplan import EclipsingSystem

>>> epoch = Time(2452826.628514, format='jd', scale='utc')
>>> period = 3.52474859 * u.day
>>> duration = 0.1277 * u.day
>>> now = Time('2016-09-15')

>>> hd209458 = EclipsingSystem(epoch, period, duration)
>>> print(hd209458.next_primary_eclipse_time(now, n_eclipses=3))
['2016-09-16 23:37:44.154'
 '2016-09-20 12:13:22.433'
 '2016-09-24 00:49:00.711']
```

There are also complementary methods in the `constraints` module for use with the `periodic` system framework. Users can determine which eclipse events are observable from an observatory with a list of constraints. We include a brief tutorial for using the `periodic` module with queries from online exoplanet parameter databases in the published appendix.

A.2.4 Scheduling Observations

The scheduling framework enables users to define *observing blocks*, which denote an observation of a target or group of targets for an amount of time in a particular instrument configuration. Each observing block can be assigned a numerical *priority*, which by convention spans the range $[0, 1]$ where zero is low priority. Priorities can be assigned by an observer based on which potential observations are most important to them to get scheduled. A set of observing blocks gets assigned a *rank*, which for example, might be the rank a proposal receives from a telescope time allocation committee (TAC).

Each observing block has a list of associated *constraints*. We compute a *score* for each constraint on an observing block, which can be a boolean or float in the range $[0, 1]$ where zero is unfavorable. For example, the score computed from an airmass constraint will be highest when the airmass is low, while the score computed from an altitude constraint will be highest when the altitude is high. Other constraints, like the `AtNightConstraint`, yield boolean scores.

These scored observing blocks can be assigned to time slots by a *scheduler*, which chooses the order for which observing blocks get scheduled first, and the times to assign them. Each scheduler creates an observing schedule based on one of several strategies for filling time slots with observing blocks. As of `astroplan` version 0.4, there are two schedulers implemented: the sequential and priority schedulers.

The *sequential scheduler* begins by selecting the best-scored observing block at the beginning of the observing time. It then continues to choose the next best-scored block for the next observation, until all available observing time is allocated, or all observing blocks have been allocated.

The *priority scheduler* takes a prioritized list of observing blocks. The priority for each observing block could be assigned by an observatory TAC for example, or by an individual observer who needs to schedule their observations given their scientific priorities. The scheduler will first allocate the highest priority observing block to the best-scored time slot for that observing block, and then schedule the next priority block at its best time, etc.

The two schedulers presently implemented are most useful for planning an individual observer's observations; a complete example is available in published Appendix. We intend to continue to develop the scheduling module to support queue scheduling for observatories with many observing programs. A wide range of strategies exist for planning observations, however, so the code for the schedulers is adaptable for users to adopt to other strategies either via subclassing or creating new scheduler classes. The package welcomes contributions of this sort from the community.

A.2.5 Testing & Development

`astroplan` has an extensive testing suite. In addition to simple unit tests which check that sensible inputs yield sensible outputs, there are also many tests which compare the accuracy of `astroplan` outputs. The tests are executed remotely whenever changes are made to the source code or documentation within the `astroplan` repository. The `astroplan` outputs are commonly compared against outputs from the independent python ephemeris package `pyephem` (Rhodes, 2011). The difference in rise and set times with `astroplan` and `pyephem` is always < 8 minutes (with atmospheric refraction), and the differences are probably attributable to intrinsically different interpretations of these times.

Contributions to the package from the community are welcome. The source code is hosted on GitHub⁴, where users can contribute new features. `astroplan` follows the open development model refined by `astropy`, and many tutorials on contributing to the source code of either package are available in the `astropy` documentation⁵.

A.3 Documentation

A.3.1 Online Documentation

Detailed, tested, living documentation for `astroplan` is available online via Read the Docs⁶. This paper is intended as a brief introduction to `astroplan`'s core functionality and the algorithms used throughout the package, so we refer the reader to the online documentation for the complete API description, and complete tutorials for each module with examples.

⁴ GitHub: <https://github.com/astropy/astroplan>,
static Zenodo archive: <https://doi.org/10.5281/zenodo.1035883>

⁵ http://docs.astropy.org/en/stable/development/workflow/development_workflow.html

⁶ <http://astroplan.readthedocs.io/>

A.3.2 astroplan in the classroom

astroplan is incorporated into the curriculum for undergraduate majors in astronomy at the University of Washington, in the “Introduction to Programming for Astronomical Applications” course. The lesson plan on observing with Python is built around the task of planning astronomical observations. Along the way, it guides students through using the time, coordinate and quantity objects of **astropy**, building up to their combined use in observation planning with **astroplan**. Jupyter notebooks guiding students through these lessons are freely available online⁷.

A.4 Summary

astroplan is a pure-Python, open source, Astropy affiliated package for observation planning and scheduling. It provides methods for computing common observational quantities such as target rise, set, transit times; and it specifies a framework for testing the “observability” of targets given observing constraints.

⁷ <https://github.com/UWashington-Astro300/astroplan-in-the-classroom>

Appendix B

AESOP: THE ARC ECHELLE SPECTROGRAPH OBSERVATION PIPELINE

This chapter was first published in the Journal of Open Source Software in collaboration with Trevor Dorn-Wallenstein (Morris & Dorn-Wallenstein, 2018).

The ARC Echelle Spectroscopic Observation Pipeline, or `aesop`, is a high resolution spectroscopy software toolkit tailored for observations from the Astrophysics Research Consortium (ARC) Echelle Spectrograph mounted on the ARC 3.5 m Telescope at Apache Point Observatory. `aesop` picks up where the traditional IRAF reduction scripts leave off, offering an open development, object-oriented Pythonic analysis framework for echelle spectra.

Basic functionality of `aesop` includes: (1) blaze function normalization by polynomial fits to observations of early-type stars, (2) an additional/alternative robust least-squares normalization method, (3) radial velocity measurements (or offset removals) via cross-correlation with model spectra, including barycentric radial velocity calculations, (4) concatenation of multiple echelle orders into a simple 1D spectrum, and (5) approximate flux calibration.

Some handy additional utilities include methods for download PHOENIX model spectra (Husser et al., 2013), and methods for measuring the Mount Wilson Observatory-calibrated CaII H K “S” index (Morris et al., 2017c). `aesop` was built from the Astropy package-template, and thus includes self-building documentation and continuous integration (The Astropy Collaboration et al., 2018).

Appendix C

ARCESETC: ARC ECHELLE SPECTROGRAPH EXPOSURE TIME CALCULATOR

The ARC Echelle Spectrograph (ARCES) Exposure Time Calculator, or `arcesetc`, is a simple exposure time calculator for the ARCES instrument on the Astrophysical Research Consortium (ARC) 3.5 m Telescope at Apache Point Observatory for stellar spectroscopy. Users can supply `arcesetc` functions with the spectral type of their target star, the V band magnitude, and either: the desired exposure time in order to determine the counts and signal-to-noise ratio as a function of wavelength; or the desired signal-to-noise ratio at a given wavelength to determine the required exposure time.

We estimate the count rates for stars as a function of wavelength by fitting 15th-order polynomials to each spectral order of real observations of a star of each spectral type. These polynomial coefficients and some wavelength metadata are stored in an HDF5 archive for compactness and easy of reconstruction. Then upon calling `arcesetc`, the archive is opened and the spectral order closest to the wavelength of interest is reconstructed from the polynomial coefficients, for a star of the closest available spectral type to the one requested

At present, the 79 stellar spectral types included in the `arcesetc` library span from mid F to mid M stars on the main sequence, a variety of M giants, a handful of O and B, and a white dwarf and a Wolf-Rayet star. Contributions from the community are welcome to expand the library to include other spectral types.

`arcesetc` was built from the Astropy package-template, and thus includes self-building documentation and continuous integration (The Astropy Collaboration et al., 2018).

VITA

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