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Drivers of Turbulence in
the Neutral Interstellar Medium
of Dwarf Galaxies

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Abstract

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The cause of H I velocity dispersions in the interstellar medium (ISM) of galaxies is often attributed to star formation, but recent evidence has shown these two quantities are not connected in regions of low star formation. This lack of connection is most apparent in dwarf galaxies and the outer disks of spiral galaxies. However, unique data sets have recently been collected that can help address this discrepancy. The ACS Nearby Survey Treasury Project (ANGST) has measured time-resolved star formation histories (SFHs) in ~ 70 nearby galaxies. The followup Very Large Array-ANGST survey (VLA-ANGST) provides complementary H I observations of a subset of ANGST galaxies. In this thesis, I explore the connection between star formation and H I kinematics in a number of nearby dwarf galaxies.

I first present the Very Large Array-ACS Nearby Galaxy Survey Treasury Project (ANGST). VLA-ANGST was designed to provide high spatial and velocity resolution observations of the H I component of the interstellar medium (ISM) in ANGST galaxies. I describe the data calibration and imaging procedures, and then present the publicly-available data products. The observations from this survey and from The H I Nearby Galaxy Survey (THINGS) comprise the majority of data in my thesis.

Using VLA-ANGST and THINGS data, I present a method to measure the average H I kinematics in a number of nearby dwarf galaxies by co-adding individual line-of-sight profiles. These “superprofiles” are composed of a central narrow peak ($\sim 6\text{--}10\text{ km s}^{-1}$) with

higher velocity wings to either side. When scaled to the same half-width half-maximum, the shapes of the superprofiles are very similar. I interpret the central peak as representative of the average turbulent motion; the wings are then due to H I moving faster than expected compared to the average kinematics. I then compare the superprofile parameters to physical properties such as mass surface density and star formation intensity. The average velocity dispersion correlate most strongly with H I surface density, and do not show correlations with star formation intensity unless higher mass galaxies were included. The properties of the wings are more connected with star formation. By applying energy arguments, I determine that star formation can provide enough energy to drive the H I kinematics over ~ 10 Myr timescales, while a gravitational instability cannot.

I then extend this analysis to spatially-resolved scales in these galaxies, and generated superprofiles in regions determined by radius or by star formation intensity. These superprofiles provide a more direct comparison between H I kinematics and local ISM properties compared to the analysis on global scales. The spatially-resolved superprofiles indicate that star formation does not uniquely determine the H I velocity dispersion, but it does appear to provide a lower floor below which velocity dispersions cannot fall. I also find that the coupling efficiency between star formation and H I kinematics decreases with increasing star formation surface density, which may indicate that star formation energy couples more consistently to other phases of the ISM.

I finally explore the timescale over which H I responds to star formation using a combination of VLA-ANGST, THINGS, and ANGST data. Using time-resolved SFHs from ANGST, I measure the average star formation rate as a function of time and compared it to present-day H I kinematics. I find that the H I kinematics are most strongly correlated with star formation that occurred $\sim 30 - 40$ Myr ago, which supports the idea that supernova explosions are one driver of H I kinematics even in low star formation systems.

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DEDICATION

To my parents, John and Pam Stilp,
for always believing in me.

Chapter 1

INTRODUCTION

Neutral hydrogen (H I) is an ideal tracer of the kinematics of the warm interstellar medium (ISM) in disk galaxies. It is linked to a number of physical processes in the ISM, such as star formation. Clumps of H I in the ISM cool to temperatures where molecular hydrogen (H₂) and then stars are able to form. These stars release energy back into the ISM through stellar winds and supernova explosions (SNe) in a process known as “feedback.” Understanding the relationship between star formation and H I is fundamental to characterizing the driver of energy in the warm ISM.

In this thesis I explore the connection between H I kinematics and star formation in nearby dwarf galaxies.

1.1 Background Information

Hydrogen is the most abundant element in the universe ($\sim 67\%$ of the baryonic mass content; Komatsu et al., 2011) and comes in a variety of forms. The neutral atomic form of hydrogen, H I, is composed of a proton with a bound electron, while ionized hydrogen (H II) is a single proton that lacks a bound electron. At cold temperatures and high densities, H₂ can form. This thesis focuses on the H I component of the ISM. I discuss our current understanding of H I in nearby galaxies in the following sections.

1.1.1 The Interstellar Medium

The ISM in nearby galaxies is composed of gas, dust and other particles. Far from a relaxed, homogeneous environment, the ISM is thought to exist in a number of different phases in pressure equilibrium with each other (e.g., Cox, 2005). One widely-used model categorizes the ISM into cold, warm, and hot phases (e.g., McKee & Ostriker, 1977; Cox, 2005). The cold ISM is composed primarily of cold H I at $T \sim 100$ K, molecular hydrogen (H₂), and

other molecules such as CO. The warm ISM is made up of atomic H I and ionized H II with temperatures $T \sim 8000$ K, while the hot ISM is primarily highly ionized elements at $T > 10^4$ K. These phases can be further subdivided into additional ranges further describing the temperature and species of the components. (e.g., van der Hulst, 1996). In the three-phase model, the warm H I component of the ISM cools to produce the cold phase, which can then participate in star formation through either the formation of H₂ (e.g., Blitz, 1993; Fukui & Kawamura, 2010) or potentially the direct formation of stars from atomic gas (e.g., Krumholz, 2012). The SNe and stellar winds that result from star formation then shock heat surrounding regions of the ISM, producing the highly-ionized species that comprise the hot component. By applying thermal balance equations, Wolfire et al. (1995) found two stable temperatures for H I: $T \sim 50$ K for the CNM and $T \sim 7000$ K for the WNM. The properties of the ISM, including the H I component, and of star formation are closely linked. An understanding of the ISM, as traced partially by H I, is therefore necessary for understanding star formation.

1.1.2 H I 21-cm Line Production

The ground state ($1s$) of atomic hydrogen is split into two hyperfine levels that couple the spin of the proton to the spin of the electron. The state in which the spins are parallel is slightly higher than that in which they are antiparallel. This energy difference is only $\Delta E = 5.87 \times 10^{-6}$ eV, which corresponds to a wavelength of $\lambda = 21.1$ cm (Gould, 1994). The transition probability is given by the Einstein A_{ul} coefficient. For the 21-cm hyperfine transition, $A_{ul} = 2.884 \times 10^{-15} \text{ s}^{-1}$, which corresponds to an average lifetime of $\sim 1.1 \times 10^7$ yr (Gould, 1994). Because the lifetime of this state is so long and its energy is so small, collisions in the ISM populate the levels based on their statistical weights, so $n_u/n_l = g_u/g_l = 3$. (Rohlfs & Wilson, 2004). Normally such a small transition probability would be disheartening, but the large number of H I atoms in the universe means that H I emission is indeed observable.

1.1.3 H I in Nearby Galaxies

H I is found in the ISM of nearly all disk spiral and irregular galaxies. The fraction of gas mass to dynamical mass, $M_{\text{gas}}/M_{\text{dyn}}$, is approximately $\sim 10^{-2.5} - 10^{-0.5}$ in spirals (Binney & Merrifield, 1998, and references therein). H I contributes a larger fraction of the baryonic mass of galaxies and shows strong variations with galaxy morphological classification, varying between 10% of the baryonic mass in Sa galaxies to up to 95% in low surface brightness dwarf galaxies (Schombert et al., 2001, and references in therein). The sharp difference in baryonic mass fraction is thought to be due to star formation efficiency: spiral galaxies have used up more of their initial gas reservoirs in star formation, while dwarfs have formed proportionally fewer stars and are therefore left with a higher fraction of their initial gas reservoir (e.g., McGaugh & de Blok, 1997; Schombert et al., 2001). Even though many studies focus on larger spiral galaxies (e.g., Walter et al., 2008), dwarfs make up 85% of the Local Volume galaxies by number (Karachentsev et al., 2004). A complete understanding of the H I properties of disk galaxies, especially dwarfs, is essential to understanding the baryonic components as well as the evolution of these systems.

Both H I and stars in spiral galaxies are typically found in a disk shape, but the H I often extends to a larger radius than the stellar component (Giovanelli & Haynes, 1988). H I is therefore ideal for tracing large scale galactic dynamics, such as rotation curve analyses that can place constraints on the dark matter mass in galaxies (e.g., de Blok et al., 2008; Oh et al., 2011). The large radial extent of H I emission also means that it can indicate the presence of large scale features such as warps (e.g., García-Ruiz et al., 2002; Oosterloo et al., 2007). Average H I surface density profiles often exhibit a central depression in spiral galaxies, where a majority of the gas has potentially been used up in star formation (e.g., van Woerden et al., 1983) or converted to molecular hydrogen (e.g., Bigiel et al., 2008; Leroy et al., 2008).

The H I content of dwarf irregular galaxies shows both similarities and differences compared with their larger mass spiral counterparts. The H I is still often located in a rotating disk, but many more irregularities are present in dwarfs when compared with the well-behaved disks of spiral galaxies (e.g., Begum et al., 2008). These irregularities could be at-

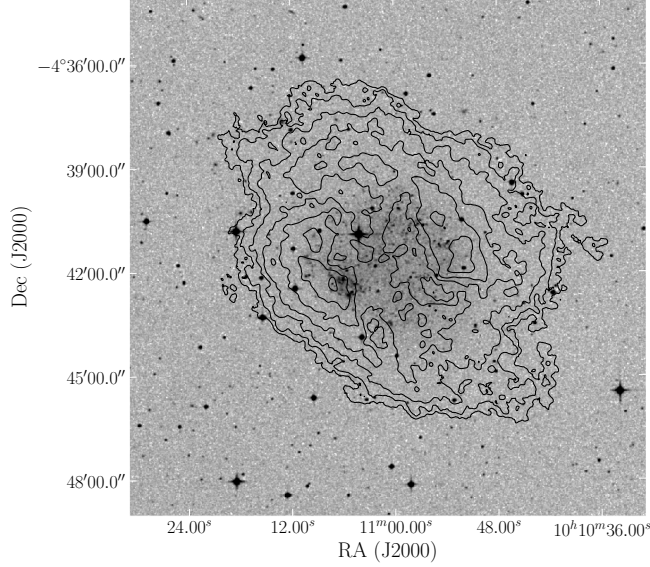


Figure 1.1 The H I morphology of Sextans A (contours), compared to optical B-band light from the Digital Sky Survey (greyscale). The optical light shows a very boxy shape. The H I is more disk-like and extends to larger radii than the B-band emission.

tributed to the fact that dwarf galaxies inhabit lower gravitational potential wells compared to their larger counterparts (e.g., Skillman, 1996). In addition, the H I surface brightness distribution can be markedly different than the optical appearance of these galaxies. An example of this can be seen in Figure 1.1, which shows the optical and H I morphology of Sextans A. While the optical appearance of this galaxy is boxy, the H I is clearly in a more disk-like shape. Similar disconnects between the optical and H I morphologies of dwarf galaxies can be found in many other examples, such as IC 10 (Wilcots & Miller, 1998) and UGC 8508 (Warren et al., 2011). However, H I is still often present at radii where optical emission has dropped off, and in some cases extends fractionally farther than in large spirals – out to 2 Holmberg diameters (Huchtmeier et al., 1981; Swaters et al., 2002). These dwarfs can but do not always exhibit the same central surface brightness distribution as large spirals (e.g., Swaters et al., 2002).

1.1.4 H I Observations

A large number of nearby galaxies have been imaged in H I, both with single dish telescopes and with modern interferometers such as the Very Large Array (VLA) or the Australia Telescope Compact Array (ATCA). These observations provide not only the spatially resolved distribution of H I on the sky but also spectral distribution of H I emission along each line-of-sight. These line-of-sight spectra allow us to characterize the kinematics of the neutral ISM.

The H I component of the ISM exhibits spatially-resolved line widths that range between $5 - 15 \text{ km s}^{-1}$ with remarkably little variation across a wide range of galaxy physical properties, such as type, star formation rate, luminosity, and halo mass (e.g., Tamburro et al., 2009). On average, the line widths decrease with increasing radius in the central regions of galaxies, but flatten to $\sim 5 \text{ km s}^{-1}$ in the outskirts of galaxies (e.g., Dickey et al., 1990; Boulanger & Viallefond, 1992; Petric & Rupen, 2007). In order to maintain the observed line widths, energy must be injected into the neutral ISM from some source. A number of drivers have been proposed to provide this energy, such as star formation, thermal heating from the UV background, or the magneto-rotational instability (MRI).

1.1.5 Potential Causes of H I line widths

The two stable temperatures for H I are $T \sim 150 \text{ K}$ and $T \sim 7000 \text{ K}$ in galaxies, which imply line widths of $\sim 1 \text{ km s}^{-1}$ or $\sim 7 \text{ km s}^{-1}$ (Wolfire et al., 1995). As seen in the previous section, line widths in nearby galaxies are often higher than these temperatures. The larger line widths plus the short cooling timescale for gas at the temperatures implied by the observed line widths ($\sim 10^3 \text{ yr}$) suggests that the line widths are likely due to turbulent motions. Many of the mechanisms for generating H I line widths are therefore for generating turbulence. However, heating from background UV radiation has also been proposed as a driver for line widths, especially in regions where turbulence cannot be efficiently generated (e.g., Schaye, 2004).

1.1.6 Turbulence in the ISM

Turbulence can generally be thought of as random gas motions across a range of scales (Mac Low & Klessen, 2004). Turbulent motions dissipate energy at an approximate rate for typical Milky Way conditions given by:

$$\dot{e} = (3 \times 10^{-27} \text{ erg s}^{-1} \text{ cm}^{-3}) \left(\frac{n}{1 \text{ cm}^{-3}} \right) \left(\frac{\sigma}{10 \text{ km s}^{-1}} \right) \left(\frac{\lambda}{100 \text{ pc}} \right) \quad (1.1)$$

where $\dot{e}$ is the energy dissipation rate, n is the gas number density, σ is the turbulent velocity dispersion, and λ is the turbulent driving scale (Mac Low, 1999; Mac Low & Klessen, 2004).

The fiducial timescale over which these motions dissipate is given by Mac Low (1999):

$$\tau_D \sim e/\dot{e} \simeq (9.8 \text{ Myr}) \left(\frac{\lambda}{100 \text{ pc}} \right) \left(\frac{\sigma}{10 \text{ km s}^{-1}} \right)^{-1}. \quad (1.2)$$

For typical ISM conditions, this time scale is typically ~ 10 Myr. Because τ_D is short compared to the age of the universe, energy must continually be injected to drive turbulent motions at a rate roughly comparable to the dissipation rate in Equation 1.1. This energy can come from a variety of sources in the ISM. The most-commonly accepted driver is feedback from massive stars, which release mechanical energy back into the ISM through stellar winds and supernovae explosions (e.g., Mac Low & Klessen, 2004; Dib et al., 2006; Joungh et al., 2009). Effects from magnetic fields have also been proposed as turbulence drivers through the magneto-rotational instability (“MRI”: e.g., Balbus & Hawley, 1991; Sellwood & Balbus, 1999). Other proposed mechanisms are due to large-scale galaxy kinematics, such as gravitational instabilities; swing-amplified shear instabilities or shocks due to spiral arms (e.g., Roberts, 1969; Huber & Pfenniger, 2001; Schaye, 2004). However, if turbulence is the primary cause behind H I line widths, any physical cause must explain turbulent motions observed not only in large spiral galaxies but also in their smaller dwarf counterparts. Mac Low & Klessen (2004) provides a good overview of the energy available from a variety of turbulent sources. I now give a brief overview of some of these proposed mechanisms.

1.1.6.1 Star Formation Feedback

Stellar feedback is the most commonly-accepted driver of turbulence in the literature today. Spitzer (1978) first proposed that star formation can return energy to the ISM through

stellar winds, ionizing photons, and finally, SNe. These processes are collectively known as “feedback” and are primarily driven by young, massive stars. A myriad of simulations have characterized the effects of feedback on the surrounding ISM (e.g., Dib et al., 2006; Governato et al., 2007; Joung et al., 2009). While stellar winds and ionizing photons do provide some energy, the most important feedback process in shaping the ISM is typically thought to be SNe (e.g., Norman & Ferrara, 1996; Mac Low & Klessen, 2004; Elmegreen & Scalo, 2004).

During a Type II supernova, the degenerate iron core of a massive star collapses under its own gravity, releasing the outer stellar layers into the ISM at velocities $\sim 10^4 \text{ km s}^{-1}$. A single SNe releases $\sim 10^{51}$ ergs of mechanical energy back into the ISM, which shock-heats the surrounding ISM over $\sim 10^6 - 10^7 \text{ yr}$ (McKee & Ostriker, 1977). At values appropriate for the Milky Way, the rate of energy input from SNe is approximately

$$\dot{e}_{\text{SN}} = (3 \times 10^{-26} \text{ erg s}^{-1} \text{ cm}^{-3}) \left(\frac{\epsilon_{\text{SN}}}{0.1} \right) \left(\frac{\sigma_{\text{SN}}}{1 \text{ SN yr}^{-1}} \right) \left(\frac{h_z}{100 \text{ pc}} \right)^{-1} \times \left(\frac{R_{\text{SF}}}{15 \text{ kpc}} \right)^{-2} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right) \quad (1.3)$$

as given by Mac Low & Klessen (2004). Here, ϵ_{SN} is the efficiency at which the SN energy couples to the surrounding gas, σ_{SN} is the number of SNe per year, h_z is the scale height of the galaxy in the z direction, R_{SF} is the star forming radius, and E_{SN} is the amount of energy released per SNe. The energy injection rate due to SNe is comparable to the dissipation rate of turbulent H I energy, so it is the most likely candidate for driving turbulent motions in regions with high enough star formation.

1.1.6.2 MRI

The MRI has been proposed as a non-stellar driver of turbulence in differentially-rotating disk galaxies (Balbus & Hawley, 1991; Sellwood & Balbus, 1999) and is occasionally cited as the cause for turbulence in the outskirts of H I disks where star formation drops dramatically (Tamburro et al., 2009). The MRI requires that particles in disks must be differentially rotating (i.e., decreasing angular velocity with radius; $\partial\Omega/\partial r < 0$), and have increasing angular momentum with radius ($\partial(r^2\Omega)/\partial r > 0$), magnetic fields, and a non-zero ionization

fraction.

The physical mechanism behind the MRI given by Sellwood & Balbus (1999) is as follows. Initially, a parcel of gas is magnetically coupled to a neighboring parcel of gas at a slightly different radius. Over time, the galactic rotational shear pulls apart the two gas parcels; the inner parcel moves azimuthally farther its orbit than the outer. Due to the magnetic coupling, the force between the two parcels increases as if they were connected by a spring. This force causes the inner particle to slow down and the outer particle to speed up relative to their existing orbits. In this exchange, the inner particle loses angular momentum and the outer particle gains angular momentum. Because angular momentum is conserved, the inner particle therefore moves farther inward and the outer particle moves outward. The separation of the two particles increases the difference in their rotational velocities and therefore produces a stronger restoring force between them, resulting in the transfer of even more angular momentum and thus further separation. The instability therefore runs away.

The conditions necessary for the MRI are generally met in the outer disks of spiral galaxies, where rotation curves tend to be flat:

$$\frac{\partial(r^2\Omega)}{\partial r} = \frac{\partial}{\partial r} r^2 \left(\frac{v_{\text{flat}}}{r} \right) = v_{\text{flat}} > 0 \quad (1.4)$$

$$\frac{\partial\Omega}{\partial r} = \frac{\partial}{\partial r} \frac{v_{\text{flat}}}{r} = -\frac{v_{\text{flat}}}{r^2} < 0, \quad (1.5)$$

where r is the galactocentric radius and v_{flat} is the velocity of the flat part of the rotation curve. Magnetic fields are also expected to thread the disks of galaxies (e.g., Heiles et al., 1993; Heiles, 1996), and motions induced in ionized gas by the MRI can couple to the neutral gas through collisions. The rate of energy injection due to the MRI can be approximated as:

$$\dot{e}_{\text{MRI}} = (3 \times 10^{-29} \text{ erg s}^{-1} \text{ cm}^{-3}) \left(\frac{B}{3 \mu\text{G}} \right)^2 \left(\frac{\Omega}{(220 \text{ Myr})^{-1}} \right), \quad (1.6)$$

where B is the magnetic field strength and Ω is the angular velocity of rotation (Mac Low & Klessen, 2004). This equation is valid in the flat regime of the rotation curve as found in the outskirts of the Milky Way and other large spiral galaxies. A number of studies (e.g., Sellwood & Balbus, 1999; Dziourkevitch et al., 2004; Tamburro et al., 2009) have cited the MRI as a possible driver of the velocity dispersion in the outer regions of spirals where

the star formation rate is low but H I still shows appreciable velocity dispersions of $\sigma \sim 6$ km s⁻¹.

However, the ability for the MRI to function efficiently in dwarf galaxies is questionable. Dwarfs often have solid body rotation and constant angular velocity, so the conditions necessary for the MRI to function effectively are not met:

$$\frac{\partial\Omega}{\partial r} = 0 \quad (1.7)$$

even though the second condition is satisfied:

$$\frac{\partial(r^2\Omega)}{\partial r} = r\Omega > 0. \quad (1.8)$$

Because slowly-rising or flat rotation curves produce little to no shearing motions with increasing radius, the MRI should be less effective in dwarf galaxies. As an additional limitation, the magnetic field strengths are often much lower in dwarfs compared to large spirals (e.g., Chyży et al., 2011), so the energy input rate from MRI would be decreased. Therefore, the MRI may play a role in driving turbulence in the outskirts of large spiral galaxies, but is likely not a large contributor to turbulent motions in dwarfs even though H I velocity dispersions are comparable.

1.1.6.3 Gravitational Instabilities

A number of gravitational instabilities could potentially provide turbulent energy to the ISM, but as with the MRI, many are only efficient in large spirals. Some of these instabilities rely on spiral structure, which is typically lacking in dwarf galaxies. In the presence of spiral structure, gas that flows through spiral arms is shocked by gravitational instabilities, which can produce motion in the z -direction that contribute to turbulence (e.g., Roberts, 1969; Lin & Shu, 1964; Martos & Cox, 1998). Other proposed mechanisms link the gravitational potential to turbulent motions, sometimes requiring shearing motions (e.g., Vollmer & Beckert, 2002) but not always explicitly (e.g., Wada et al., 2002). However, estimates of the energy injection rate for the Wada et al. (2002) gravitational instability are not high

enough to replenish the energy dissipated by turbulence (Mac Low & Klessen, 2004):

$$\dot{e}_{\text{grav}} = (4 \times 10^{-29} \text{ erg s}^{-1} \text{ cm}^{-3}) \left(\frac{\Sigma_g}{10 \text{ M}_{\odot} \text{ pc}^{-2}} \right)^2 \left(\frac{h_z}{100 \text{ pc}} \right)^{-2} \left(\frac{\lambda}{100 \text{ pc}} \right)^2 \times \left(\frac{\Omega}{(220 \text{ Myr})^{-1}} \right), \quad (1.9)$$

where Σ_g is the disk gas surface density, h_z is the scale height in the z -direction, λ is the scale length of turbulence, and Ω is the angular velocity of rotation.

1.1.7 Non-turbulent Drivers

While many studies attribute the cause of H I line widths to turbulence, other sources are certainly possible. These additional sources are usually invoked to explain line widths in the outskirts of spiral galaxies, where line widths are substantial even though the main culprit, star formation, falls off dramatically (e.g., Tamburro et al., 2009). For example, the ISM in the solar region of the Milky Way has temperatures ~ 5000 K, with a substantial fraction in the unstable region between $500 \lesssim T \lesssim 5000$ K (Heiles & Troland, 2003; Redfield & Linsky, 2004). These temperatures correspond to a maximum line width of $\sim 6 \text{ km s}^{-1}$, as is often observed in the outer regions of disk galaxies. However, the local star formation rate surface density (Σ_{SFR}) of the Milky Way is $\sim 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ (Kennicutt & Evans, 2012, and references therein), which is comparable to Σ_{SFR} values measured in our sample. Therefore, the temperatures in the outskirts of disk galaxies could indeed be thermal, not turbulent. However, the thermal energy in these lines decays much more quickly than turbulent energy, on a timescale of $\sim 10^3 \text{ yr}$ (e.g., Wolfire et al., 2003), so a high energy injection rate is necessary to sustain observed line widths if they are thermal in origin. H I energy in the outer regions of galaxies could potentially be supplied by a thermal UV background (Schaye, 2004; Tamburro et al., 2009).

1.2 Motivation

The source of H I line widths, while often attributed to star formation energy, is still uncertain in the low star formation intensity regime. As discussed above, studies have shown that star formation can provide enough energy to drive H I velocity dispersions in the in-

ner regions of spiral galaxies. However, H I lines still show appreciable velocity dispersions even in regions of low star formation, such as the outer regions of spiral galaxies, low surface brightness galaxies, and dwarfs. Our understanding of the cause of H I kinematics is therefore incomplete.

A number of recent surveys have given us the ability to provide a handle on coupling the H I kinematics to local ISM properties, including star formation. Uniform, high-resolution H I surveys of nearby galaxies have been undertaken in the past 10 years, such as WHISP (“Westerbork H I Survey of Irregular and Spiral Galaxies”; Swaters et al., 2002); FIGGS (“Faint Irregular Galaxies GMRT Survey”; Begum et al., 2006); THINGS (“The H I Nearby Galaxy Survey”; Walter et al., 2008); VLA-ANGST (“Very Large Array ACS Nearby Galaxy Survey Treasury”; Ott et al., 2012). Similarly, time-resolved star formation histories have been generated for ~ 70 galaxies in the local universe with the ACS Nearby Galaxy Survey Treasury (“ANGST”; Dalcanton et al., 2009; Williams et al., 2011; Weisz et al., 2011). The combination of H I data with detailed star formation properties potentially allows a better understanding of the coupling between star formation energy and ISM kinematics, and therefore probes the cause of H I line widths in these systems.

1.2.1 A New Era of H I Surveys

Since the detection of the 21-cm H I line in the mid-twentieth century (Ewen & Purcell, 1951), the facilities for H I observations have vastly improved, as we not only have large single dish telescopes ideal for sensitive studies of global H I characteristics in galaxies (e.g., Green Bank, Arecibo) but also interferometers that provide detailed information on the spatial and kinematic structure of H I (e.g., the VLA or the ACTA).

Until the last ~ 20 years, there were few systematic studies of the spatially-resolved structure of H I in nearby galaxies. Previously, interferometric studies of H I in galaxies were often non-uniform and limited to individual galaxies, while single-dish studies lacked the resolution necessary to study H I emission on fine scales in most disk galaxies. However, a number of large, systematic surveys have recently been undertaken to provide more uniform H I observations, such as WHISP and THINGS. In the last 5-10 years, new H I surveys have

been focused on nearby dwarf galaxies, such as FIGGS, LITTLE THINGS, and VLA-ANGST.

In addition to providing a uniform sample of high spatial resolution H I observations of nearby galaxies, these surveys also have much higher velocity resolution than many literature studies of spiral galaxies. This high velocity resolution has historically only been possible for dwarf galaxies with relatively narrow line widths, as the available correlator bandwidth required a trade-off between the velocity resolution of the observation and the velocity range that could be covered. Since dwarf galaxies have the narrowest integrated H I line spectra, they are among the few galaxies that can be observed with a narrow total bandwidth and therefore high velocity resolution. Such high velocity resolution is necessary in many of these galaxies, as the turbulent velocities can be of the same order of magnitude as the rotational velocities. Recent work has shown that high velocity resolution is necessary to distinguish rotational gradients across the disk of the lowest-mass dwarfs (e.g., Begum et al., 2008), as previous observations with coarse velocity resolution erroneously indicated that H I in dwarfs was primarily chaotic with no rotational component (Lo et al., 1993). Instead, is clearly not the case; even small dwarfs show rotational gradients across their disks (Begum et al., 2008; Ott et al., 2012).

1.2.2 Detailed Star Formation Surveys

ANGST provides uniform, multi-color *Hubble Space Telescope* (*HST*) photometry of the stellar populations in nearby galaxies. The data calibration pipeline and resulting distance measurements are discussed in detail in Dalcanton et al. (2009). The sample consists of galaxies outside the Local Group but within ~ 4 Mpc. Observations were taken using the Advanced Camera for Surveys (ACS) or using Wide Field Planetary Camera 2 (WFPC2) for those observations after the ACS failure. If available, archival data were used. Galaxies with recent star formation were observed in three filters (F475W, F606W, F814W), while those without strong recent star formation were only observed in two (F475W, F814W). The photometric depth of ANGST observations reaches several magnitudes below the tip of the red giant branch, allowing for the calculation of precise distances to these systems.

The photometric measurements of resolved stars also allow us to construct color-magnitude diagrams (CMDs) for the systems.

From the CMDs, star formation histories (SFHs) of the galaxies can be determined by fitting isochrones from model stellar populations. These SFHs can provide an estimate of the amount of energy returned to the ISM as a function of time on both spatial and disk-averaged scales. Projects capitalizing on this idea have been undertaken using either ANGST or other similar *HST* observations. Dohm-Palmer et al. (2002) determined the SFH of Sextans A on both time- and spatially-resolved scales, and others extended this analysis in comparisons between stellar feedback to H I holes (e.g., Weisz et al., 2009a,b; Warren et al., 2011). Johnson et al. (2012) has shown that the recent SFHs are non-uniform in dwarf galaxies, in contrast with common assumptions made when using broadband tracers to determine SFR. The high-quality H I necessary for these types of studies was only available for a handful of nearby galaxies until the advent of the H I surveys discussed in § 1.2.1.

1.2.3 Remaining Questions

The cause of H I line widths remains unknown in the outer regions of disk galaxies and in dwarf galaxies where star formation rates are low (e.g., Dickey et al., 1990; Petric & Rupen, 2007; Tamburro et al., 2009). I can attempt to address these questions with the combination of resolved SFHs and the high-resolution H I surveys of nearby dwarf galaxies. The high velocity resolution of VLA-ANGST and THINGS allows for detailed studies of ISM kinematics, as traced by H I, and their relationship to star formation, as traced by FUV. Meanwhile, ANGST time-resolved SFHs allow for estimates of the energy input to the ISM over the past ~ 100 Myr. The combination of these surveys allows studies of the relationship between star formation and the ISM that until recently have only been possible in a handful of nearby galaxies.

1.3 Outline

In Chapter 2 I describe the VLA-ANGST survey and the calibrated H I data it provides. The survey primarily targets dwarf galaxies, providing high spatial and spectral resolution observations that paint a more complete view of the nearby galaxy population. The sample

spans a large range in physical properties: between -8 to -18 in absolute B-band magnitude, 10^{-4} to $10^{-1} \text{ M}_{\odot} \text{ yr}^{-1}$ in SFR, and 10^5 to $10^9 \text{ M}_{\odot}$ in H I mass. I describe the calibration and imaging pipelines as well as the final, publicly-available data products. When combined with H I data from THINGS, these data form the basis for the rest of the scientific studies presented in this thesis.

In Chapter 3 I present a method for measuring a single, average velocity dispersion for a galaxy. I first generate flux-weighted, average H I spectra by co-adding individual line-of-sight spectra after removing the approximate rotational velocity. These “superprofiles” are composed of a narrow central peak with wings of higher velocity gas to either side. The superprofiles are very similar from galaxy to galaxy when scaled to the half-width at half-maximum of the central peak. I interpret the central peak as representing the average turbulent velocity dispersion, with the wings arising from H I that has been accelerated to higher velocities compared to the average. I then compare kinematic properties of the superprofiles to galaxy physical properties, such as average surface mass densities and star formation intensities.

In Chapter 4 I extend the techniques in Chapter 3 to spatially-resolved scales in a subset of the global sample. I generate superprofiles in radial annuli and in regions determined by the local Σ_{SFR} . I again compare the properties of these superprofiles to the local ISM properties. I also examine whether star formation can provide enough energy to drive the observed H I kinematics for each superprofile.

In Chapter 5, I combine analysis of H I kinematics with time-resolved star formation properties from the ANGST program. I generate superprofiles from VLA-ANGST and THINGS data cubes for galaxies also in the ANGST sample. To search for the timescale over which star formation affects the surrounding ISM, I compare the H I kinematics to the star formation rate averaged over a wide range of timescales between 0 – 100 Myr.

Finally, in Chapter 6, I present the overall conclusions of the work presented in this thesis and discuss future scientific studies based on this work.

Chapter 2

THE VLA-ANGST H I SURVEY

Sections 2.3.3 - 2.4.3.3 and Figures 2.1 - 2.31b of this chapter originally appeared in Ott et al. (2012), and have been reproduced by permission of the AAS.

Star formation in galaxies is driven by complex processes in the ISM. It is thought that stars form from cold ISM gas, and then return their energy back to the ISM through complex feedback processes (e.g., Mac Low & Klessen, 2004; Dib et al., 2006; Krumholz et al., 2009). To better understand the star formation cycle, we must therefore study the local conditions of the ISM.

One of the best tracers of the warm ISM is H I. Roughly 10% of spiral galaxies’ baryonic mass is in H I with substantially larger fractions in dwarf galaxies (e.g., Schombert et al., 2001, and references therein). Additionally, it provides a tracer of ISM kinematics out to radii typically much larger probed than optical observations (Giovanelli & Haynes, 1988). H I is also thought to be affected by star formation feedback, as massive stars, stellar winds, and supernova explosions release mechanical energy back into the ISM (Mac Low & Klessen, 2004; Joung et al., 2009). Star formation and H I are therefore intricately linked in galaxies, and observations of both components are required to provide a full understanding of the physical processes that occur in galaxies.

A number of large, interferometric H I surveys of nearby galaxies have been completed in recent years, providing high-quality H I data for both large spirals and dwarfs. Detailed spatial information on H I kinematics for over 100 galaxies is now available from these surveys, which include the survey discussed in this chapter, VLA-ANGST (“The Very Large Array ACS Nearby Galaxy Survey Treasury”; Ott et al., 2012) as well as THINGS (“The H I Nearby Galaxy Survey”; Walter et al., 2008), FIGGS (“Faint Irregular Galaxies GMRT Survey”; Begum et al., 2008), LITTLE THINGS (“Local Irregulars That Trace Luminosity

Extremes”; Hunter et al., 2012), SHIELD (“Survey of H I in Extremely Low-mass Dwarfs”; Cannon et al., 2011), and LVHIS (“The Local Volume H I Survey”; Koribalski & Jerjen, 2008).

Our understanding of the interplay between star formation and the ISM cannot be furthered by H I alone, but must include information about star formation as well. Recent complementary surveys provide knowledge of the star current and recent star formation rates for many of these galaxies. Thanks to the Local Volume Legacy survey (“LVL”; Dale et al., 2009) and the Spitzer Infrared Nearby Galaxies Survey (“SINGS” Kennicutt et al., 2003), broadband far ultraviolet (FUV) and $24\mu\text{m}$ observations are available for a number of these galaxies. The combination of FUV and $24\mu\text{m}$ observations from these surveys provides spatially-resolved measurements of recent star formation on timescales of $\tau \sim 10 - 100$ Myr. Shorter star formation timescales ($\tau \sim 5$ Myr) can be traced by H α measurements, as provided by 11HUGS (Kennicutt et al., 2008). However, understanding star formation over better-resolved timescales may be necessary for constraining the relationship between star formation feedback and H I kinematics.

Recently, uniform, multi-color observations of resolved stellar populations have become available for a volume-limited sample of galaxies through the ANGST program. Observations such as these can only be made with the high angular resolution available from the *Hubble Space Telescope* (*HST*). The color-magnitude diagrams (CMDs) derived from ANGST observations allow measurements of the time-resolved star formation histories of the sample galaxies over the past ~ 500 Myr. The ANGST observations cover a wide range of galaxy physical properties and environments, yielding information about star formation in a variety of different ISM conditions.

To complement the ANGST observations, the VLA-ANGST H I survey was undertaken. VLA-ANGST provides detailed VLA H I maps for a number of ANGST galaxies at high spatial ($\sim 6''$) and spectral ($0.6 - 2.6 \text{ km s}^{-1}$) resolution. The resulting maps not only allow us to study the warm ISM in a number of nearby dwarfs for the first time ever but also allow us to tie the ANGST star formation histories to current ISM conditions. A number of the data products from VLA-ANGST have been made publicly-available to the community.

In this chapter, I discuss the VLA-ANGST survey in more detail. Section 2.1 gives

general properties of the VLA-ANGST sample. I describe the observational setup of the survey in §2.2 and the data reduction and imaging pipeline in §2.3. Finally, I present the final data products from VLA-ANGST in §2.4.

2.1 Sample Selection

The VLA-ANGST targets were chosen as a subset of the 69 ANGST galaxies. ANGST targeted all galaxies, excluding the Local Group, that met the following conditions: (1) $D < 3.5$ Mpc (or $D < 4$ Mpc for the M81 and Sculptor groups) to provide the spatial resolution necessary for resolved stellar photometry; and (2) Galactic latitudes $|b| > 20^\circ$ to avoid contamination from Milky Way stars (Dalcanton et al., 2009).

While some of the ANGST galaxies had existing high-quality H I observations available when the project was undertaken, a number either lacked any H I observations or were not observed with high enough spatial and spectral resolution to achieve the goals of the project. The majority of galaxies without high-quality H I observations were low-mass dwarfs. The VLA-ANGST sample was chosen from ANGST to meet the following criteria:

1. No existing high-quality H I observations;
2. Observable with the VLA (i.e., north of -30° declination);
3. Show evidence of gas or star formation (i.e., galaxies with late-type morphologies or signs of recent star formation in their optical colors).

The final sample is listed in Table 2.1, as reproduced from Ott et al. (2012). The columns are (1) galaxy name; (2-3) central right ascension and declination; (4) distance as derived from ANGST TRGB measurements or as given in Karachentsev et al. (2004) if marked; (5) absolute B-band magnitude; (6) de Vaucouleurs galaxy morphological classification as given by Karachentsev et al. (2004); and (7) SFR derived from FUV measurements, where $\text{SFR} = 1.4 \times 10^{-28} L_{\text{FUV}}$ ($\text{ergs s}^{-1} \text{ Hz}^{-1}$). As can be seen from the table, the final sample spans a wide range of galaxy properties, including morphology (Types 3 - 10), B-band luminosity ($-8.6 > M_B > -17.9$), and star formation rate ($10^{-4} < \text{SFR} < 10^{-1}$). The

Table 2.1: **The VLA-ANGST Sample:** sample galaxies and their global properties. This table has been reproduced with minor formatting changes from Ott et al. (2012). References — (5) TRGB distance from Dalcanton et al. (2009); (6) taken from Dalcanton et al. (2009) and converted to physical diameters; (7) apparent blue magnitude from Karachentsev et al. (2004) converted to absolute blue magnitude; (8) converted from IR fluxes given by Dale et al. (2009); (9) T-type from Dalcanton et al. (2009); (10) converted from GALEX FUV asymptotic magnitudes given by Lee et al. (2011) using $\text{SFR} = 1.4 \times 10^{-28} L_\nu$ ($\text{erg s}^{-1} \text{Hz}^{-1}$) (Kennicutt, 1998).

1	2	3	4	5	6	7	8	9	10
Name	Alt. Name	RA [hh:mm:ss]	DEC [dd:mm:ss]	D [Mpc]	D_{25} [kpc]	M_B [mag]	νL_ν [$10^6 L_\odot$]	Type	SFR [$10^{-3} M_\odot \text{yr}^{-1}$]
NGC 247	ESO 540-G022, UGCA 11	00:47:08.3	-20:45:36	3.50	15.7	-17.86	270.52	7	229
DDO 6	ESO 540-G031, UGCA 15	00:49:49.3	-21:00:58	3.31	1.6	-12.41	...	10	1.4
NGC 404	UGC 718	01:09:26.9	35:43:03	3.05	2.2	-16.21	...	-1	6.6
KKH 37	LEDA 95597	06:47:45.8	80:07:26	3.26	1.1 ^a	-11.17	0.69	10	0.3
UGC 4483	CGCG 331-051	08:37:03.0	69:46:31	3.41	1.2	-12.71	0.57	10	4.0
KK 77	LEDA 166101	09:50:10.0	67:30:24	3.55	2.5 ^a	-11.45	...	-3	...
BK3N	PGC 28529	09:53:48.5	68:58:09	3.86	0.6	-9.15	<0.03	10	0.3
AO 0952+69 ^b	Arp's Loop	09:57:29.0	69:16:20	3.78	2.0	-11.09	...	10	1.1
Sextans B	UGC 5373, DDO 70	10:00:00.1	05:19:56	1.39	2.1	-13.87	2.48	10	4.5
NGC 3109	ESO 499-G036, DDO 236	10:03:07.2	-26:09:36	1.26	6.2	-15.11	12.40	10	28.7
Antlia	PGC 29194	10:04:04.0	-27:19:55	1.29	0.8	-9.36	...	10	1.8
KDG 63	UGC 5428 DDO 71	10:05:07.3	66:33:18	3.53	1.7	-11.73	1.36	-3	...
Sextans A	UGC 205, DDO 075	10:11:00.8	-04:41:34	1.38	2.2	-13.84	1.82	10	12.3
HS 117	...	10:21:25.2	71:06:58	3.82	1.7	-11.41	1.08	10	...

Continued on next page

Table 2.1, continued

DDO 82	UGC 5692	10:30:35.0	70:37:10	3.80	3.8	-14:33	...	9	2.6
KDG 73	PGC 32667	10:52:55.3	69:32:45	4.03	0.7	-10.94	0.81	10	0.3
NGC 3741	UGC 6572	11:36:06.4	45:17:07	3.24	1.9	-13.17	1.29	10	6.2
DDO 99	UGC 6817	11:50:53.0	38:52:50	2.59	3.1	-13.37	1.43	10	5.5
NGC 4163	NGC 4167, UGC 7199	12:12:08.9	36:10:10	2.86	1.6	-13.65	3.66	10	4.0
NGC 4190	UGC 07232	12:13:44.6	36:38:00	3.50 ^c	1.7	-14.20	5.80	10	10.1
DDO 113	UGCA 276	12:14:57.9	36:13:08	2.95	1.3	-11.65	0.61	10	...
MCG +09-20-131	CGCG 269-049	12:15:46.7	52:23:15	1.60 ^d	0.6	-10.72	...	10	0.4
DDO 125	UGC 7577	12:27:41.8	43:29:38	2.58	3.2	-14.11	4.15	10	5.3
UGCA 292	PGC 42275	12:38:40.0	32:46:00	3.62	1.1	-11.69	0.48	10	2.9
GR 8	UGC 8091, DDO 155	12:58:40.4	14:13:03	2.08	0.7	-11.98	0.34	10	2.4
UGC 8508	IZw 60	13:30:44.4	54:54:36	2.58	1.3	-12.94	1.40	10	...
DDO 181	UGC 8651	13:39:53.8	40:44:21	3.14	2.1	-13.03	1.51	10	3.8
DDO 183	UGC 8760	13:50:51.1	38:01:16	3.22	2.1	-13.09	1.63	9	3.2
KKH 86	LEDA 2807150	13:54:33.6	04:14:35	2.59	0.5 ^a	-10.19	0.22	10	0.1
UGC 8833	PGC 49452	13:54:48.7	35:50:15	3.08	0.8	-12.29	0.60	10	1.4
KK 230	KKR 3	14:07:10.7	35:03:37	1.97	0.3 ^a	-8.57	0.05	10	0.2
DDO 187	UGC 9128	14:15:56.5	23:03:19	2.21	1.1	-12.34	0.39	10	1.1
DDO 190	UGC 9240	14:24:43.5	44:31:33	2.79	1.5	-14.13	3.12	10	6.1
KKR 25	LEDA 2801026	16:13:47.6	54:22:16	1.93	0.6 ^a	-9.98	<0.02	10	...
KKH 98	LEDA 2807157	23:45:34.0	38:43:04	2.54	0.8 ^a	-10.32	0.40	10	0.6

^a for the KK-listed objects, the diameters are taken at the 26.5 mag arcsec⁻² surface brightness level

^b object might be a feature in the spiral arm of M81 rather than a galaxy

^c TRGB distance from Karachentsev et al. (2004)

^d the TRGB branch was not unambiguously identified in Dalcanton et al. (2009)

powerful combination of ANGST with its counterpart VLA-ANGST allows study of detailed effects of star formation on the surrounding ISM on temporal and spatially-resolved scales.

I also show a comparison between general properties of the VLA-ANGST and THINGS samples in Figure 2.1. The VLA-ANGST galaxies are on average closer as they were selected from the ANGST sample. On average, they also have later T-types than the THINGS galaxies. The total stellar mass (M_{star} , derived from $3.6\mu\text{m}$ luminosity) and H I mass (M_{HI}) also tend to be lower. When the two surveys are combined, one obtains a sample that spans a wide range of galaxy properties.

2.2 *Observational Setup*

The VLA-ANGST observational setup was chosen to mimic the THINGS survey as closely as possible to provide a complementary data set. Each VLA-ANGST target was observed in three different VLA configurations (B, C, and D) to combine the high spatial resolution of B-configuration with the sensitivity of D-configuration to extended structures up to $16'$ at 1.4 GHz. Observing times for each configuration (B: 9 hours; C: 3 hours; D: 2 hours) were chosen to reach a combined noise level of $\sim 1 \text{ mJy beam}^{-1}$ in the final images. An additional dynamically-scheduled hour of D-configuration observing time was awarded to the project to compensate for data loss due to the presence of EVLA antennas. The problems associated with these antennas that led to data loss are discussed in more detail in § 2.2.1. In order to produce a more circular beam at southern latitudes, the four galaxies with $\delta < -20^\circ$ (NGC 3109, NGC 247, Antlia, and DDO 6) were observed with hybrid configurations (BnA, CnB, DnC) in which antennas along the northern arm have more elongated spacings than the standard configurations.

Due to the limited bandwidth available from the VLA correlator, the correlator mode and therefore the spectral resolution were chosen to cover the full H I line of the galaxy plus $\sim 20\%$ for continuum subtraction. Online Hanning smoothing was not applied to any observation, but was performed offline for the five galaxies imaged with the inclusion of archival observations where online Hanning smoothing was used. This process helps prevent Gibbs ringing when sharp spectral line features are processed in the correlator,

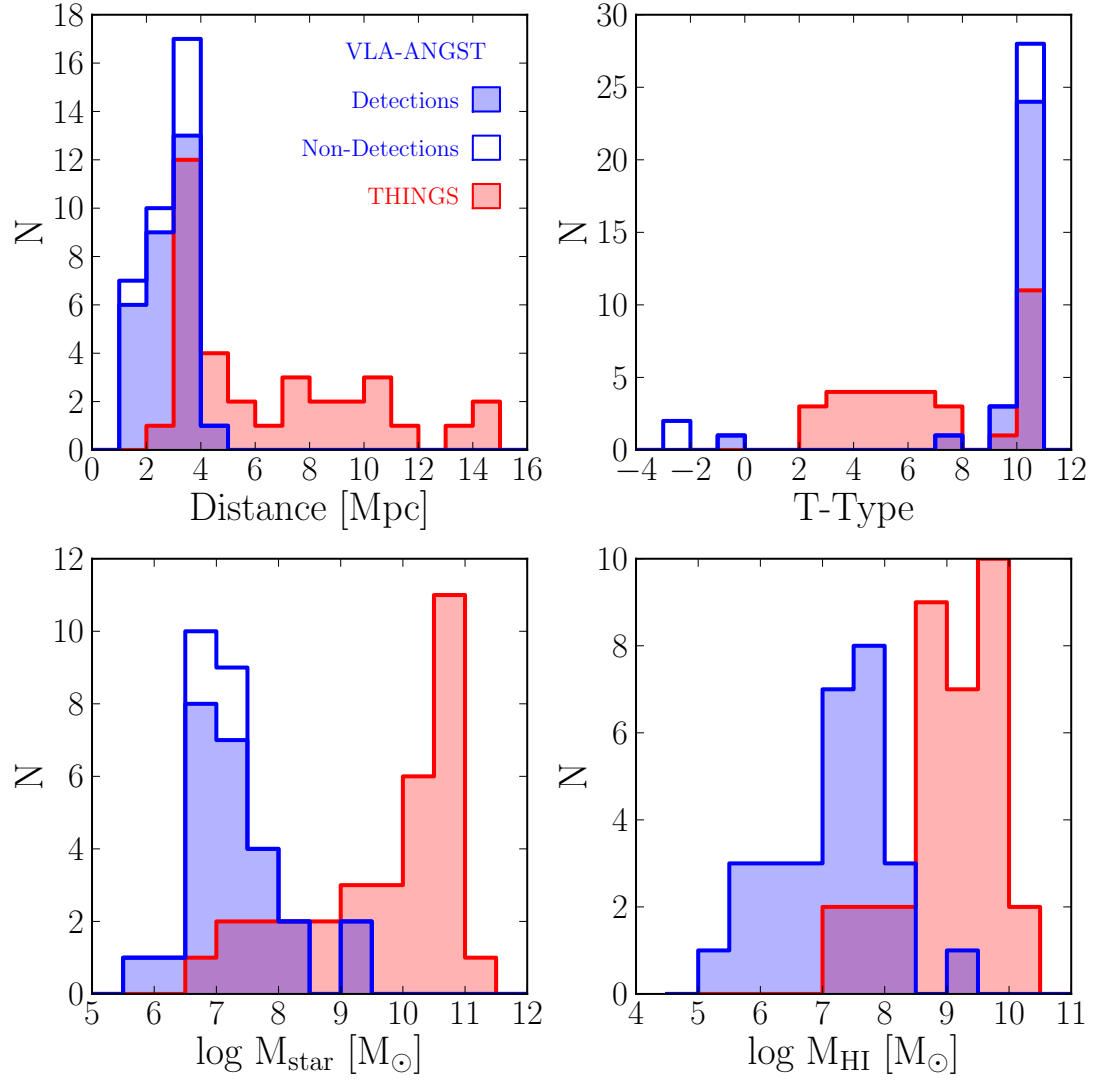


Figure 2.1 Properties of the detected VLA-ANGST sample (blue) compared with THINGS (red). VLA-ANGST non-detections are shown in white. VLA-ANGST galaxies are closer and have later T-types, lower stellar masses, and lower H I masses. The combination of VLA-ANGST with THINGS traces a wide range of galaxy properties.

but the H I signals from the VLA-ANGST galaxies are typically not strong enough to be affected by Gibbs ringing. For all observations, a 25 MHz front-end filter was used during the observations to reduce spurious signals from radio frequency interference (RFI).

Nineteen galaxies were observed with 0.78 MHz bandwidth and 256 channels, which corresponds to a channel spacing of $\Delta v \sim 0.6 \text{ km s}^{-1}$ over a range of $\sim 150 \text{ km s}^{-1}$. Fourteen galaxies had single-dish H I spectra that were too wide for this configuration and thus were observed with 1.56 MHz bandwidth and 256 channels, or $\Delta v \sim 1.3 \text{ km s}^{-1}$ over $\sim 300 \text{ km s}^{-1}$. Due to the inclusion of archival data later in the imaging process, five of the above galaxies were later imaged at coarser velocity resolutions. The remaining two galaxies, KK 77 and NGC 247, were observed with the 4IF correlator mode at $\Delta v = 2.6 \text{ km s}^{-1}$ over $\sim 500 \text{ km s}^{-1}$. For NGC 247, the 4IF mode was required to cover its full line width, which is too large to be captured by any 2IF correlator mode at 2.6 km s^{-1} resolution. In the case of KK 77, the systemic velocity of the galaxy was unknown. We therefore sought to maximize the detection chance by searching over the widest possible velocity range at our chosen spectral resolution.

A typical observing track is as follows. The track started with a ~ 10 minute observation of a flux calibrator — either 3C 286 or 3C 48, depending on visibility. To track the phase shifts introduced by the atmosphere, it was then necessary to bracket any source observation with phase calibrator scans over time scales appropriate for L-band (~ 45 minutes). The telescope therefore switched to the phase calibrator for ~ 3 minutes, chosen such that the calibrator was nearby ($\lesssim 1^\circ$), had a flux of $\gtrsim 1 \text{ Jy}$, and was listed as a primary calibrator for L-band as given in the VLA Calibrator Manual¹. The telescope then alternated between pointing at the galaxy for ~ 40 minutes and observing the phase calibrator for ~ 3 minutes until the end of the track. At the end of long observations, a second observation of the flux calibrator was made, again for ~ 10 minutes. B- and C-configuration observations typically had only a single galaxy per track. To minimize calibrator overhead and maximize uv -coverage for D-configuration observations, a number of galaxies were typically observed in a single observing block. In these cases, the flux calibrator was observed in the beginning at

¹Located at <http://www.vla.nrao.edu/astro/calib/manual/>

all source frequencies. Each phase calibrator-source-phase calibrator observation was then performed once. The observation cycled through source observations, bracketed by their phase calibrators, until the end of the observation block, leaving enough time to re-observe the flux calibrator at all source frequencies.

For fourteen galaxies, emission from the MW was present at a line-of-sight velocity that could potentially contaminate either the calibrator or source observations. In these cases, the flux calibrator was observed at ± 4 MHz offsets from the source frequency. The phase calibrator, however, was observed at the source frequency to prevent phase shifts at frequency changes in EVLA-VLA baselines (see § 2.2.1). Any channels in the phase calibrator observation that showed MW interference were then flagged by hand before calibration.

2.2.1 Issues Posed by the EVLA-VLA Transition

Observations for VLA-ANGST were taken between October 2007 and August 2008, while the VLA was being upgraded to the “Expanded Very Large Array” (EVLA). A number of EVLA antennas were therefore present in the observations, with the fewest number (~ 10) during B-configuration observations and the most ($\gtrsim 15$) during D-configuration observations. To provide telescope functionality during the transition, the EVLA antennas were retrofitted to work with the existing VLA correlator. The effects of this transition period posed a number of problems for VLA-ANGST observations.

First, the digital signals from EVLA antennas were converted to analog signals that could be read by the VLA correlator. This conversion introduced aliased power into the first ~ 0.5 MHz of the observing band. Since this false signal was only present in EVLA antennas, only EVLA-EVLA baselines showed the signal after cross-correlation; the signal correlated out in EVLA-VLA baselines. Because no adequate post-processing solutions were available, we flagged all EVLA-EVLA baselines for our observations. Since the most EVLA antennas were present in the array in D-configuration, we received an hour of dynamically-scheduled time to compensate for the loss of data from these baselines.

The aliasing on EVLA antennas also caused non-standard bandpass shapes. Historically, VLA antennas have had a very flat bandpass across the inner $\sim 80\%$ of the band. Amplitude

and phase calibration was then typically performed on a pseudo-continuum “Channel 0” (CH 0) data set that was automatically generated from the inner 75% of channels. The amplitude and phase calibration for the CH 0 was then applied to the line data, and as a last step the line data were bandpass-calibrated. Because the bandpasses of EVLA antennas were not flat over this channel range, a bandpass correction had to be applied and a new CH 0 data generated before calibration. This effect resulted in an alteration of the standard order of calibration steps for spectral line data.

A second problem with the transitional EVLA-VLA array introduced random phase shifts on VLA-EVLA baselines with small observing frequency shifts. It was therefore necessary to re-observe the phase calibrator any time the observing frequency changed by even a small amount. The use of Doppler tracking on VLA-EVLA would have introduced small frequency shifts multiple times over a single observing track (up to 9 hours) to correct for the motion of the earth with respect to the source, with the intent to provide channels constant in velocity space as opposed to frequency space. The random phase shifts introduced by Doppler tracking would have rendered our observations useless. We therefore observed all galaxies without the use of Doppler tracking. However, a post-calibration correction (CVEL) was applied to re-align the channels to uniform source velocity instead of uniform observing frequency.

2.3 Data Reduction Pipeline

In this section I discuss the pipeline implemented by the VLA-ANGST team to perform consistent data calibration, data imaging, and generation of data products. To produce a data set as uniform as possible compared to THINGS, we followed the procedure outlined in Walter et al. (2008) when possible. However, the order of some steps have changed to mitigate effects from the inclusion of EVLA antennas in the array. We first performed bandpass, amplitude, and phase calibration on a pseudo-continuum data set generated from our spectral line data (§ 2.3.1). We then performed additional post-calibration steps to the data, such as continuum subtraction and re-alignment of velocity channels (§ 2.3.2). Next, we generated maps from the UV data and deconvolved the synthesized beam from the image (§ 2.3.3). Finally, we calculated the total spectra and H I mass of the galaxies (§ 2.3.6).

2.3.1 *uv* Data Calibration

We performed all calibration using the AIPS² package. Due to the presence of EVLA antennas and their effects in our observations (see § 2.2.1), our reduction pipeline differed significantly from the standard spectral line reduction scheme. The standard procedure is to: (1) flag bad visibilities; (2) calibrate fluxes using the flux calibrator on the CH 0 data; (3) calibrate phases using the phase calibrator on the CH 0 data; (4) copy calibration to the line data; and (5) perform bandpass calibration on the line data using the bandpass calibrator. We shifted the order of some of the above steps in our pipeline to account for EVLA effects.

Data from separate observation tracks were individually calibrated and combined into one large data set immediately before imaging. We typically had 4 separate observations of each galaxy to combine: 1 from B-configuration, 1 from C-configuration, and two from D-configuration. These numbers varied based on the inclusion of archival data and catastrophic problems with an observation that prevented its inclusion. The calibration procedure was an iterative process; if we found that additional flagging was necessary after some calibration steps were performed, we re-ran all calibration steps after the new flags were applied.

We first prepared each separate observation of the source for calibration. After reading the data into the AIPS (task FILLM), we cropped $\sim 10\%$ of channels on either side of the bandpass to eliminate spurious effects from edge channels with low signal-to-noise (UVCOP). To mitigate the effects of EVLA antennas on our data, all EVLA-EVLA baselines were immediately flagged; EVLA-VLA and VLA-VLA baselines were retained (UVFLG). We first inspected all calibrator *uv* data by eye for bad visibilities, and any untrustworthy visibilities were then flagged (UVFLG, TVFLG, SPFLG, WIPER). Some calibrators showed the effects of solar interference, which is characterized by high signal on short baselines. In these cases, we excluded the inner ~ 1 k λ of baselines from calibration, depending on the extent of the interference. We then corrected for the position of EVLA antennas as recommended by NRAO to provide correct *uv* values for EVLA visibilities (VLANT). It was also necessary to choose a reference antenna for calibration. Ideally, this antenna was well-

²The Astronomical Image Processing System (AIPS) has been developed by the NRAO.

behaved throughout the observation, situated near the center of the array, and on either the east or west arm to prevent shadowing from nearby antennas. After these preparation steps, the data were run through the pipeline.

For galaxies without any potential interference from MW H I, the pipeline was as follows. We first performed bandpass correction to account for the EVLA bandpass shapes. We set the flux of the flux calibrator using known values from NRAO (SETJY). Bandpass calibration was then performed (BPASS); this task assumes that the flux calibrator has a flat slope across the bandpass and that all deviations are antenna-based. In this step, the antenna bandpasses were also inspected for any unexpected artifacts such as jumps across small numbers of channels or unexpected slopes; any antennas exhibiting questionable effects were flagged. After bandpass calibration was applied, we generated a correct CH 0 map with AVSPC, which averages the inner 75% of channels into a single pseudo-continuum data set. The contribution from the remaining 25% of channels is discarded, as these channels are more strongly affected by lower sensitivity on the edges of the bandpass.

With the correct CH 0 data set in hand, the pipeline calculated the amplitude and phase calibration. The AIPS task CALIB determines the appropriate calibration for a single calibrator given a source model by deriving a complex gain for each antenna. We used empirically-derived source models provided by NRAO for all flux calibrators. These realistic models provide a better estimate of calibration than the standard point source model. Since the number of phase calibrators used at the VLA is much larger than the number of standard flux calibrators, empirical source models were unavailable for the phase calibrators, so all phase calibrators were therefore modeled as point sources. Since phase calibrators were chosen to appear as point sources within a specific uv -range, the lack of empirical models for the phase calibrators is not problematic. If recommended in the VLA calibrator manual, this uv -range was specified. Otherwise, all uv -ranges were used for calibration. If CALIB produced significant closure errors on baselines, those baselines were carefully scrutinized for any unflagged bad data, and additional flagging was performed if necessary. In some cases, however, closure errors persisted even with the lack of any obvious bad data. The output calibration solutions were also inspected for time stability. Smoothly-varying phase changes were acceptable, as they typically represented phase changes due to atmospheric variation

and are therefore calibrated out. If any antenna showed a strong phase jump between adjacent phase calibrator observations, an antenna-based problem likely occurred during the source scan. In these cases, the source visibilities between the two phase calibrator observations were flagged, as we were unable to determine the precise time of the phase jump.

After determining appropriate calibration based on source models, the flux of the phase calibrator was calculated using the calibration solutions derived in the previous step (task GETJY). Next, we ran CLCAL to interpolate linearly the calibration solutions between phase calibrator observations.

Once all calibration was completed, we again manually inspected data quality to ensure that the flux calibrator showed relatively uniform fluxes across all baselines and that there were no large phase jumps in the phase calibrator observations. Small variations in calibrated amplitude and phase are expected due to noise in the observations. Finally, the source uv data was separated from the multi-source file (SPLIT); the final calibration was fully applied to the data during this stage.

The pipeline differed slightly from above for galaxies whose H I emission was in the same spatial and velocity range MW foreground emission. In these cases, the flux/bandpass calibrator was observed at ± 4 MHz offsets from the source frequency; each frequency offset was calibrated separately. The offset calibrator bandpasses were compared to the bandpass derived from the phase calibrator. The bandpass from the phase calibrator typically had a signal-to-noise too low to use for calibration. Its shape, however, should qualitatively match the offset frequency bandpasses. The bandpass of the phase calibrator, as well as its spectrum, also indicated if the visibilities of the phase calibrator were affected by H I emission from the MW. Any phase calibrator channels showing strong MW H I emission were flagged for all calibration steps. If bandpasses for both offset frequencies were nearly identical to that of the phase calibrator, the absolute calibration was then determined by averaging the calibration for each offset frequency. In a number of cases, unfortunately, a fault in the VLA observing software incorrectly tuned the VLA local oscillators to a frequency on the edge of the 25 MHz front-end filter. This error often caused the bandpasses of one of

the offset frequencies to include the shape of the edge of the front-end filter³. The effect was only present in VLA antennas, since signals from EVLA antennas follow a different path. Because this was an instrumental effect that affected only the offset frequency and not the source frequency, offset frequencies that displayed this behavior could not be used for calibration. In those cases, we extrapolated the calibration from only the unaffected offset frequency. This introduced small calibration errors into our data at levels $\lesssim 5\%$.

2.3.2 *Post-Calibration Data Processing*

Once calibration was completed, a number of steps were performed to prepare the uv data for imaging. We first examined the source data for problems, as only the calibrator observations had been inspected for bad data; any anomalous visibilities were flagged. For the two galaxies observed with the 4IF correlator mode, we joined both IFs together with proper offset velocities into a single frequency range (UJOIN). Next, the baseline continuum level of the line-free channels was subtracted (UVLSF). Since Doppler tracking was unavailable for our observations, all visibilities were shifted to their correct source velocity channel (CVEL). This task also placed our observations, taken at different times and at different observing frequencies relative to the observatory, onto identical velocity grids. After CVEL, a dirty image was made from the uv visibilities for each observation to perform a penultimate check for remaining unflagged bad data. Bad data typically showed up as stripes in the map, indicating a visibility with an anomalously-high amplitude in a single or a few baselines. Occasionally, the visibilities from all baselines in a single arm were affected. Any instances of bad source data were flagged.

Some observations from the archive had mismatched bandwidths and channel spacings compared to new VLA-ANGST observations of the same galaxy. In these cases, a number of additional post-calibration steps were applied to the uv data. Different combinations of the following steps were used, depending on the specific archival data setup. If necessary, channels were averaged (SPECTR) before proceeding so that the new VLA-ANGST observations had twice the channels and half the channel spacing as the archival data. Next, Hanning

³This behavior was discovered by the author while in Socorro, and confused a number of VLA engineers and scientists for approximately a day before the cause was tracked down by Ken Sowiński.

smoothing was manually applied to the new VLA-ANGST observations (CVEL), as all of the archival data had Hanning smoothing applied online. The 3-channel Hanning smoothing kernel averages each channel by summing 0.5 times that channel plus 0.25 times the channels on either side. Every other channel of the smoothed data is therefore redundant; these channels were discarded (SPLAT). The remaining smoothed visibilities were then re-aligned to the velocity grid specified by the archival data, which was always observed with Doppler tracking (CVEL). Additionally, a number of the archival data observations had been taken in B1950 coordinates, and were precessed to J2000 with two passes of UVFIX.

Once all necessary post-calibration steps were completed, data from each configuration was combined into a single, large data set using DBCON. After the full uv data set was created, we generated a dirty map from the calibrated visibilities for the galaxy and inspected it to ensure that no further flagging was required.

2.3.3 Mapping and Deconvolution

After satisfactory calibration and source editing, we used the AIPS task IMAGR to generate data cubes and final data products. We followed the THINGS protocol when possible so that the two data sets could be easily compared. For each VLA-ANGST galaxy, we imaged the visibilities with two different weighting schemes: one using natural weighting and one using the “robust” weighting (originally described by Briggs, 1995, with small modifications as described in the AIPS help files). Natural weighting yields high sensitivity at moderate resolution (typically $\sim 6 - 12''$ for our galaxies, or about $\sim 90 - 170$ pc for a distance of 3 Mpc), while robust weighting decreases the size of the synthesized beam at the cost of reduced surface brightness sensitivity. We applied a robust parameter of 0.5, which was found to be a good compromise between resolution and sensitivity and matches the maps generated by THINGS. When compared to the naturally-weighted cubes, the noise in the robust-weighted cubes is typically $\sim 20\%$ higher and the beam size $\sim 40\%$ smaller. Depending on the angular extent of each galaxy’s H I emission, the cubes were imaged with either 1024^2 pixels at $1.5''$ per pixel or 2048^2 pixels at $1.0''$ per pixel. The cubes were deconvolved using the Clark CLEAN deconvolution algorithm (Clark, 1980), stopping at a

residual flux threshold of 2.5 times the noise level as measured in the cubes. Finally, we produced primary beam corrected data cubes that were later used in the moment map analysis (§ 2.4.3).

The properties of all data cubes are listed in Table 2.2 where column (1) lists the galaxy names followed by columns (2), (3), (4), and (5) that contain the weighting algorithms and the resulting beam major and minor axes sizes as well as the position angles of the deconvolved data. The average root mean squared noise per channel is shown in column (6) and the channel width in (7), the number of pixels in each plane in column (8) followed by the pixel size in column (9).

To ensure that our datacubes would be as directly comparable to the THINGS datacubes as possible, we reduced THINGS observations using our calibration, mapping, and deconvolution protocols. Comparisons of our reductions of THINGS observations with the publicly available THINGS datacubes showed no significant differences. The most important difference between the VLA-ANGST datacubes and the THINGS datacubes is the higher velocity resolution in the majority of the VLA-ANGST datacubes which was possible because of the overall smaller range in velocity of detectable H I in the VLA-ANGST sample of galaxies.

2.3.4 Mask Generation

To suppress noise for the production of moment maps, we generated image cube masks that defined regions containing detectable H I emission from the galaxies. To do so, we convolved the natural-weighted images to twice the original beam major axis and applied spectral Hanning smoothing with a three channel wide kernel. New “mask” cubes containing predominantly H I signal were constructed by keeping all regions corresponding to H I emission above the 1σ noise level and blanking all other regions. To remove the effects of sidelobes, noise spikes, or other spurious signals from the masks, any individual regions with an area smaller than the beam size were automatically removed. We then eliminated any remaining non-emission regions by eye inspection.

The result is a single mask cube per galaxy that we applied prior to the generation of the integrated spectra and moment maps. The same mask is used for both the natural

Table 2.2: Imaging properties of the VLA-ANGST data cubes. This table has been reproduced with minor formatting changes from Ott et al. (2012).

1	2	3	4	5	6	7	8	9
Galaxy	Weighting	B_{major}	B_{minor}	BPA	Noise	Δv	N_{pixels}	Pixel scale
		[$''$]	[$''$]	[$^\circ$]	[mJy beam $^{-1}$]	[km s $^{-1}$]		[$''$]
NGC 247	Natural	9.0	6.2	10.5	0.9	2.6	2048 ²	1.0
	Robust	6.5	4.8	12.7	0.9			
DDO 6	Natural	12.3	10.3	52.0	1.9	0.65	1024 ²	1.5
	Robust	7.2	6.3	49.0	2.1			
NGC 404	Natural	13.7	12.4	-34.7	0.9	2.6	1024 ²	1.5
	Robust	7.1	6.1	-32.6	0.9			
KKH 37 ^a	Natural	9.7	8.1	-86.2	1.6	0.65	1024 ²	1.5
	Robust	6.5	5.8	-66.9	1.8			
UGC 4483	Natural	12.2	9.8	61.3	0.5	2.6	1024 ²	1.5
	Robust	7.6	5.7	57.1	0.6			
KK 77 ^a	Natural	12.2	8.1	-79.0	0.9	2.6	1024 ²	1.5
	Robust	6.1	5.8	-66.6	0.7			
BK3N	Natural	12.0	8.1	-85.1	1.8	0.65	1024 ²	1.5
	Robust	6.3	5.8	61.5	1.8			
AO 0952+69	Natural	10.1	8.8	73.5	1.3	1.3	1024 ²	1.5
	Robust	6.4	5.9	-71.0	1.2			
Sextans B	Natural	15.0	14.1	10.5	0.8	1.3	1024 ²	1.5
	Robust	9.5	7.5	41.6	1.0			
NGC 3109	Natural	10.3	8.8	22.0	1.6	1.3	2048 ²	1.0
	Robust	7.6	5.0	8.8	1.7			
Antlia	Natural	14.1	13.9	-81.3	1.0	1.3	1024 ²	1.5
	Robust	10.5	9.6	71.1	1.2			
KDG 63 ^a	Natural	10.8	9.2	85.5	1.4	0.65	1024 ²	1.5
	Robust	6.2	6.0	77.0	1.6			
Sextans A	Natural	11.8	10.1	38.5	1.2	1.3	1024 ²	1.5
	Robust	7.3	6.0	35.1	1.3			
HS 117 ^a	Natural	13.2	8.5	-59.6	1.6	0.65	1024 ²	1.5
	Robust	8.6	6.1	-77.8	1.7			
DDO 82	Natural	9.3	7.7	-81.0	1.3	1.3	1024 ²	1.5
	Robust	5.8	5.7	65.0	1.4			
KDG 73	Natural	10.0	7.6	84.3	1.6	0.65	1024 ²	1.5
	Robust	6.9	5.6	65.2	1.7			
NGC 3741	Natural	7.6	6.2	81.1	1.0	1.3	1024 ²	1.5
	Robust	5.5	4.8	75.4	1.1			

Continued on next page

Table 2.2, continued

DDO 99	Natural	12.4	7.6	-86.7	1.0	1.3	1024 ²	1.5
	Robust	7.7	5.2	72.5	1.1			
NGC 4163	Natural	12.3	10.4	-89.6	1.3	0.65	1024 ²	1.5
	Robust	7.6	5.4	-85.2	1.4			
NGC 4190	Natural	10.5	8.9	83.8	0.9	1.3	1024 ²	1.5
	Robust	6.1	5.3	81.4	1.0			
DDO 113 ^a	Natural	15.0	14.0	-55.2	1.4	1.3	1024 ²	1.5
	Robust	9.9	7.7	82.8	1.5			
MCG +09-20-131	Natural	9.7	7.4	69.7	1.0	1.3	1024 ²	1.5
	Robust	6.1	5.3	69.1	1.1			
DDO 125	Natural	11.5	10.6	-68.2	1.5	0.65	1024 ²	1.5
	Robust	6.3	5.4	-80.1	1.5			
UGCA 292	Natural	9.7	6.9	69.4	1.5	0.65	1024 ²	1.5
	Robust	7.0	5.0	65.2	1.6			
GR 8	Natural	7.6	7.3	-55.9	1.5	0.65	1024 ²	1.5
	Robust	5.8	5.4	-28.8	1.6			
UGC 8508	Natural	13.9	12.1	83.6	1.3	0.65	1024 ²	1.5
	Robust	8.2	6.4	86.1	1.5			
DDO 181	Natural	12.8	9.5	-75.7	1.0	1.3	1024 ²	1.5
	Robust	7.6	5.5	-80.4	1.1			
DDO 183	Natural	12.7	10.9	-76.7	1.1	1.3	1024 ²	1.5
	Robust	7.6	6.2	88.2	1.2			
KKH 86	Natural	11.0	9.9	-8.2	1.5	0.65	1024 ²	1.5
	Robust	7.5	5.8	-21.2	1.7			
UGC 8833	Natural	16.4	15.4	-87.4	0.6	2.6	1024 ²	1.5
	Robust	12.4	11.2	81.4	0.6			
KK 230	Natural	8.2	7.3	-56.5	1.4	0.65	1024 ²	1.5
	Robust	5.9	5.2	-41.6	1.5			
DDO 187	Natural	12.2	10.4	-82.4	0.9	1.3	1024 ²	1.5
	Robust	7.1	5.7	88.5	1.0			
DDO 190	Natural	15.6	14.2	88.1	0.6	2.6	1024 ²	1.5
	Robust	10.8	9.9	84.1	0.6			
KKR 25 ^a	Natural	8.5	5.0	63.8	0.4	0.65	1024 ²	1.5
	Robust	5.5	4.4	65.0	0.4			
KKH 98	Natural	9.9	7.4	82.2	1.3	0.65	1024 ²	1.5
	Robust	6.2	5.2	80.4	1.4			

^a Non-detection

and robust data cubes. New cubes containing predominantly H I signal were constructed by keeping all H I emission corresponding to unblanked regions in the mask cube. For our data, this method discriminated well between significant, low level emission and pure noise. Note that this process produces a lower limit to the total H I emission. Some very low surface brightness H I may have been eliminated from these data cubes.

Note that mask generation is not entirely automatic, and, therefore, our mask generation cannot be said to be strictly following THINGS protocols. This is exacerbated by the differences in typical channel widths, which leads to differences between VLA-ANGST and THINGS in average noise levels in the individual channels. Nonetheless, we have followed the intentions of the THINGS project to use masking to suppress the noise and to provide optimal moment maps. However, one should be aware that small differences in masks are possible and that the resulting moment maps have a small inherent systematic uncertainty.

2.3.5 Flux Densities

Recovery of the total H I flux from each channel and the resulting H I spectra is more complicated than simply summing up the total emission. Jorsater & van Moorsel (1995) have shown that standard CLEAN maps do not in actuality yield correct flux measurements. Maps in AIPS are created by summing the CLEAN components, convolved with the CLEAN beam, to the signal that is still present in the residuals. While both maps are purportedly measured in Jansky (beam area)⁻¹, the relevant beam is different in each map: the convolved CLEAN component map is measured in Jy (CLEAN beam area)⁻¹ while the residual map has units of Jy (dirty beam area)⁻¹. Because the areas of the CLEAN beam and the dirty beam are different, the flux in the CLEAN components and in the residuals must be corrected to obtain the proper H I flux. A full discussion of the following correction technique is given in Jorsater & van Moorsel (1995). The corrected flux of a channel is given by:

$$G = C + \epsilon \times R \quad (2.1)$$

where G is the corrected flux, C is the flux in the convolved CLEAN components [with units of Jy (CLEAN beam)⁻¹], R is the flux in the residual map [with units of Jy (dirty beam)⁻¹], and ϵ is the correction factor that takes into account the ratio of the dirty beam area to

the CLEAN beam area. IMAGR provides a method to automatically apply this correction and, following the THINGS protocol, we determined ϵ within the inner 50×50 pixels of the dirty and CLEAN beams. This produces a set of two new natural and robust weighted cubes with the above correction applied in addition to our standard cubes. When the residuals are scaled by ϵ , the noise in the corrected cubes is artificially suppressed. We thus produced two sets of data cubes for different analyses:

1. “Standard” cube: the standard output from our pipeline, with uncorrected H I fluxes but uniform noise properties. No primary beam correction is applied to these data. This cube should be used for any analysis that requires uniform noise properties or uses selection based on noise (e.g., fitting of individual profiles to construct velocity fields or measure profile shapes).
2. “Rescaled” cube: the cube with the flux correction applied, to be used only in regions with genuine H I emission. The flux values in this cube are correct, and therefore any analysis that requires selection based on H I fluxes should use this cube (e.g., mass and column density measurements). The “rescaled” cube is corrected for the attenuation from the primary beam.

The data products that we make available follow this recipe; all global H I spectra (§ 2.4.1) and moment maps (§ 2.4.3) were derived using the masked, “rescaled cubes”. The online data cubes themselves are the “standard” cubes, without primary beam attenuation or flux corrections.

2.3.6 Global H I Spectra and Masses

Global H I spectra are derived from the masked, rescaled data cubes. The spectra are used to derive velocity widths at 20% (w_{20}) and 50% (w_{50}) of the peak. The central H I velocity of each galaxy is calculated by taking the mid-point of the w_{20} boundaries.

We also use the integrated H I spectra to calculate the total H I masses of our galaxies

using the following equation:

$$M_{\text{HI}} [M_{\odot}] = 2.36 \times 10^5 D^2 \times \sum_i S_i \Delta v \quad (2.2)$$

where D is the distance to the galaxy in Mpc (as given in Table 2.1) and $S_i \Delta v$ is the total flux of a single channel in Jy km s^{-1} (e.g. Rohlfs & Wilson, 2004). This formula assumes that the H I emission is optically thin, an assumption that is valid over a large flux range and may begin to fail at very extreme column densities of $\gtrsim 10^{22} \text{ cm}^{-2}$ (e.g. Allen et al., 2012; Braun, 2012). At our spatial resolution, we do not observe column densities of this magnitude.

In Table 2.3, we present all of the derived H I parameters starting with the galaxy names in column (1), followed by the integrated H I flux densities S_{HI} and the derived H I masses in columns (2) and (3). For comparison, we compiled single dish fluxes $S_{\text{HI}}^{\text{SD}}$ from the literature and list them in column (4). The w_{20} and w_{50} values as well as the central velocities are shown in columns (5), (6), and (7), respectively, followed by the peak H I column density (§ 2.4.3.1) taken from the natural-weighted map in the final column (8). To derive upper limits for the non-detections, we assume an H I disk the same size as the optical diameter D_{25} and a hypothetical line width of 20 km s^{-1} . Galaxies typically exhibit H I dispersions of $5\text{--}10 \text{ km s}^{-1}$ and a line width of 20 km s^{-1} thus implies little rotation or face-on orientation.

In $\sim 70\%$ of all cases the single dish fluxes are somewhat larger than the interferometric VLA flux measurements. This difference is expected to some level given that the VLA can only image structures with an extent of up to $\sim 16'$ in D-configuration at 1.4 GHz (limited by the minimum distance between two antennas). Missing flux may therefore only be a significant issue for the most extended objects in our sample. Some single dish flux measurements deviate substantially from the trend of being slightly larger than the VLA fluxes. The deviations can be either way: galaxies like DDO 6, UGC 4483, DDO 113, and KK 230 have much larger single dish measurements whereas others like BK 3N, AO 0952+69, Sextans B, DDO 82, and DDO 190, have smaller single dish fluxes. Such discrepancies may be explained by difficulties in single dish baseline subtraction or by the larger single dish beam that tends to pick up larger fractions of Galactic H I emission as well as flux from nearby objects.

Table 2.3: H I properties of the VLA-ANGST sample. This table has been reproduced with minor formatting changes from Ott et al. (2012). References for $S_{\text{HI,SD}}$, the single dish H I flux, are compiled from a variety of sources in the literature.

1	2	3	4	5	6	7	8
Galaxy	S_{HI} [Jy km s ⁻¹]	M_{HI} [10 ⁶ M _⊙]	$S_{\text{HI}}^{\text{SD}}$ [Jy km s ⁻¹]	w_{20} [km s ⁻¹]	w_{50} [km s ⁻¹]	v_{cen} [km s ⁻¹]	Peak N_{HI} [10 ²¹ cm ⁻²]
NGC 247	382.6	1106.2	608 ^a	201.3	193.9	163.7	5.4
DDO 6	1.2	3.2	3.7 ^b	20.9	13.7	292.5	0.9
NGC 404 ^c	66.7	146.4	76 ^d	80.5	63.2	-54.0	0.5
KKH 37 ^e	< 3.4	< 0.8	1.8 ^{f,g}	...	...	...	< 0.08
UGC 4483	12.0	32.8	13.6 ^h	51.2	34.3	153.9	3.2
KK 77 ^e	< 4.4	< 2.3	< 5.5 ⁱ	...	...	...	< 0.06
BK3N	6.3	22.0	< 0.75 ^j	44.4	20.0	-42.5	0.7
AO 0952+69 ^k	61.3	206.6	< 0.59 ^j	56.0	45.6	112.8	1.3
Sextans B	91.0	41.5	72.9 ^h	58.1	40.6	302.2	2.6
NGC 3109	720.9	270.1	1148 ^a	127.7	116.0	405.1	6.6
Antlia	1.4	0.5	1.7 ^l	23.4	13.4	363.4	0.3
KDG 63 ^e	< 4.2	< 1.1	< 0.2 ^m	...	...	...	< 0.06
Sextans A	138.1	62.1	169 ^a	59.8	46.2	324.8	6.1
HS 117 ^e	< 1.7	< 0.6	...	...	...	...	< 0.03
DDO 82	0.8	2.8	< 0.62 ^j	35.8	26.7	56.2	0.9
KDG 73	0.1	0.5	1.0 ^h	9.2	8.5	116.3	0.1

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Table 2.3, continued

NGC 3741	32.8	81.1	44.6 ^o	85.4	70.6	229.1	3.4
DDO 99	29.7	46.9	47.1 ^o	51.6	28.6	242.1	2.6
NGC 4163	4.8	9.3	9.6 ^p	33.5	22.7	161.6	2.1
NGC 4190	15.5	44.8	23.2 ^p	73.2	52.8	227.0	3.5
DDO 113 ^e	< 1.6	< 0.4	23.6 ^p	...	...	...	< 0.04
MCG +09-20-131	3.1	11.9	5.2 ^q	39.0	26.1	157.6	3.3
DDO 125	18.3	28.7	21.8 ^h	39.7	27.0	196.1	2.1
UGCA 292	12.9	40.0	14.3 ^h	37.1	25.2	308.3	4.2
GR 8	5.8	5.9	7.8 ^h	30.7	21.4	213.7	1.7
UGC 8508	12.3	19.3	14.8 ^p	62.7	48.1	59.8	2.9
DDO 181	10.5	24.4	12.5 ^o	52.1	40.8	201.4	1.7
DDO 183	8.2	20.1	9.6 ^p	42.2	26.4	191.2	2.2
KKH 86	0.1	0.1	0.5 ^h	7.7	6.9	285.5	0.2
UGC 8833	5.9	13.1	6.0 ^h	41.0	29.4	225.9	2.2
KK 230	0.8	0.7	2.6 ^h	17.4	11.5	60.6	0.6
DDO 187	10.1	11.6	12.0 ^h	46.0	31.8	152.2	3.2
DDO 190	22.5	41.3	8.5 ^o	62.3	45.2	148.8	3.6
KKR 25 ^e	< 1.0	< 0.1	2.2 ^g	...	...	...	< 0.03
KKH 98	2.2	3.3	4.1 ^h	25.5	17.0	-137.8	0.8

Continued on next page

Table 2.3, continued

^a	Huchtmeier & Richter (1989)
^b	Meyer et al. (2004)
^c	NGC 404 is contaminated by foreground Milky Way H I emission.
^d	Baars & Wendker (1976)
^e	VLA-ANGST non-detection. Limits based on a width of 20 km s ⁻¹ and the optical diameter D_{25} .
^f	Karachentsev et al. (2001)
^g	might be Galactic H I
^h	Huchtmeier et al. (2003)
ⁱ	Huchtmeier et al. (2000b)
^j	van Driel et al. (1998)
^k	AO 0952+62 is contaminated by M81 tidal H I emission.
^l	Barnes & de Blok (2001)
^m	Schneider et al. (1990)
ⁿ	Barnes & de Blok (2004)
^o	Springob et al. (2005)
^p	Koribalski et al. (2004)
^q	Pustilnik & Martin (2007)
^r	Huchtmeier et al. (2000a)

2.4 Data Products

2.4.1 H I Spectra

We used the naturally-weighted data cubes to derive H I spectra (§ 2.3.6) for our galaxies given their higher surface brightness sensitivity compared to the robust-weighted data. This approach captures as much low-level, extended emission as is possible with interferometric VLA data. All fluxes are calculated from the rescaled cubes described in § 2.3.5 and are presented in Fig. 2.2a. In the case of NGC 247, velocities around 108 km s^{-1} were strongly contaminated with RFI; to estimate the H I flux in this channel, we interpolated the emission from the adjacent channels.

Since our sample is composed primarily of dwarf galaxies, the galaxy spectra typically show narrow, singly-peaked profiles. Extreme cases like KDG 73 and KKH 86 exhibit linewidths of $< 10 \text{ km s}^{-1}$, which implies very little velocity dispersion, maybe due to low signal to noise in the line wings. On the other end of the mass spectrum, a few galaxies (NGC 404 NGC 3741, DDO 190, Sextans A, DDO 181, NGC 3109, NGC 247) exhibit hints of the more familiar double-horned profile expected from larger spiral disks. The maximum linewidth is observed in NGC 247 with $w_{20} \sim 200 \text{ km s}^{-1}$.

2.4.2 Channel Maps

Channel maps of the galaxies are presented in Figs. 2.3a through 2.31a (natural weighting). Given the high spectral resolution of our data, there is typically only little flux in each velocity bin. Some galaxies, mainly the more massive ones such as NGC 247 or NGC 3109 show the classic “butterfly” pattern of a spiral galaxy, a tell-tale sign for a flat rotation curve. The bulk of galaxies exhibit rotation despite the fact that the dispersion adds a stochastic component to the velocity structure. NGC 247 also features a H I absorption feature along the line of sight to the background quasar NVSS J004713-205114 at RA (J2000)= $00^h : 47^m : 13.6^s$ and DEC (J2000)= $-20^\circ : 51' : 15''$ (e.g., Dickey et al., 1992). Some data cubes are contaminated by Galactic foreground emission, but only for NGC 404 is the Galactic H I close to the systemic velocity of the source. Other data cubes, such as that for AO 0952+69, contain emission from a nearby object. AO 0952+69, in fact, is likely not a real galaxy but

might be a feature within a spatially coincident spiral arm that belongs to the massive M 81 galaxy.

2.4.3 Moment Maps

We used the AIPS task XMOM to generate moment maps from the masked, flux-corrected cubes. For all calculations we require that each pixel in a moment map is calculated from at least four unmasked channels; pixels with fewer channels are masked in all moment maps.

2.4.3.1 Integrated HI Maps

Integrated HI column density maps are created from the masked, rescaled data cube by integrating along the velocity axis to generate the moment 0 map:

$$I_{\text{HI}} = \sum_i S_i \times \Delta v \quad (2.3)$$

where i is the channel, S_i is the flux density in the i th channel in Jy beam^{-1} , and Δv is the channel spacing in km s^{-1} . We then convert the moment maps to column density with

$$N_{\text{HI}} = 1.104 \times 10^{24} \frac{1}{b_{\text{maj}} b_{\text{min}}} \sum_i S_i \Delta v \quad (2.4)$$

where b_{maj} and b_{min} are the beam major and minor axes in arcseconds and $\sum_i S_i \Delta v$ is the value of moment 0 map at each pixel in units of $\text{Jy beam}^{-1} \text{ km s}^{-1}$. In Figs. 2.3a to 2.31a we show column density maps for all galaxies with detected HI (upper left panels on the second page of each figure) We also show column density contours overlaid on optical images for each galaxy. On these maps (upper right), we placed the footprints of the HST observations that are available through ANGST.

The maps exhibit resolved HI structures comparable to their beam sizes. Some galaxies, like KK 230, or NGC 404 have low columns with peak values of a few times $10^{20} N_{\text{HI}}$. Other galaxies like DDO 190, or UGCA 292 reach columns of a few times $10^{21} N_{\text{HI}}$ (or $\sim 10 M_{\odot} \text{ pc}^{-2}$), which is a canonical threshold for star formation (e.g., Skillman, 1987; Kennicutt, 1989; Bigiel et al., 2008; Leroy et al., 2008).

2.4.3.2 Intensity-weighted Velocity Field Maps

The H I intensity-weighted velocity fields (moment 1) maps are calculated using

$$\langle v \rangle = \frac{\sum_i S_i \times v_i}{\sum_i S_i}. \quad (2.5)$$

For well-behaved disks this equation gives a good indication of the average velocity of gas in a given pixel. However, bulk motions, outflows, and other non-circular motions can shift the derived velocity to unexpected values. Therefore, profile fitting to determine the velocity of the peak of the emission is a more reliable method for finding the average rotational velocity of the gas at a given location in the galaxy. While the velocity fields of lower mass dwarfs are less ordered than those of their larger disk counterparts, most still show velocity gradients across their disks that are indicative of rotation, which is typical for H I in dwarf galaxies (Begum et al., 2008; Walter et al., 2008). The H I intensity-weighted velocity maps are shown in the lower right panels of the second page of for each galaxy in Figs. 2.3a to 2.31a.

2.4.3.3 Second Moment Maps

The linewidth of H I emission can be characterized by the intensity-weighted second velocity moment as given by:

$$\sigma = \sqrt{\frac{\sum_i S_i \times (v_i - \langle v \rangle)^2}{\sum_i S_i}} \quad (2.6)$$

where $\langle v \rangle$ indicates the intensity-weighted velocity derived in the first moment map. While the second moment can be indicative of the turbulence of the ISM, it also reflects the influence of large scale gas flows such as expanding shells or tidal material. At lower resolution, the velocity dispersion can be artificially inflated by beam smearing over the gradient in the velocity field, especially towards the centers of the galaxies, where this gradient is steepest. Overall, the velocity dispersion values fall in a relatively narrow range of 5-15 km s⁻¹, as seen in the lower right panel on the second page of Figs. 2.3a to 2.31a).

Pixels which yield first velocity moments outside the velocity range of the data cube are blanked in all moment maps. The first and second moment maps generated from the robust

data cubes are noisier than those from natural-weighted cubes and occasionally have pixels with unrealistic values in low column density regions. To counter this problem, we blanked all pixels with column densities $N_{\text{HI}} < 3 \times 10^{19} \text{ cm}^{-2}$ in the robust moment maps.

2.4.4 Overview of Data Products

The galaxies in VLA-ANGST span a wide range of physical properties. To provide a quick comparison of HI properties in VLA-ANGST galaxies, the moment 0, 1, and 2 maps for each galaxy have been collected into three figures (Figures 2.32 - 2.34). Within each figure, the maps have been scaled so that the relative physical sizes are correct; this is equivalent to placing all galaxies at the same distance. In these images, physical size can be taken as a proxy for galaxy mass, with the caveat that high or low average surface brightnesses can also affect the size. A 1-kpc scale bar is shown in the lower left. In each figure, the distance of MCG +09-20-131 has been taken to be ~ 1.6 Mpc as listed in Dalcanton et al. (2009), but due to TRGB confusion the galaxy is more likely at a distance of ~ 4 Mpc.

Figure 2.32 shows the projected column density (moment 0) maps for all galaxies. The color scale ranges between $N_{\text{HI}} = 5 \times 10^{19}$ to $5 \times 10^{21} \text{ cm}^{-2}$ with square root scaling. No inclination corrections have been applied, so more edge-on galaxies, such as NGC 3109 and NGC 247, have higher projected column densities compared to their more face-on counterparts. The galaxies with the smallest physical sizes also have the smallest average column densities. Larger galaxies have a wider range of column densities across their disk.

Figure 2.33 shows the intensity-weighted mean velocity field (moment 1) maps for each galaxy. The color of each pixel represents the intensity-weighted mean velocity, and the brightness of each pixel is determined by relative column density. The color scale has been adjusted by hand so that any underlying rotation is visible. Almost all of the smallest galaxies in VLA-ANGST show some rotational gradient across their disks, though the velocity fields are much more chaotic than the smooth rotation seen in the larger galaxies.

Figure 2.34 shows the intensity-weighted second velocity dispersion (moment 2 map). As in Figure 2.33, the color of each pixel represents its velocity dispersion, and the brightness is determined by relative column density. The color ranges between 4 km s^{-1} (blue) and 16

km s^{-1} (red). Again, no corrections for inclination have been made, so projected velocity dispersion in more inclined galaxies may be higher than in more face-on galaxies. The galaxies with the smallest physical size also have the smallest velocity dispersions, often $\lesssim 6 \text{ km s}^{-1}$. Larger galaxies show a wider range of velocity dispersions across their disk.

2.5 Summary

In this chapter, I have given an overview of the VLA-ANGST survey. In particular, I have discussed the observational setup of the survey, the data calibration and imaging strategy used, and the final data products released to the public. The VLA-ANGST sample spans a large range in various physical properties, such as galaxy type, mass, absolute magnitude, and SFR. The calibrated VLA data for the 29 detected objects in the sample are publicly available at <https://science.nrao.edu/science/surveys/vla-angst>. For each galaxy, the data made available are as follows:

- Integrated H I spectrum, generated from the masked, flux-corrected, primary beam-corrected, natural weighted data cube;
- Standard H I data cube for both natural and robust weighting, with no primary beam correction or flux rescaling applied;
- Flux-rescaled H I data cubes for both natural and robust weighting;
- Integrated H I intensity maps for the natural and robust weighting with units of both $\text{Jy beam}^{-1} \text{ km s}^{-1}$ and H I column density, generated from the masked, flux-corrected, primary beam-corrected data cubes;
- Intensity-weighted velocity field maps for the natural and robust weighting, generated from the masked, flux-corrected, primary beam-corrected data cubes;
- Intensity-weighted velocity dispersion maps for the natural and robust weighting, generated from the masked, flux-corrected, primary beam-corrected data cubes.

In addition to providing an invaluable, publicly-available resource for HI studies, the data set presented here has formed the primary sample for science presented in the following thesis chapters.

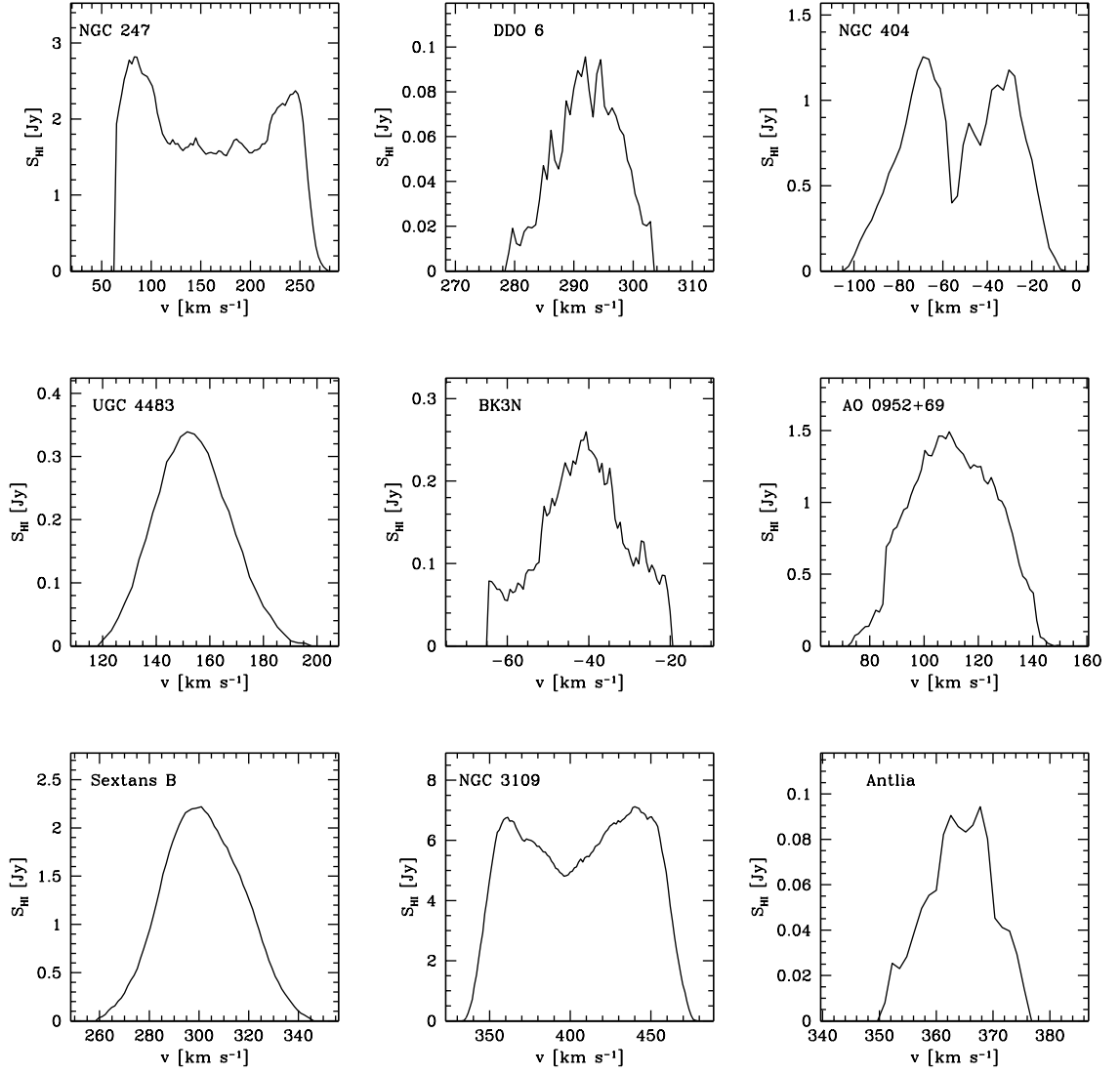


Figure 2.2a Spatially integrated H I spectra of the VLA-ANGST galaxies. *Reproduced from Ott et al. (2012).*

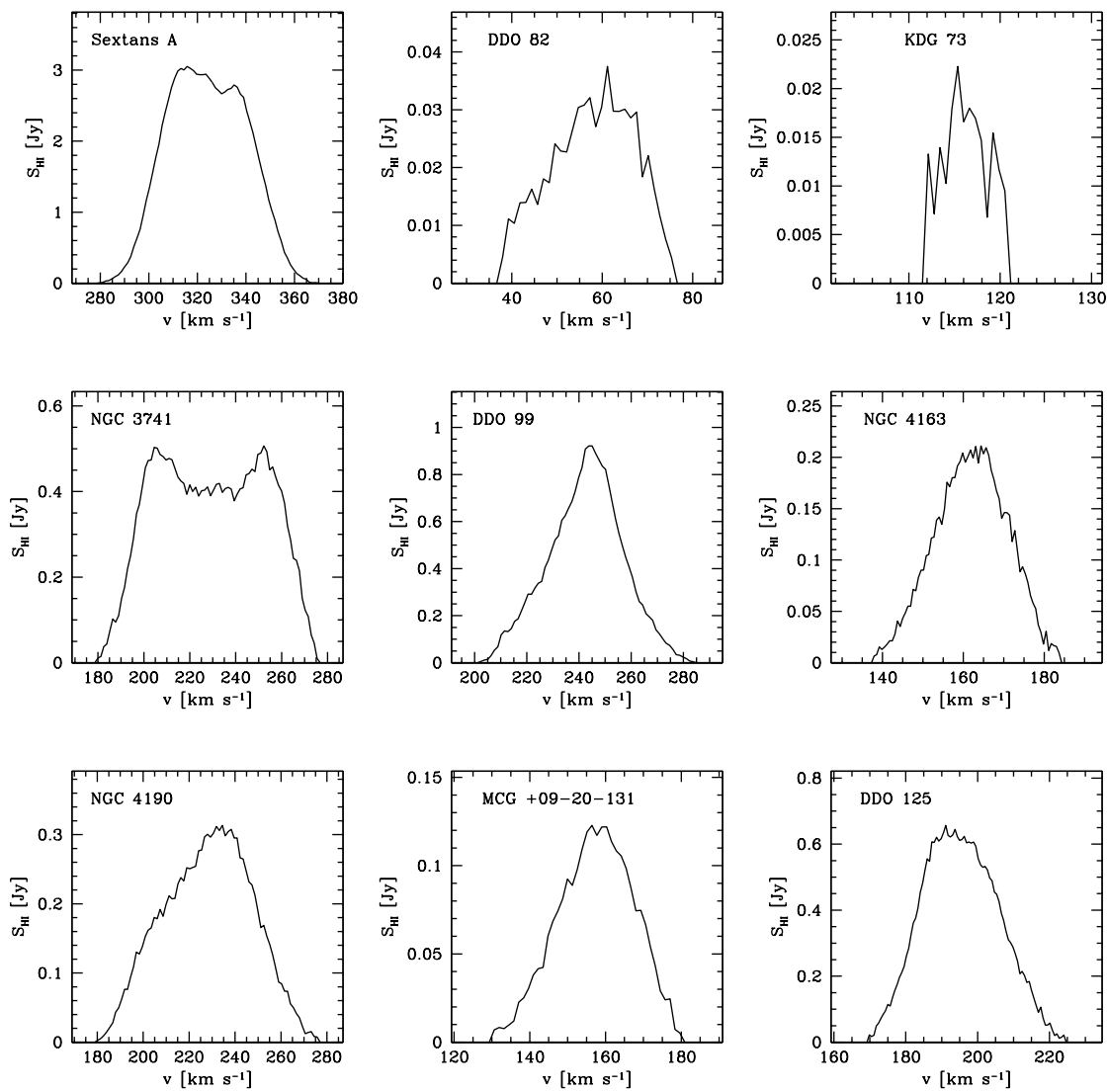


Figure 2.2b Spatially integrated H I spectra of the VLA-ANGST galaxies. *Reproduced from Ott et al. (2012).*

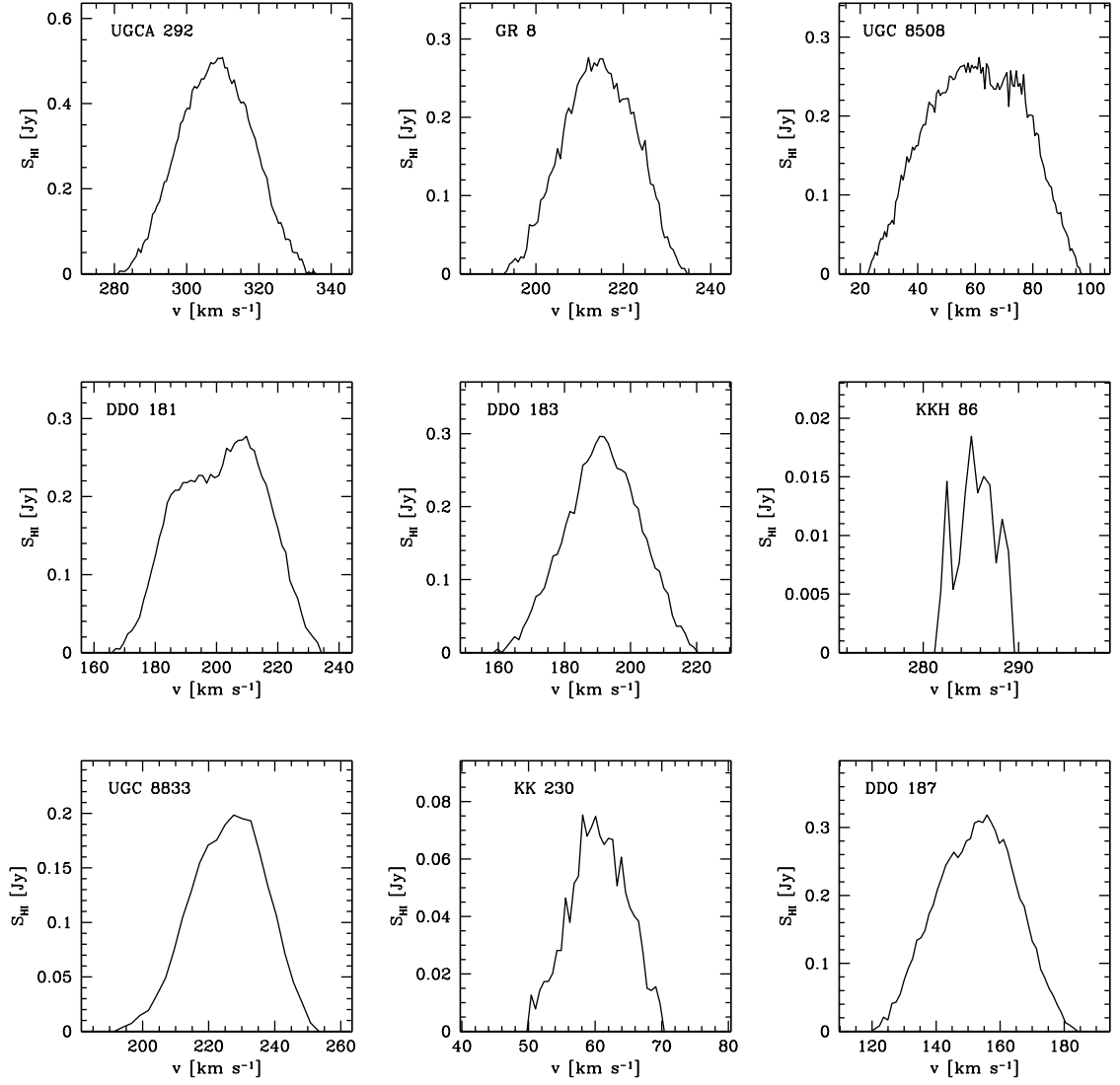


Figure 2.2c Spatially integrated H I spectra of the VLA-ANGST galaxies. *Reproduced from Ott et al. (2012).*

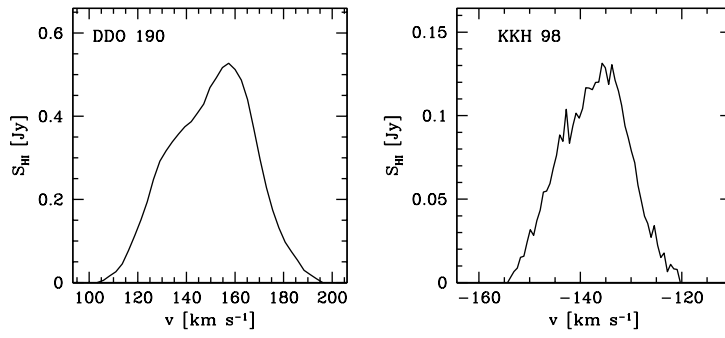


Figure 2.2d Spatially integrated H I spectra of the VLA-ANGST galaxies. *Reproduced from Ott et al. (2012).*

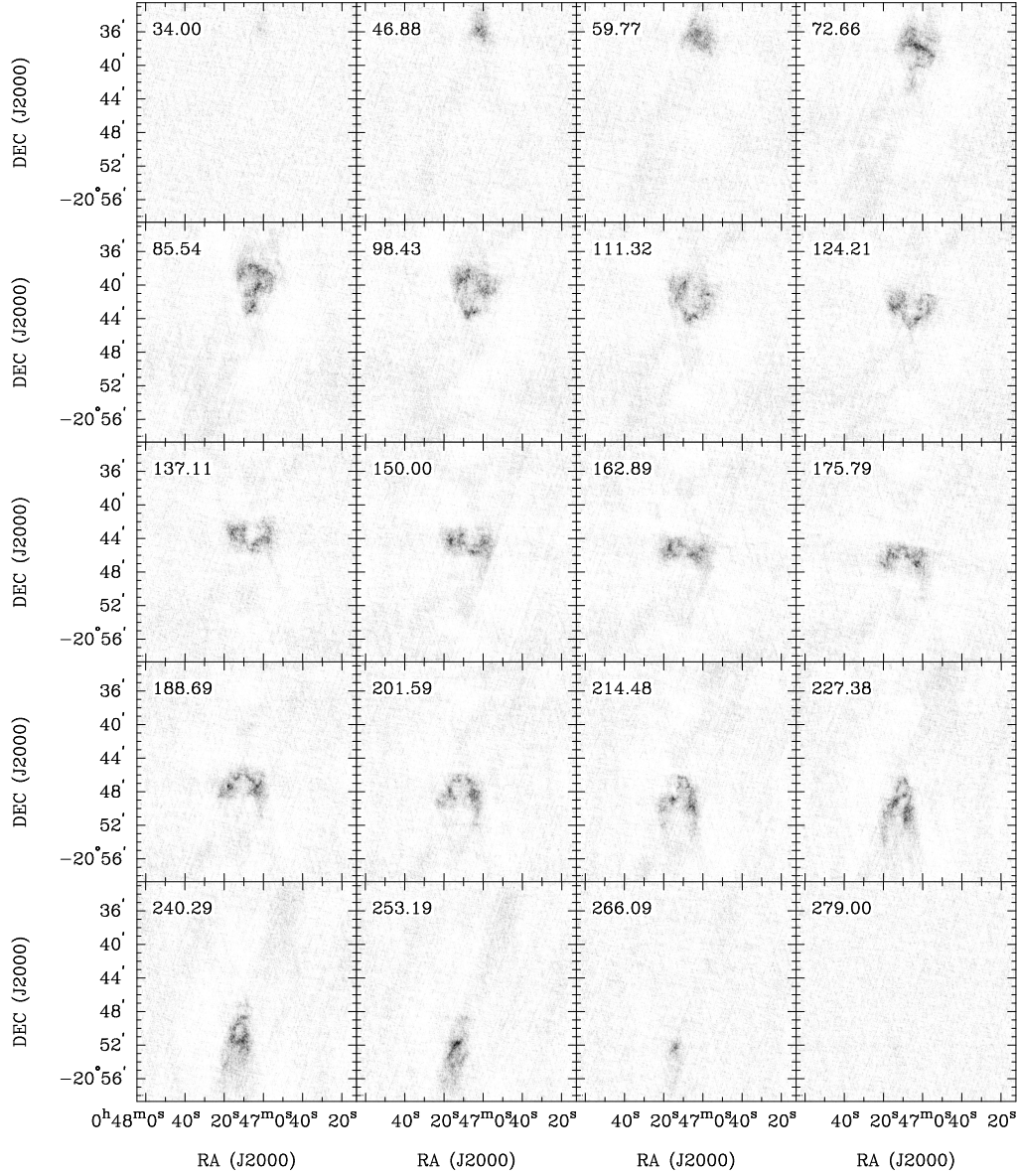


Figure 2.3a **NGC 247**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $12.2 \text{ mJy beam}^{-1}$). Every fourth channel is shown (channel width 2.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

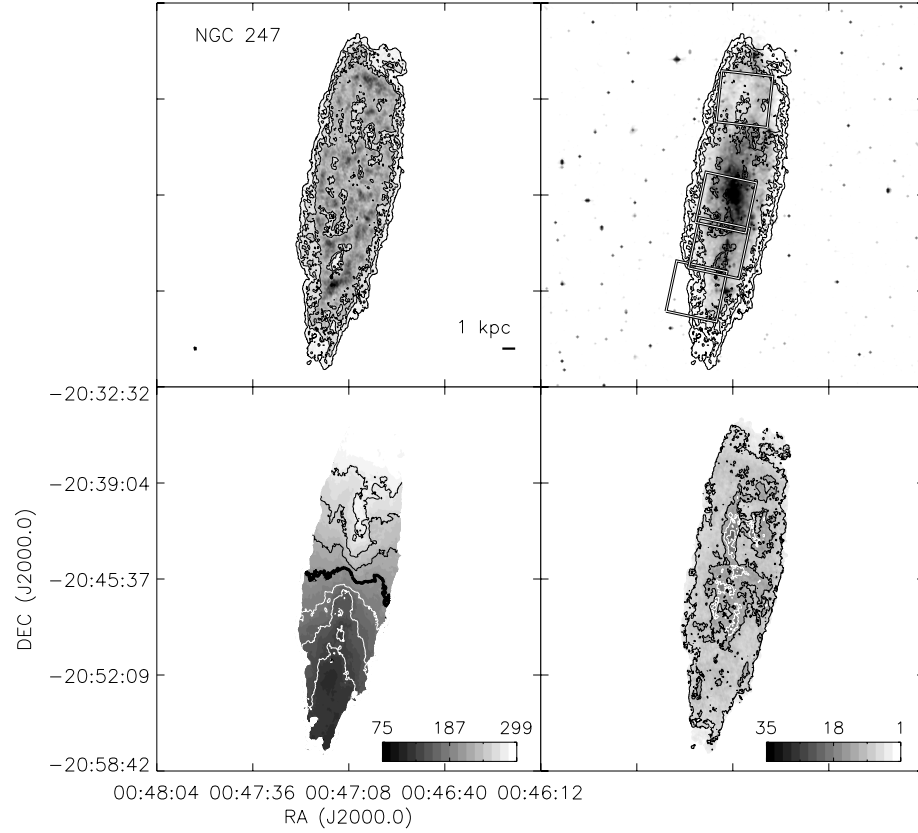


Figure 2.3b *Top left:* The integrated HI intensity map for NGC 247. The grayscale covers a range from 1×10^{19} to $5.4 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , 1×10^{21} , and $5 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical 4680 Å image from the DSS with the same column density contours overlaid. The HST ACS footprints are the fields covered by the ANGST survey. *Bottom Left:* The HI velocity field. Black contours (lighter grayscale) indicate approaching emission, white contours (darker grayscale) receding emission. The thick black contour is the central velocity ($v_{cen} = 163.7 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 25 \text{ km s}^{-1}$. *Bottom Right:* The HI velocity dispersion. Contours are plotted at 5, 10, 15, and 20 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

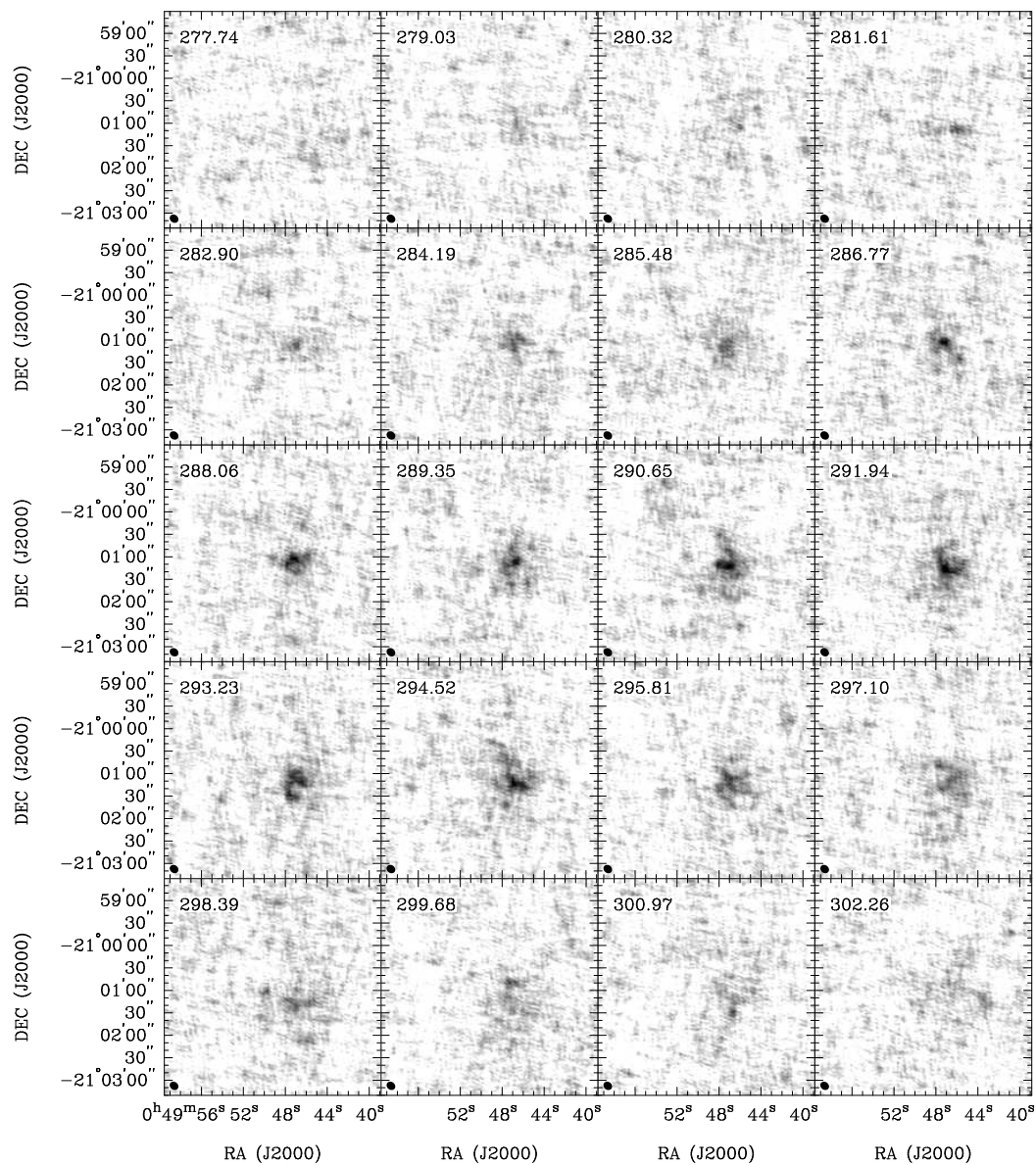


Figure 2.4a **DDO 6**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $13.3 \text{ mJy beam}^{-1}$). Every channel is shown (channel width 0.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

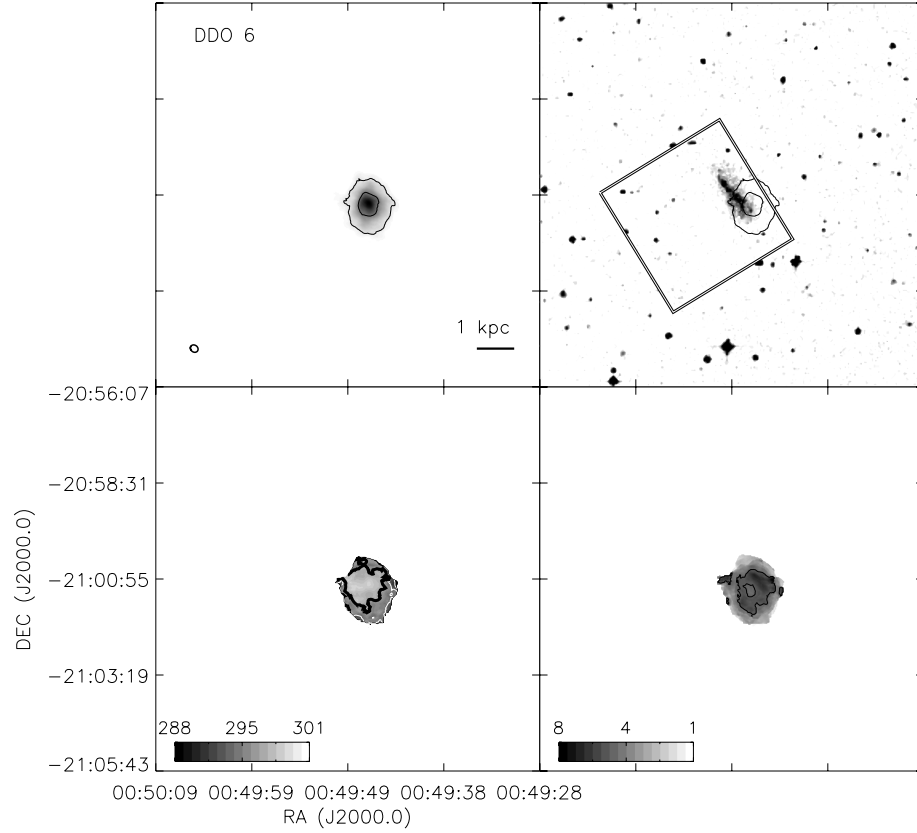


Figure 2.4b *Top left:* The integrated H I intensity map for DDO 6. The grayscale covers a range from 1×10^{19} to $9.4 \times 10^{20} \text{ cm}^{-2}$ with contours of 1×10^{20} and $5 \times 10^{20} \text{ cm}^{-2}$. *Top Right:* An optical 4680 Å image from the DSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 292.5 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 3 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. A contour is plotted at 5 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

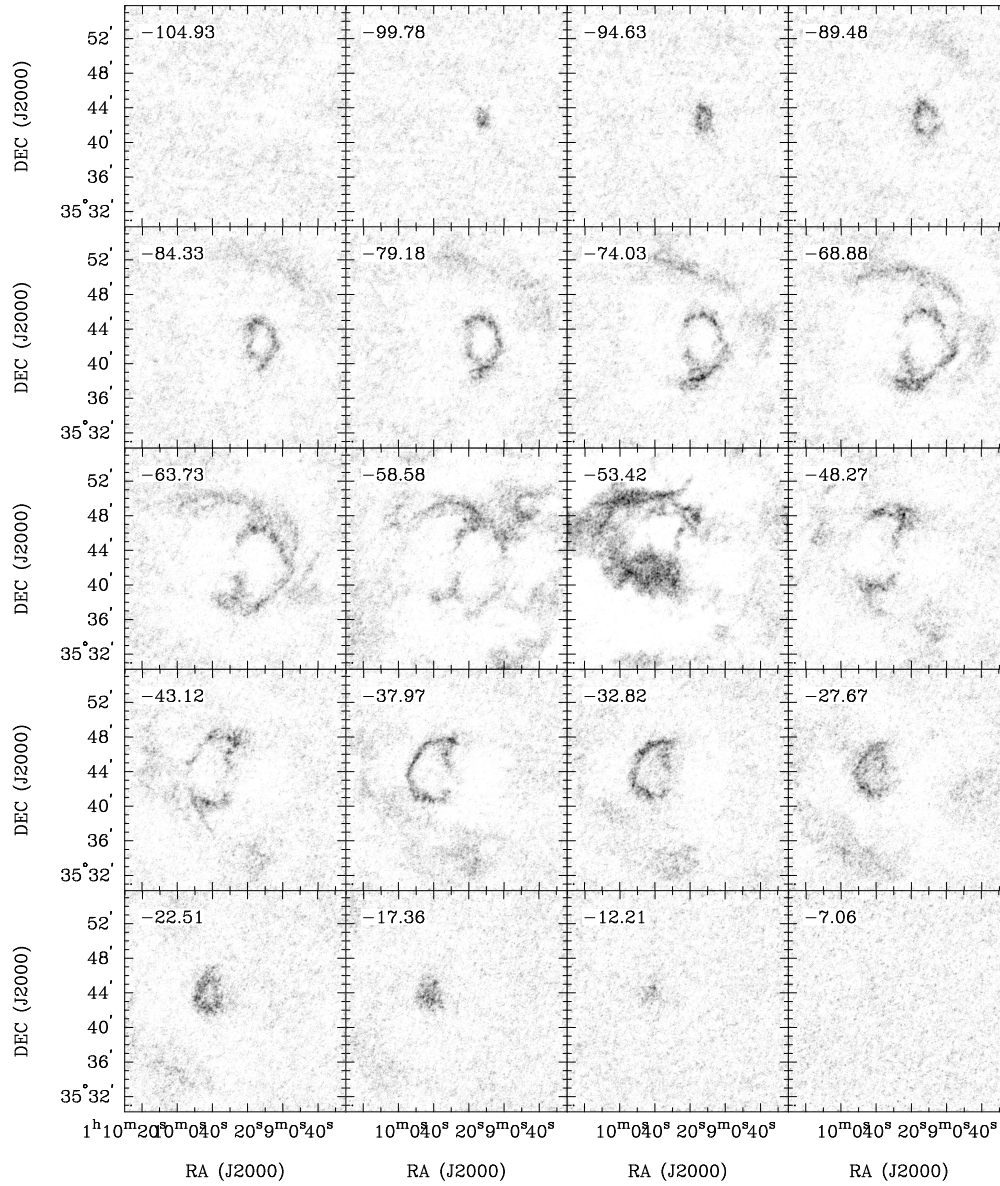


Figure 2.5a **NGC 404**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $8.5 \text{ mJy beam}^{-1}$). Every channel is shown (channel width 2.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. Confusion with H I emission from the Milky Way is present in this galaxy between velocities -58 to -50 km s^{-1} and can be seen in two of the above channels. *Reproduced from Ott et al. (2012).*

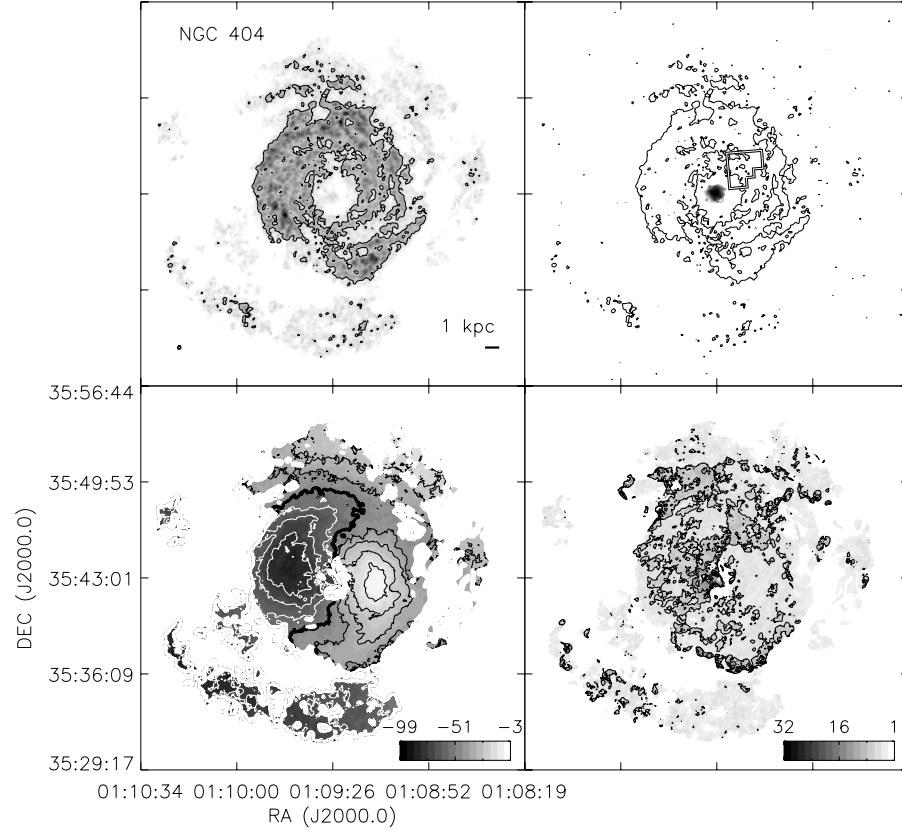


Figure 2.5b *Top left*: The integrated H I intensity map for NGC 404. The grayscale covers a range from 1×10^{19} to $5.0 \times 10^{20} \text{ cm}^{-2}$ with contours of $1 \times 10^{20} \text{ cm}^{-2}$ and $5 \times 10^{20} \text{ cm}^{-2}$. *Top Right*: An optical 6450 Å image from the DSS with the same column density contours overlaid. The HST WFPC2 footprint is the field covered by the ANGST survey. The bright, large disk in the lower right is a foreground star. *Bottom Left*: The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{\text{cen}} = -54.0 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right*: The H I velocity dispersion. Contours are plotted at 5, 10, 15, and 20 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012)*.

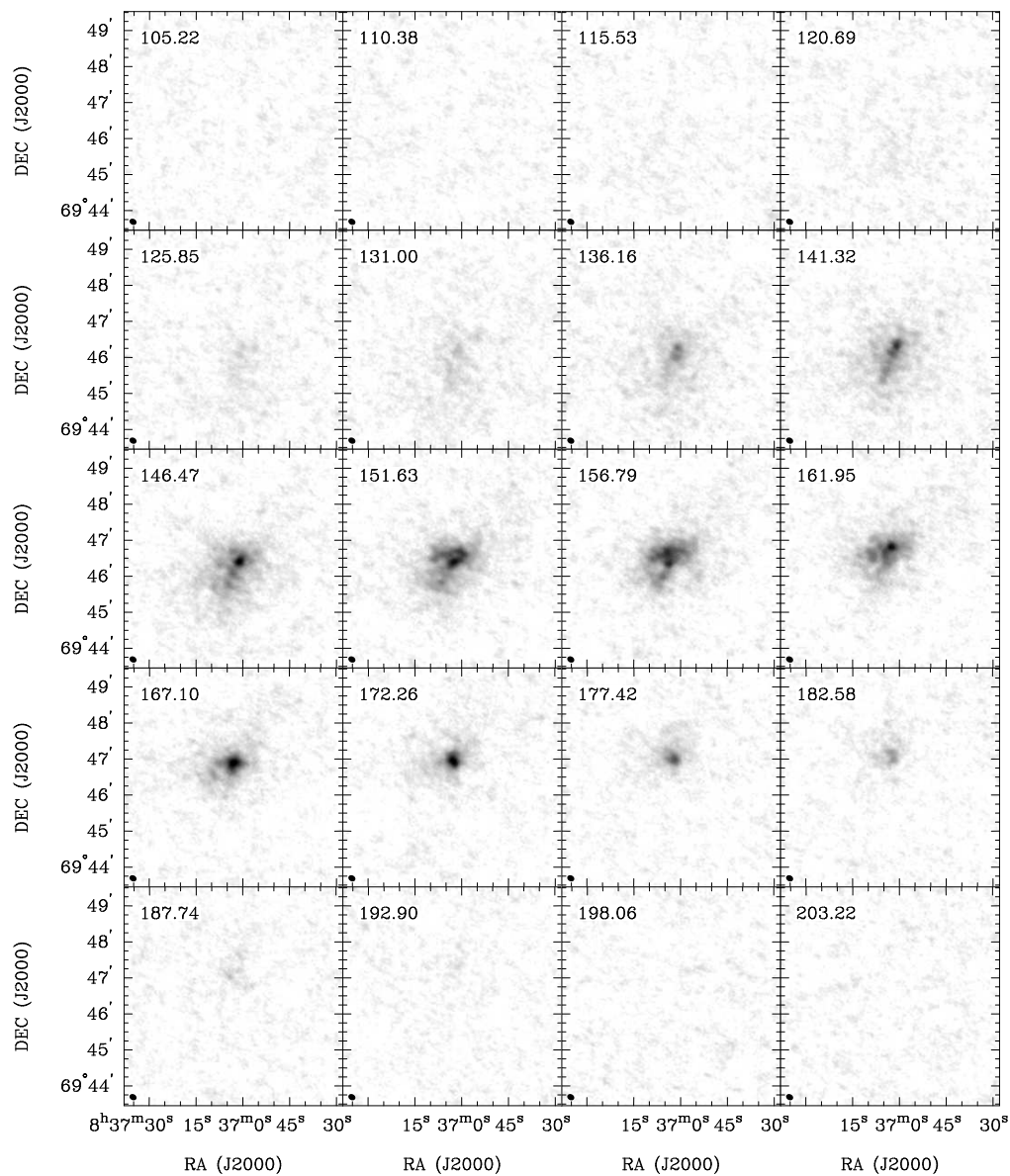


Figure 2.6a **UGC 4483**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $14.8 \text{ mJy beam}^{-1}$). Every channel is shown (channel width 2.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

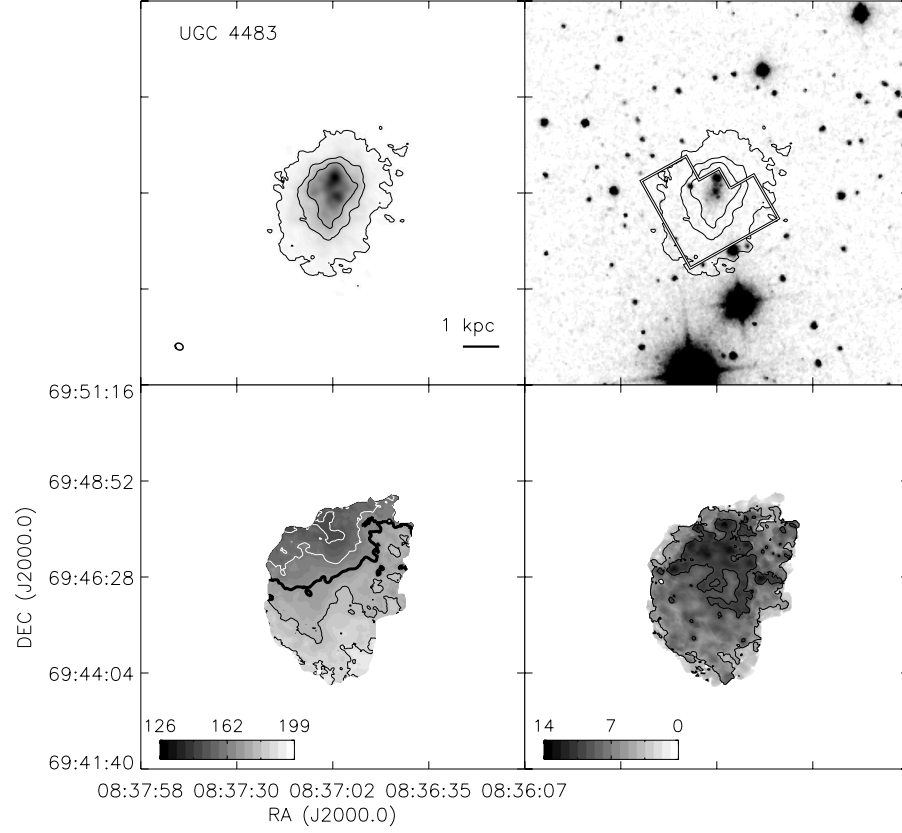


Figure 2.6b *Top left*: The integrated H I intensity map for UGC 4483. The grayscale covers a range from 1×10^{19} to $3.2 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right*: An optical 6450 Å image from the DSS with the same column density contours overlaid. The HST WFPC2 footprint is the field covered by the ANGST survey. *Bottom Left*: The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 153.9 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right*: The H I velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

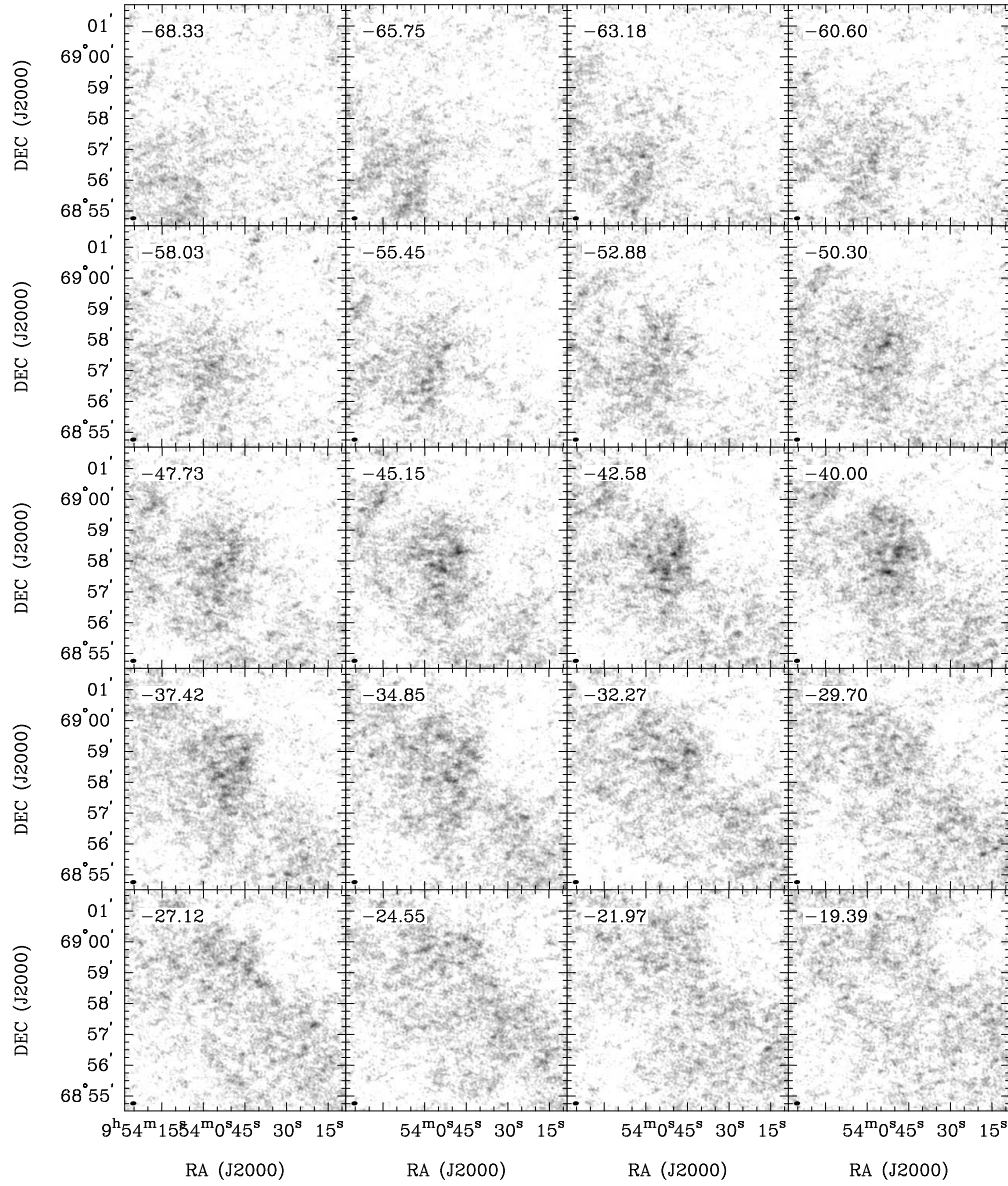


Figure 2.7a **BK3N**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $12.9 \text{ mJy beam}^{-1}$). Every third channel is shown (channel width 0.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. HI emission from M81 is present in every channel of the data cube. *Reproduced from Ott et al. (2012).*

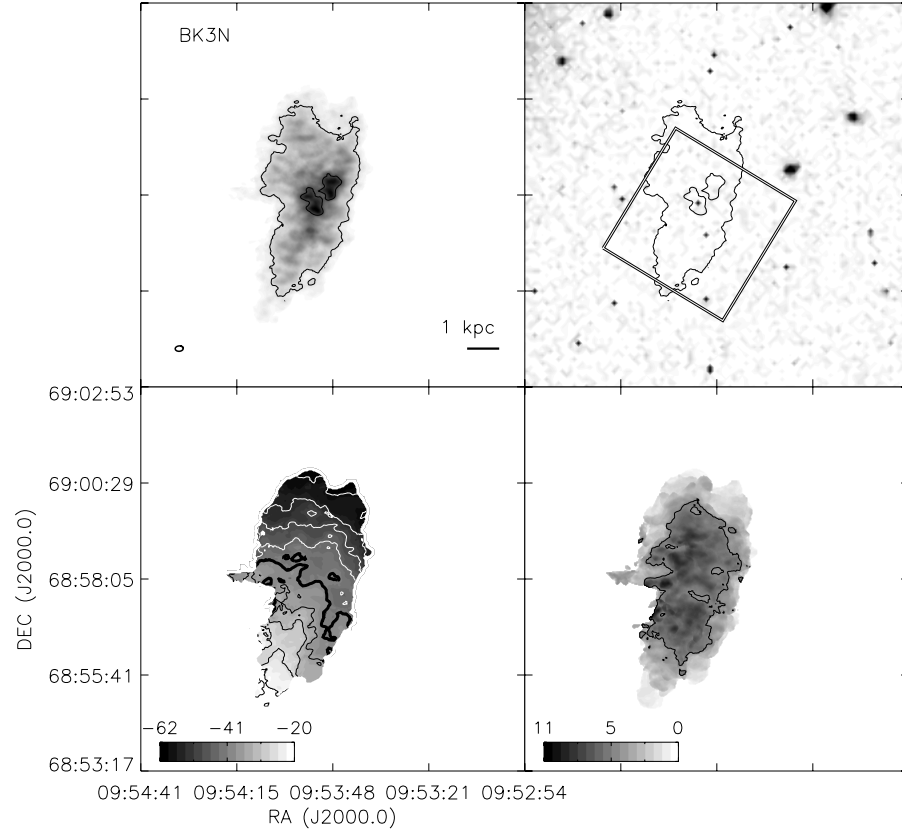


Figure 2.7b *Top left:* The integrated H I intensity map for BK3N. The grayscale covers a range from 1×10^{19} to $7.1 \times 10^{20} \text{ cm}^{-2}$ with contours of 1×10^{20} and $5 \times 10^{20} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = -42.5 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = -5 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

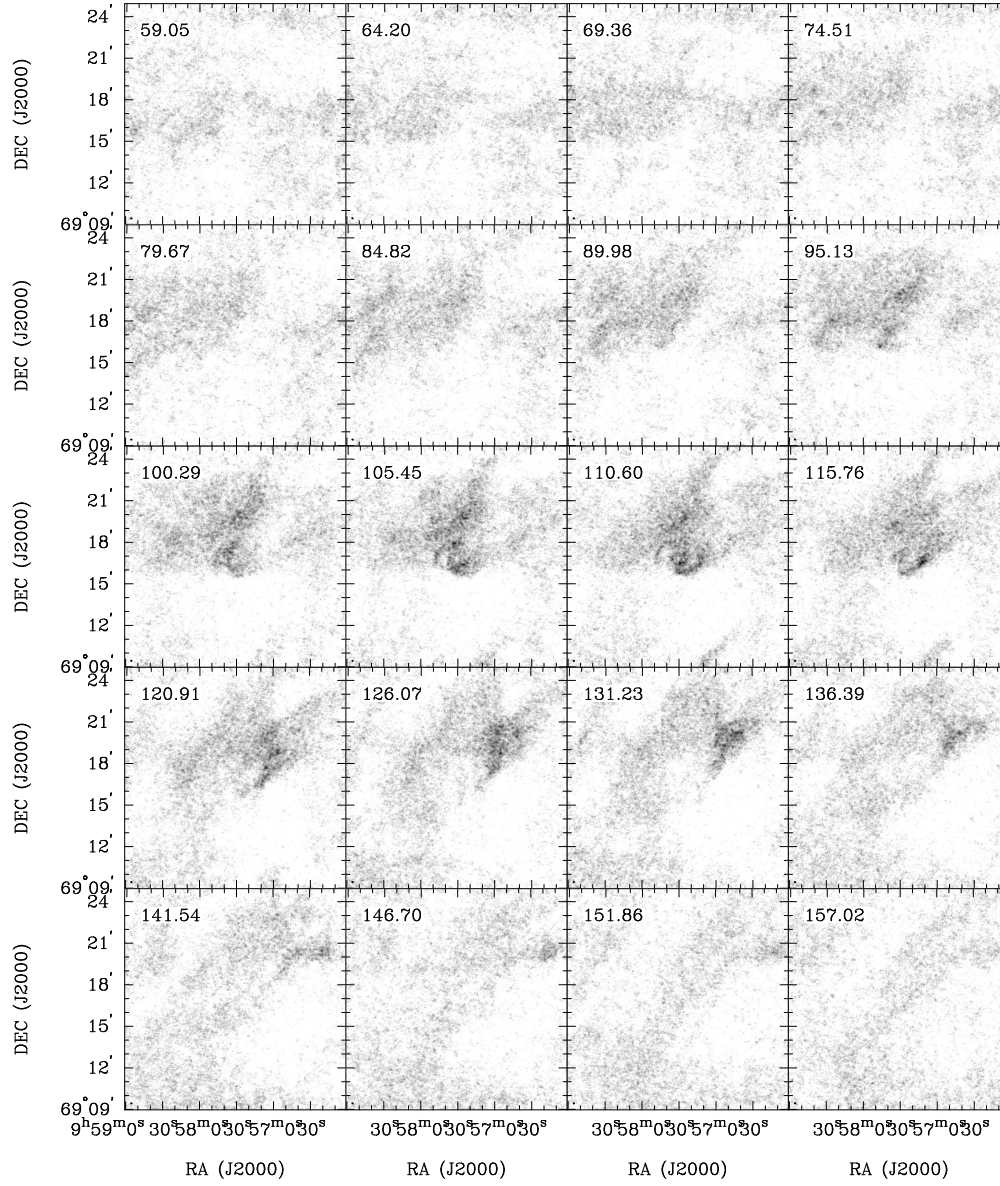


Figure 2.8a **AO 0952+69**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $10.5 \text{ mJy beam}^{-1}$). Every third channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. This field is in the M81 group and therefore tidal HI from member interactions is also visible. *Reproduced from Ott et al. (2012).*

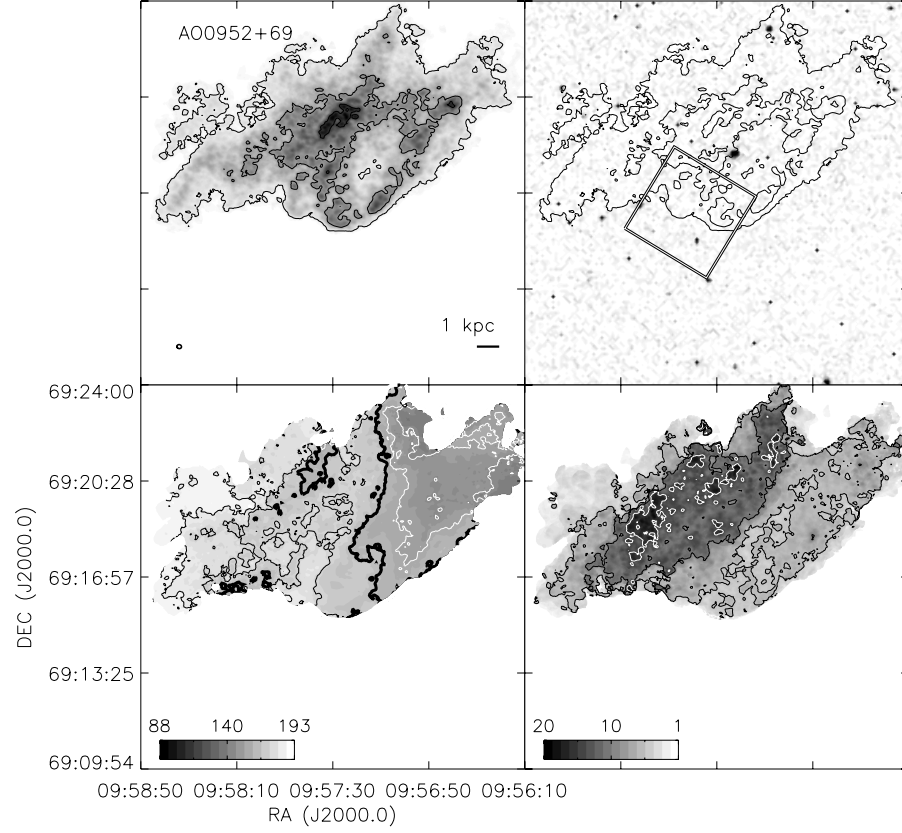


Figure 2.8b *Top left:* The integrated H I intensity map for AO 0952+69. The grayscale covers a range from 1×10^{19} to $1.13 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 112.8 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5, 10, and 15 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

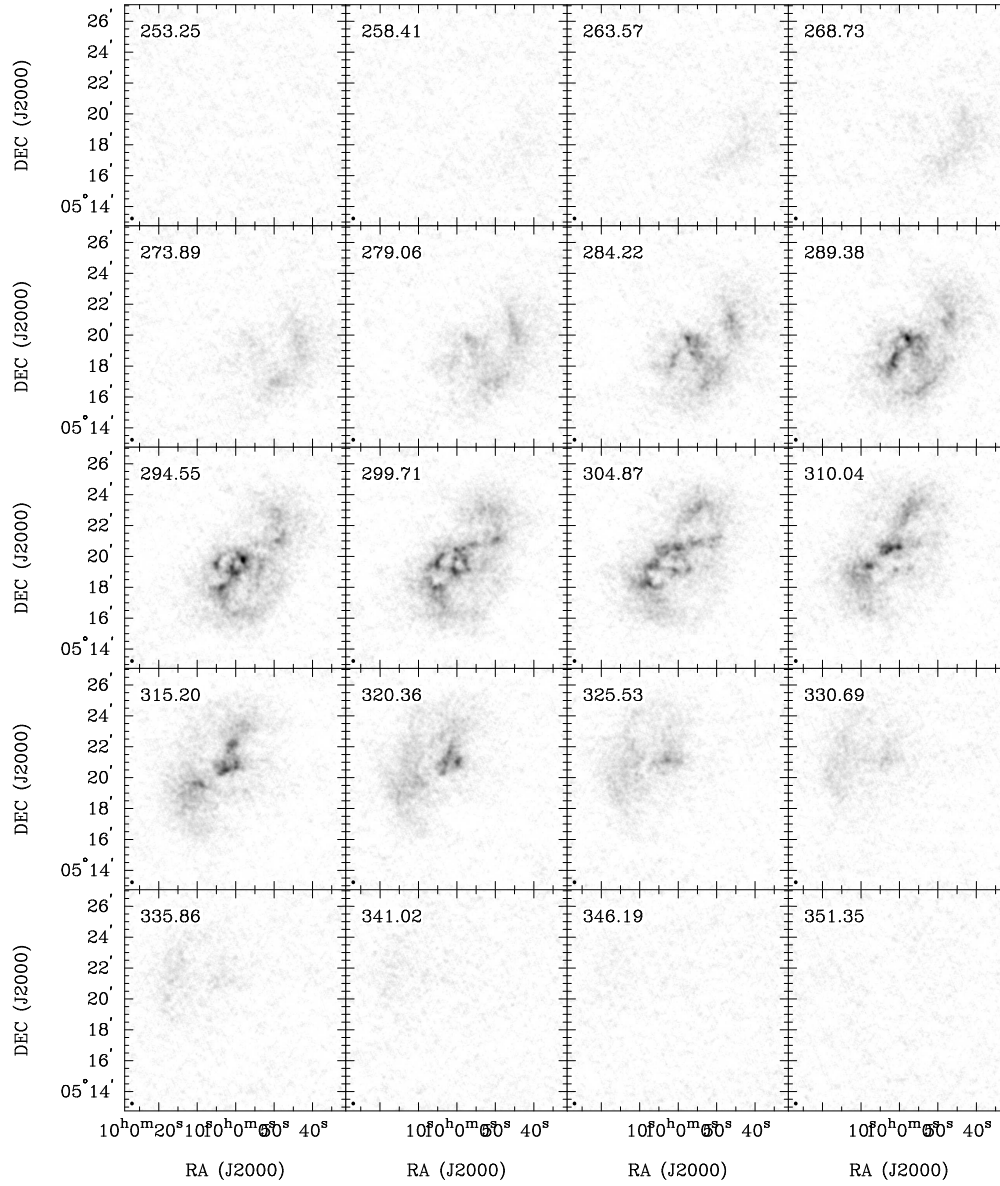


Figure 2.9a **Sextans B**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $25.3 \text{ mJy beam}^{-1}$). Every third channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

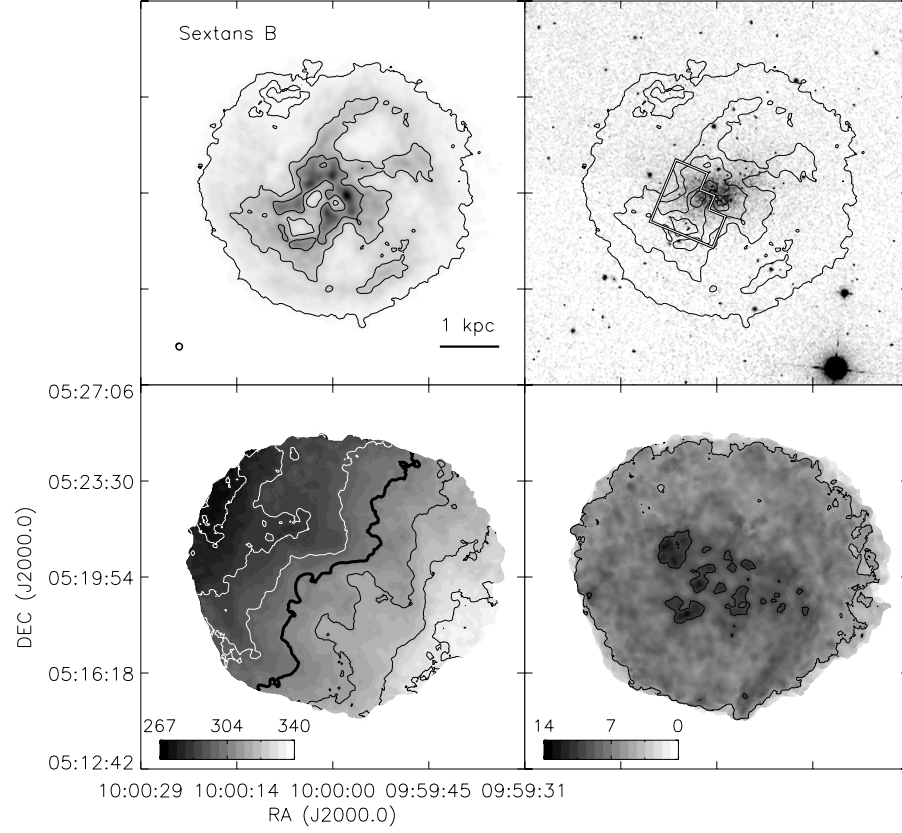


Figure 2.9b *Top left*: The integrated H I intensity map for Sextans B. The grayscale covers a range from 1×10^{19} to $2.6 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right*: An optical g-band image from the SDSS with the same column density contours overlaid. The HST WFPC2 footprint is the field covered by the ANGST survey. *Bottom Left*: The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 302.2 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right*: The H I velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

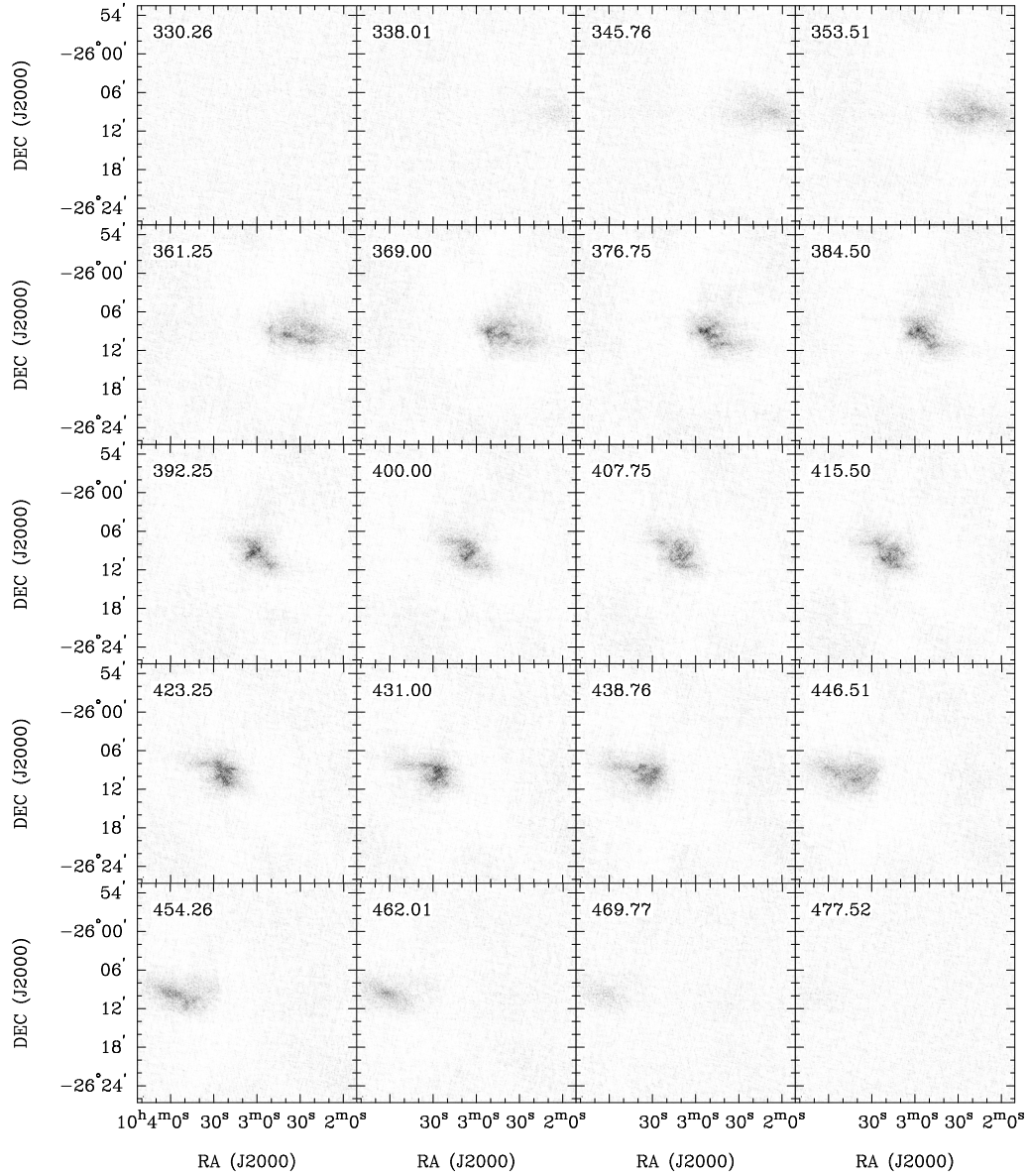


Figure 2.10a **NGC 3109**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $31.7 \text{ mJy beam}^{-1}$). Every fifth channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

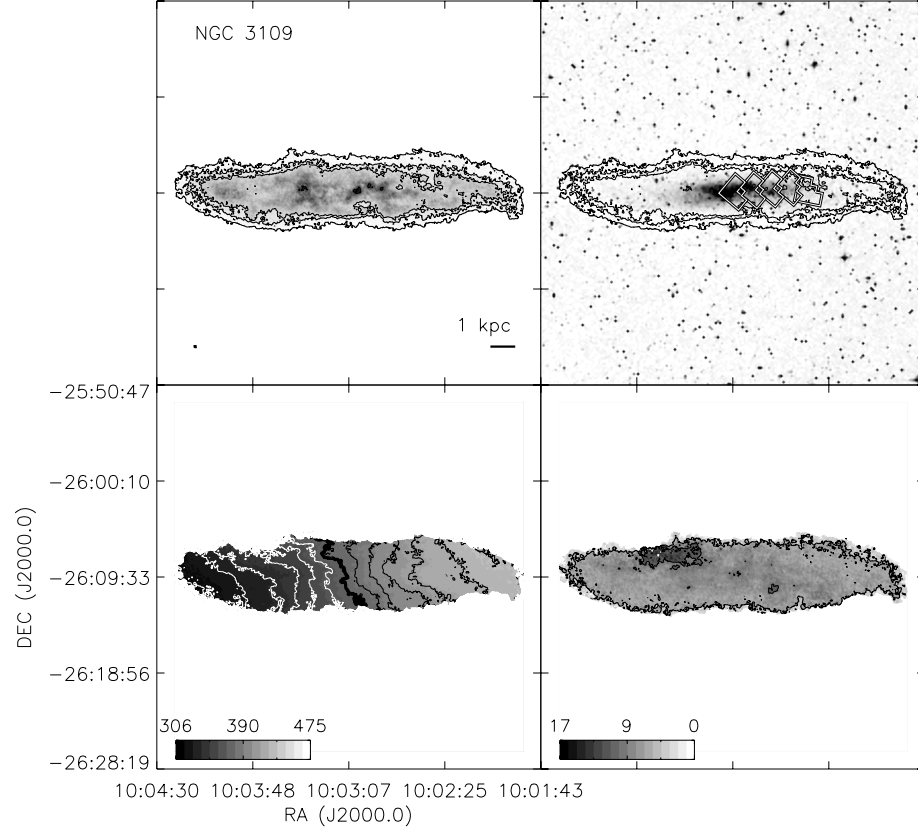


Figure 2.10b *Top left:* The integrated HI intensity map for NGC 3109. The grayscale covers a range from 1×10^{19} to $6.6 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , 1×10^{21} , and $5 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical 4680 Å image from the DSS with the same column density contours overlaid. The HST WFPC2 footprints are the fields covered by the ANGST survey. *Bottom Left:* The HI velocity field. Black contours (lighter grayscale) indicate approaching emission, white contours (darker grayscale) receding emission. The thick black contour is the central velocity ($v_{cen} = 405.1 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right:* The HI velocity dispersion. Contours are plotted at 5, 10, and 15 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

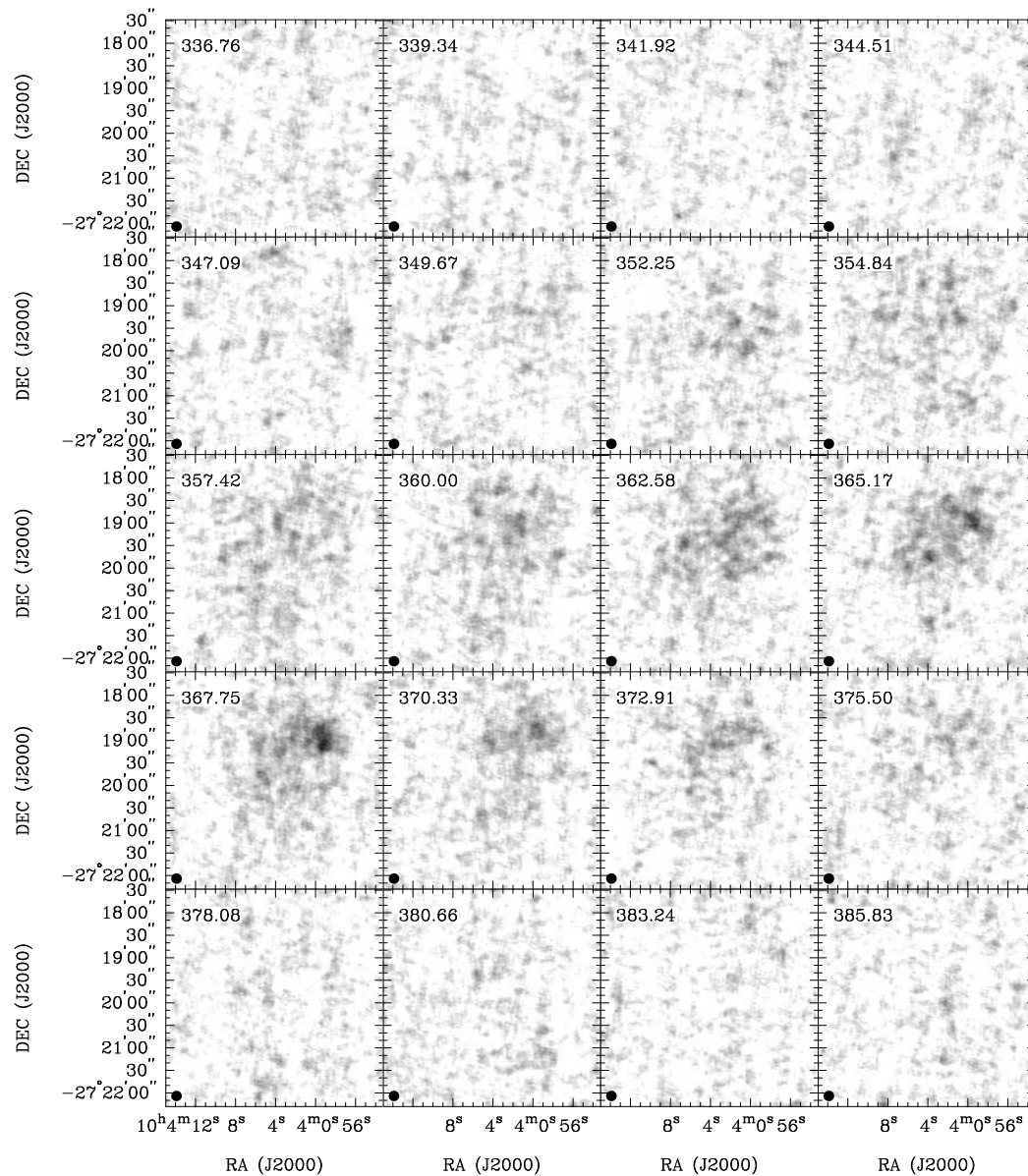


Figure 2.11a **Antlia**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $8.8 \text{ mJy beam}^{-1}$) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

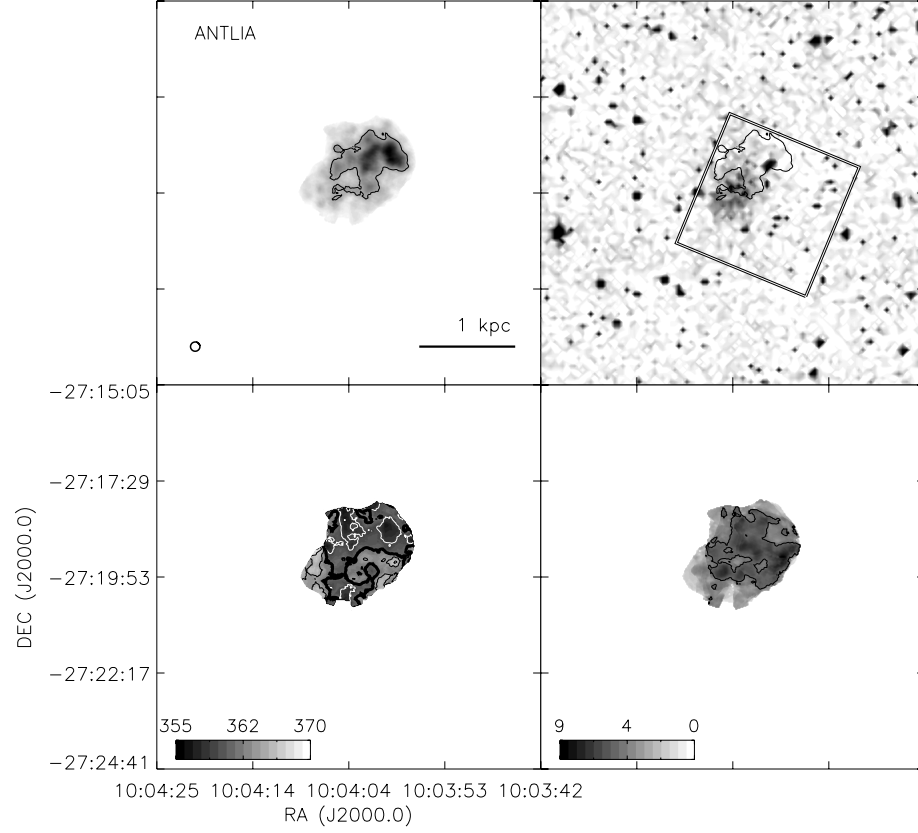


Figure 2.11b *Top left:* The integrated HI intensity map for Antlia. The grayscale covers a range from 1×10^{19} to $2.9 \times 10^{20} \text{ cm}^{-2}$ with a contour of $1 \times 10^{20} \text{ cm}^{-2}$. *Top Right:* An optical $4680 \text{ \AA}$ image from the DSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The HI velocity field. Black contours (lighter grayscale) indicate approaching emission, white contours (darker grayscale) receding emission. The thick black contour is the central velocity ($v_{\text{cen}} = 363.0 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 3 \text{ km s}^{-1}$. *Bottom Right:* The HI velocity dispersion. A contour is plotted at 5 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

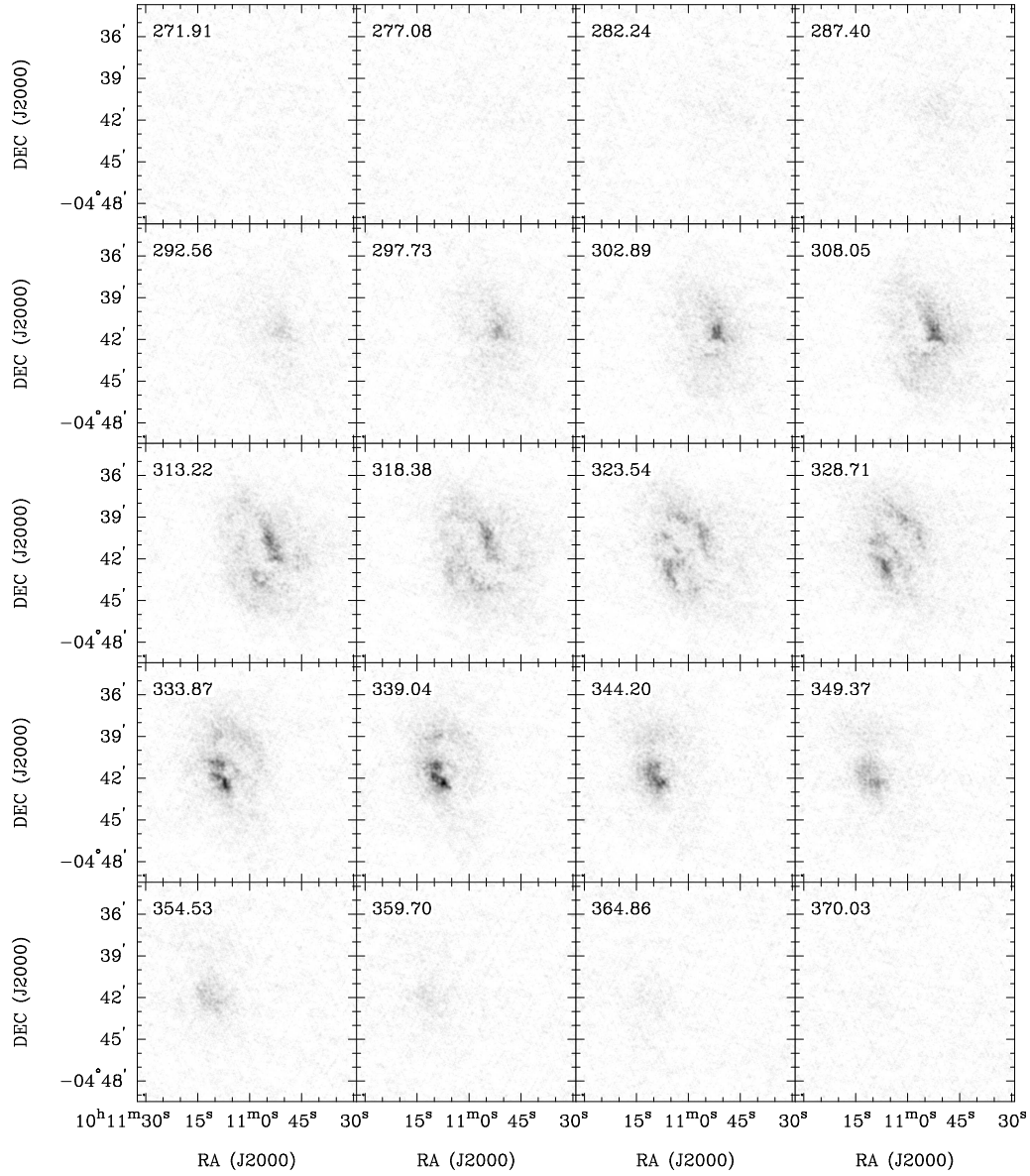


Figure 2.12a **Sextans A:** Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $35.4 \text{ mJy beam}^{-1}$). Every third channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

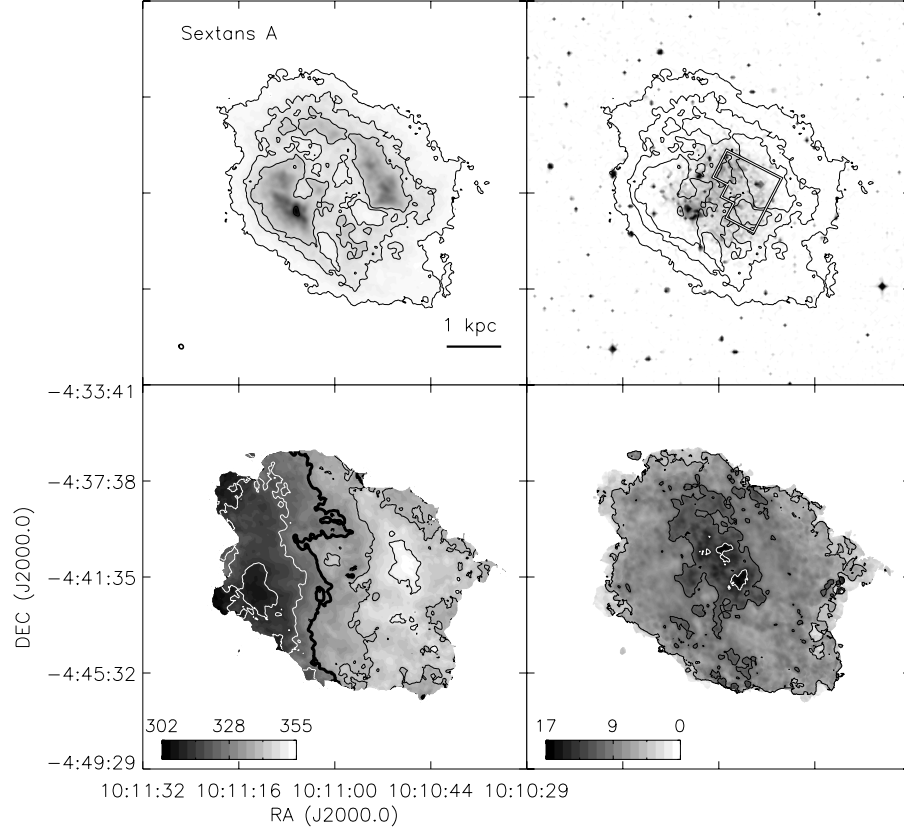


Figure 2.12b *Top left:* The integrated H I intensity map for Sextans A. The grayscale covers a range from 1×10^{19} to $6.1 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , 1×10^{21} , and $5 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical 4680 Å image from the DSS with the same column density contours overlaid. The HST WFPC2 footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 324.8 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5, 10, and 15 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

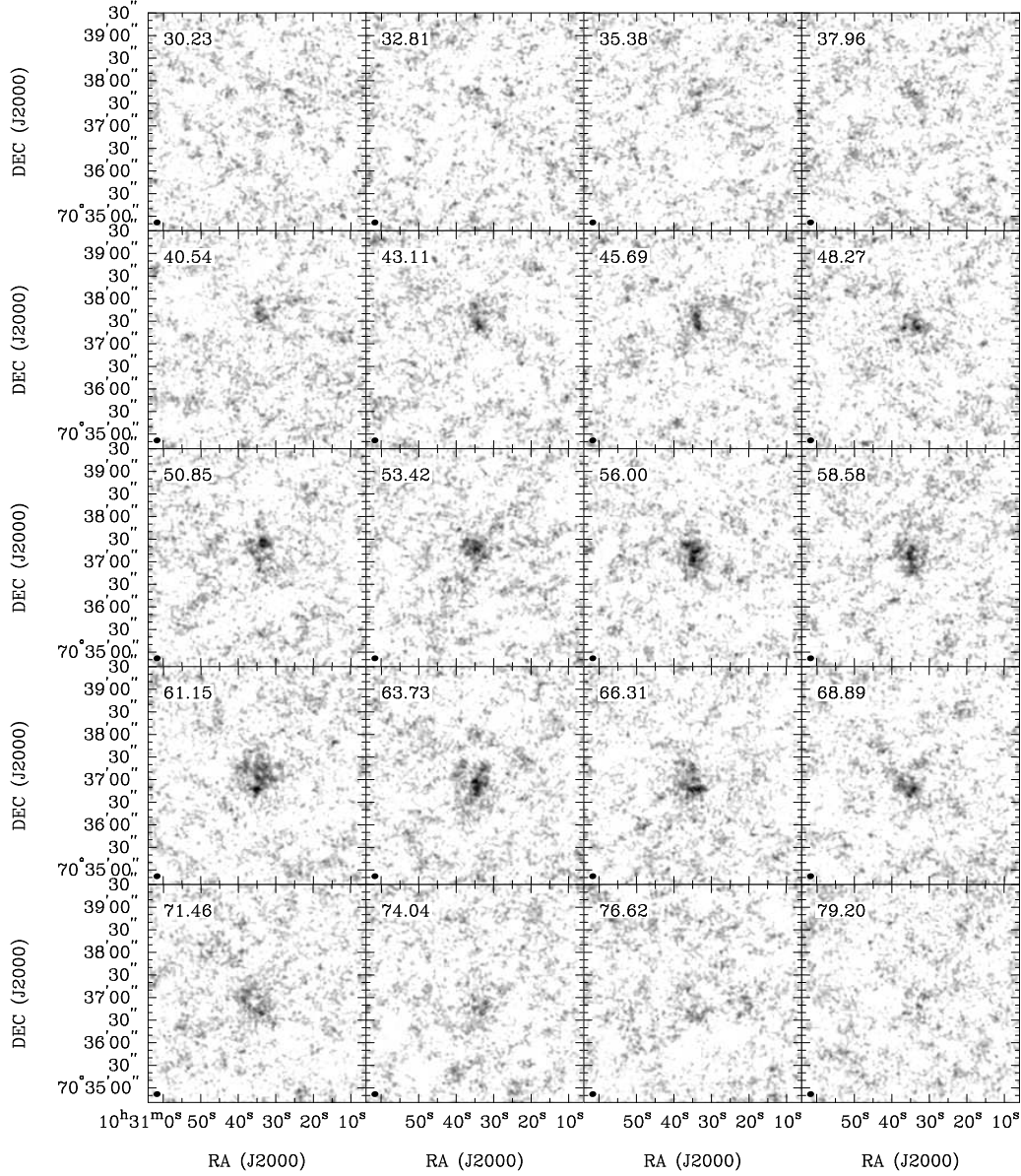


Figure 2.13a **DDO 82**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $6.7 \text{ mJy beam}^{-1}$). Every channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

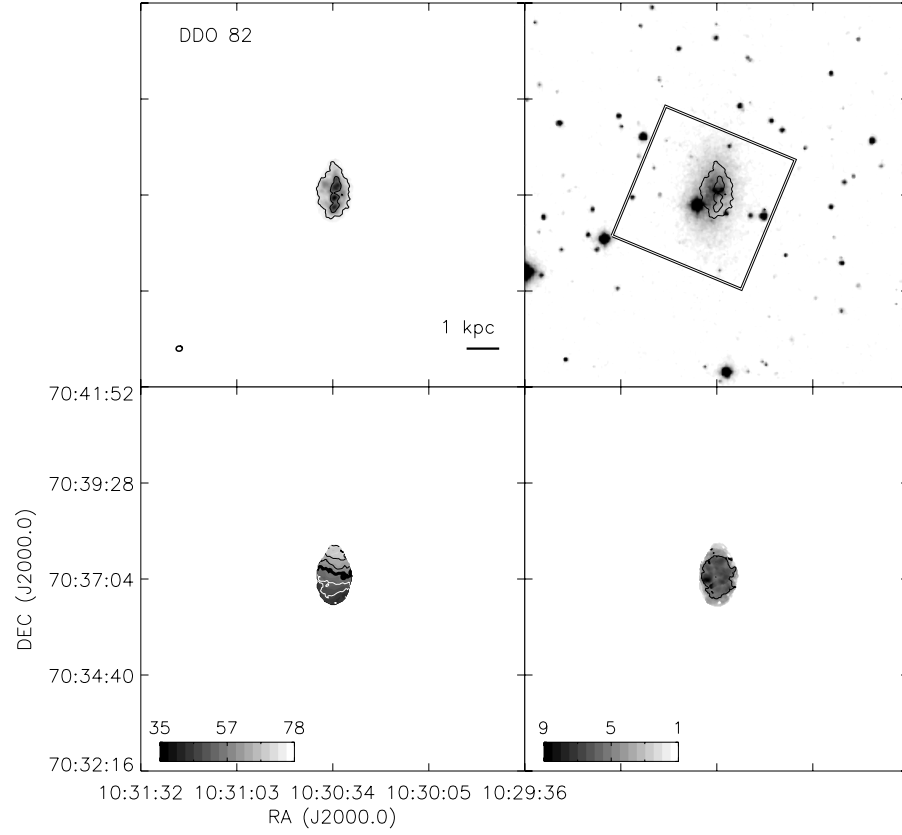


Figure 2.13b *Top left:* The integrated H I intensity map for DDO 82. The grayscale covers a range from 1×10^{19} to $9.3 \times 10^{20} \text{ cm}^{-2}$ with contours of 1×10^{20} and $5 \times 10^{20} \text{ cm}^{-2}$. *Top Right:* An optical 6450 Å image from the DSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 56.2 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 5 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. A contour is plotted at 5 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

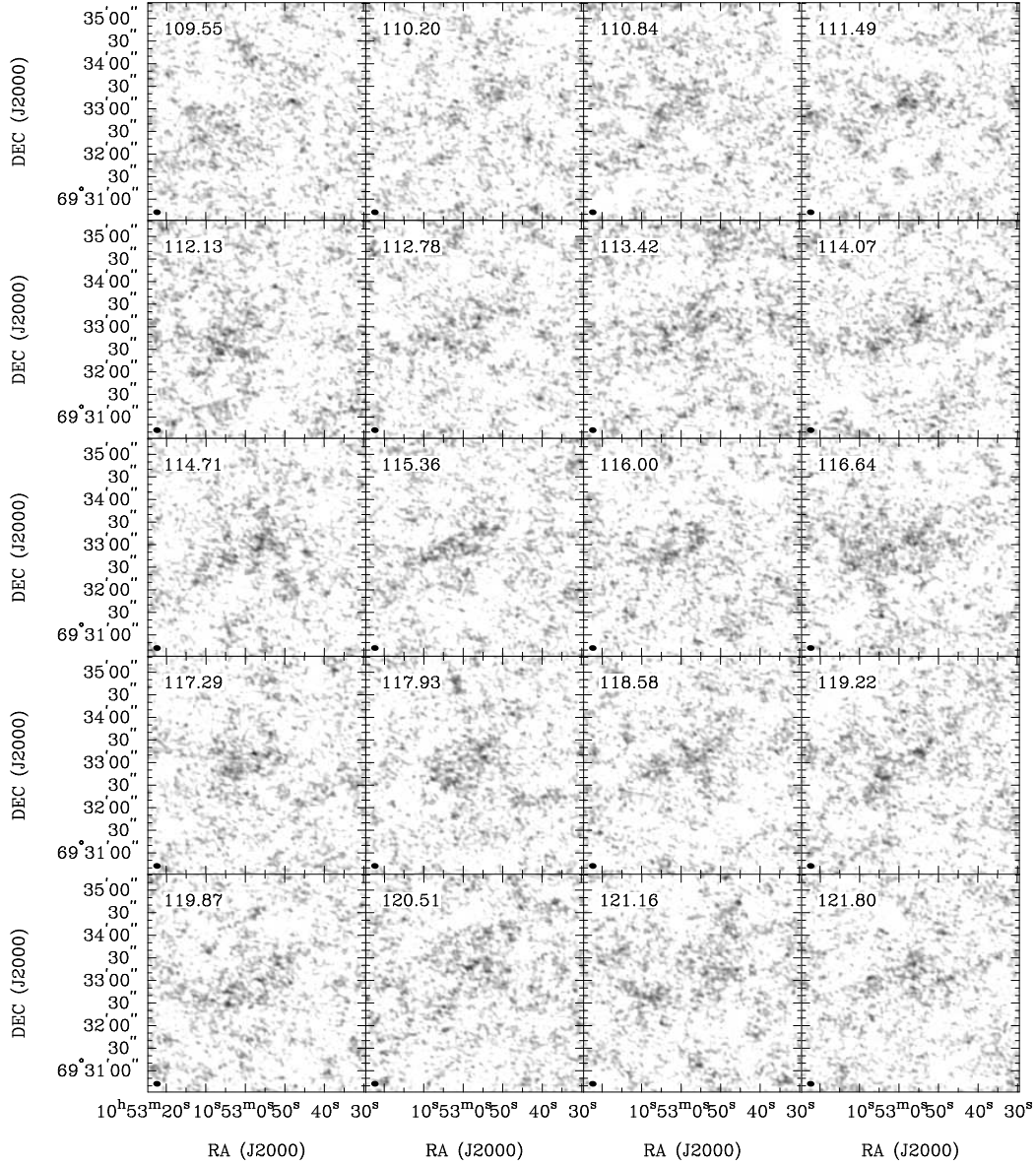


Figure 2.14a **KDG 73**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $8.6 \text{ mJy beam}^{-1}$). Every third channel is shown (channel width 0.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

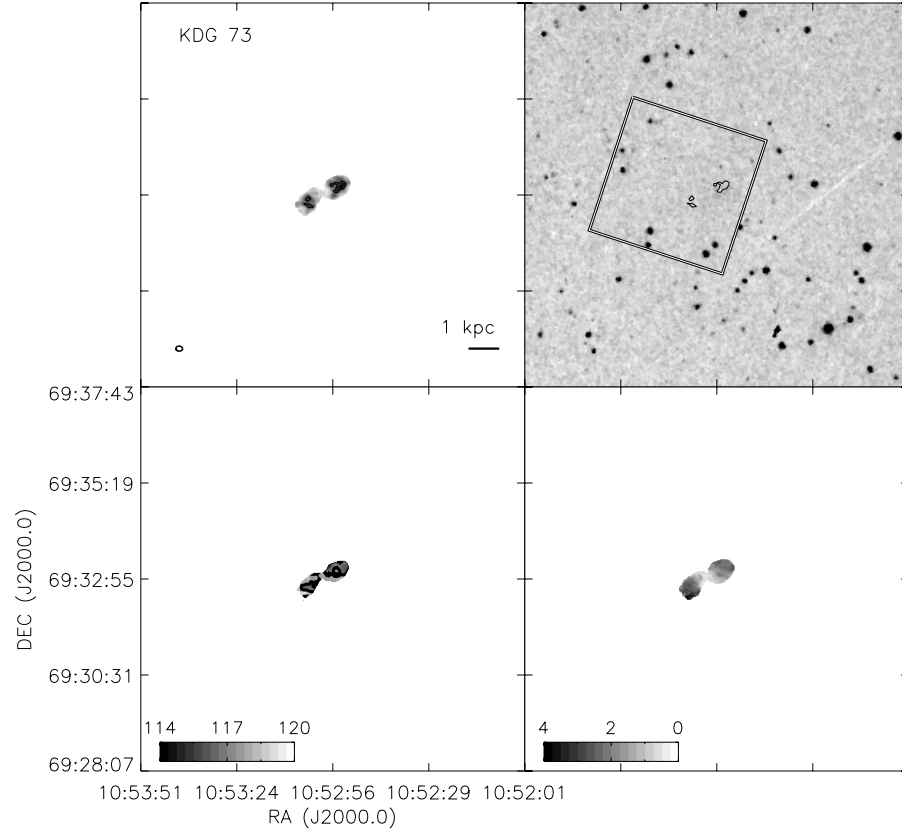


Figure 2.14b *Top left:* The integrated H I intensity map for KDG 73. The grayscale covers a range from 1×10^{19} to $1.4 \times 10^{20} \text{ cm}^{-2}$ with a contour of $1 \times 10^{20} \text{ cm}^{-2}$. *Top Right:* An optical 6450 Å image from the DSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{\text{cen}} = 116.3 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

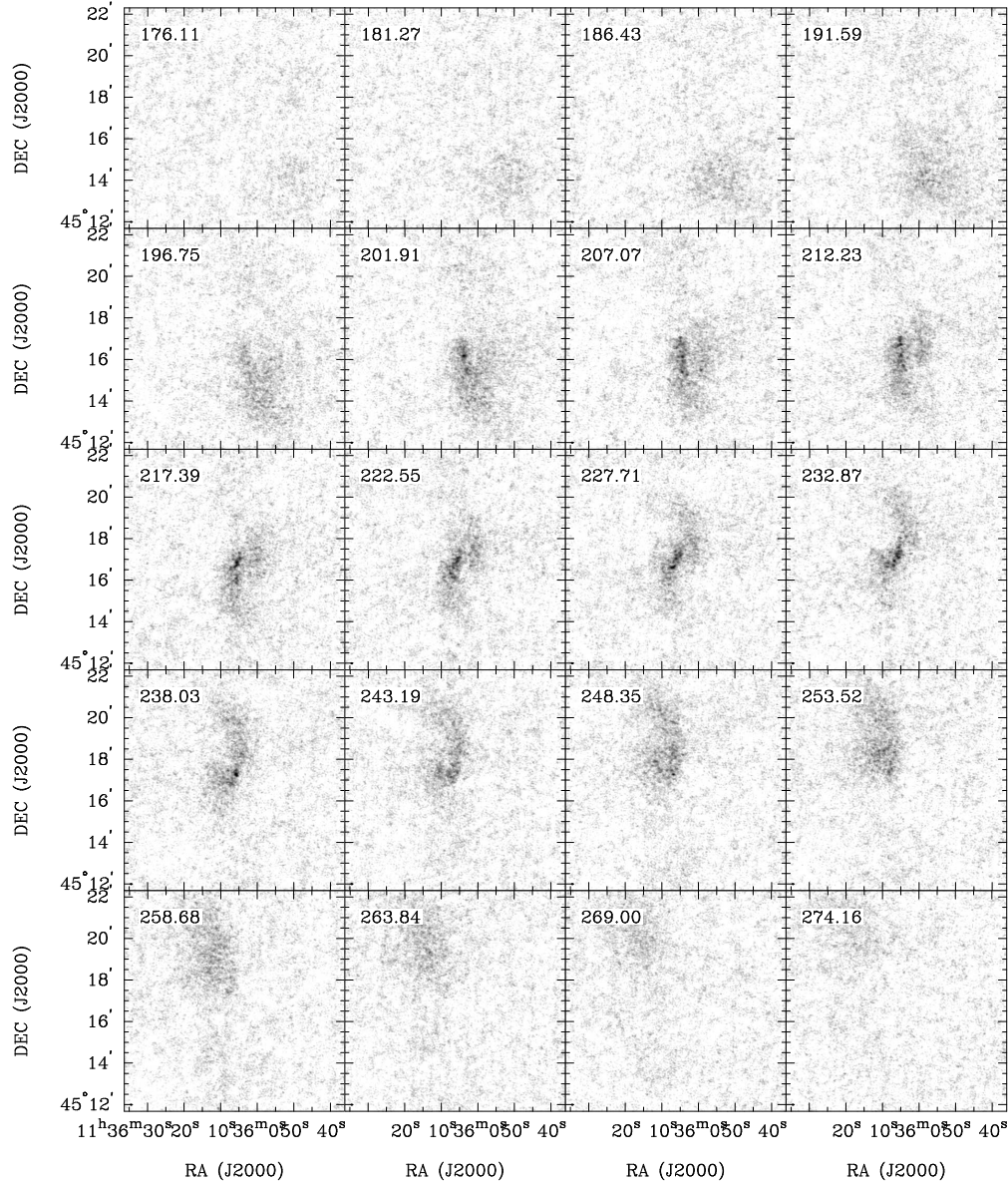


Figure 2.15a **NGC 3741**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $9.6 \text{ mJy beam}^{-1}$). Every third channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

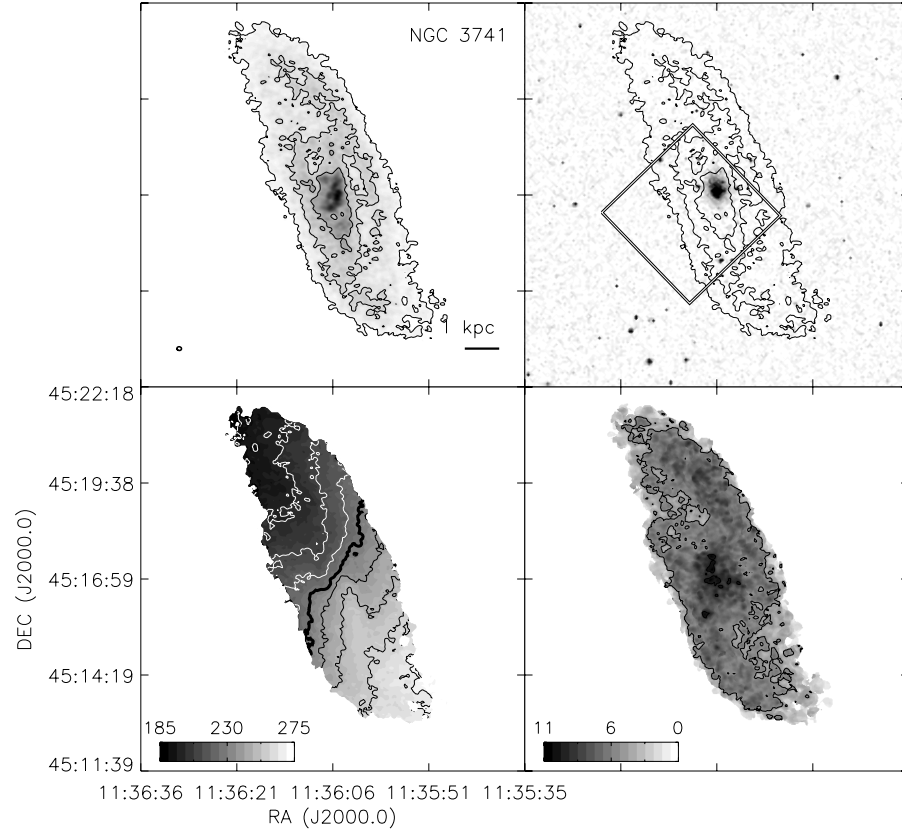


Figure 2.15b *Top left:* The integrated H I intensity map for NGC 3741. The grayscale covers a range from 1×10^{19} to $3.4 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 229.1 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

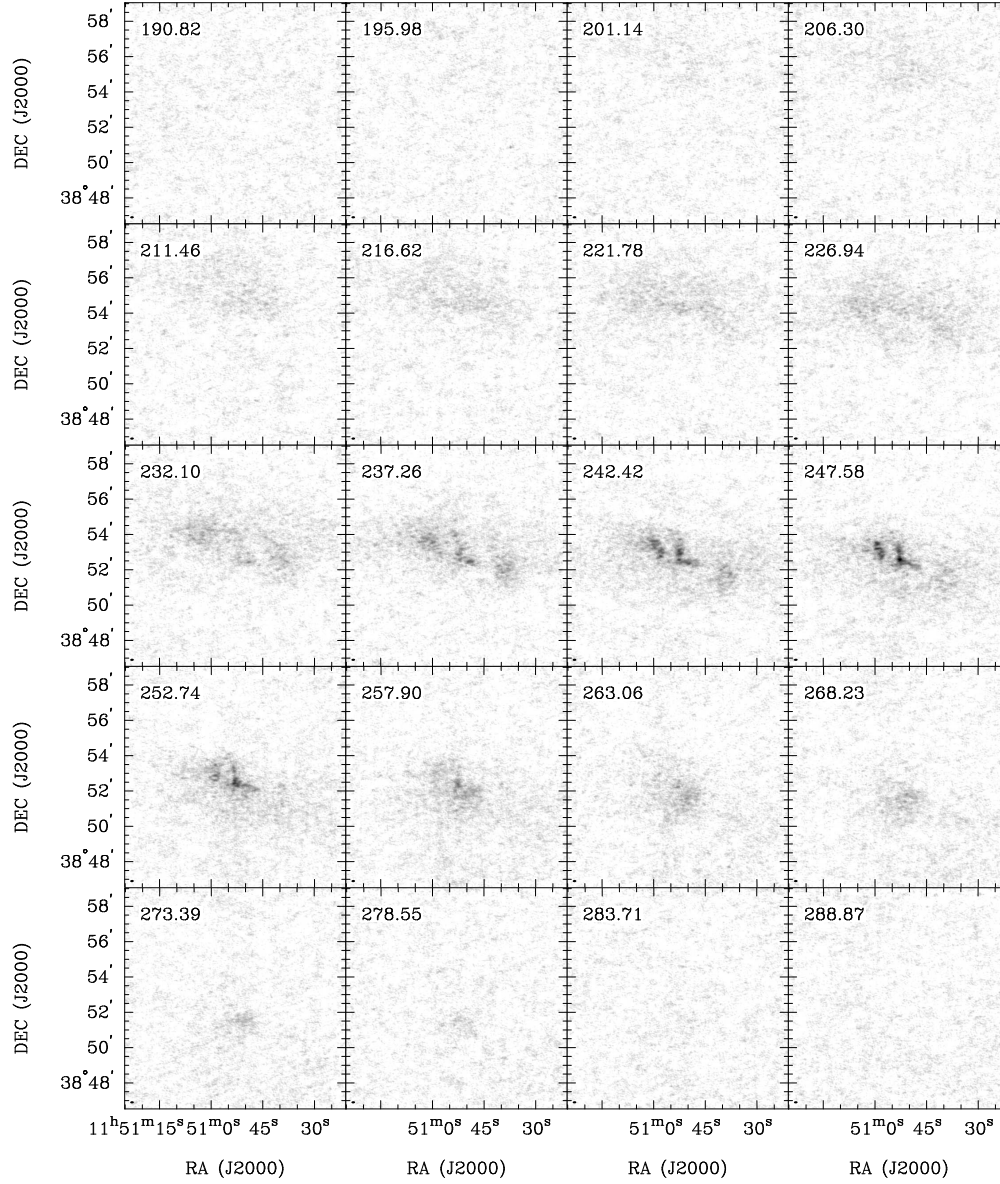


Figure 2.16a **DDO 99**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $14.7 \text{ mJy beam}^{-1}$). Every third channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

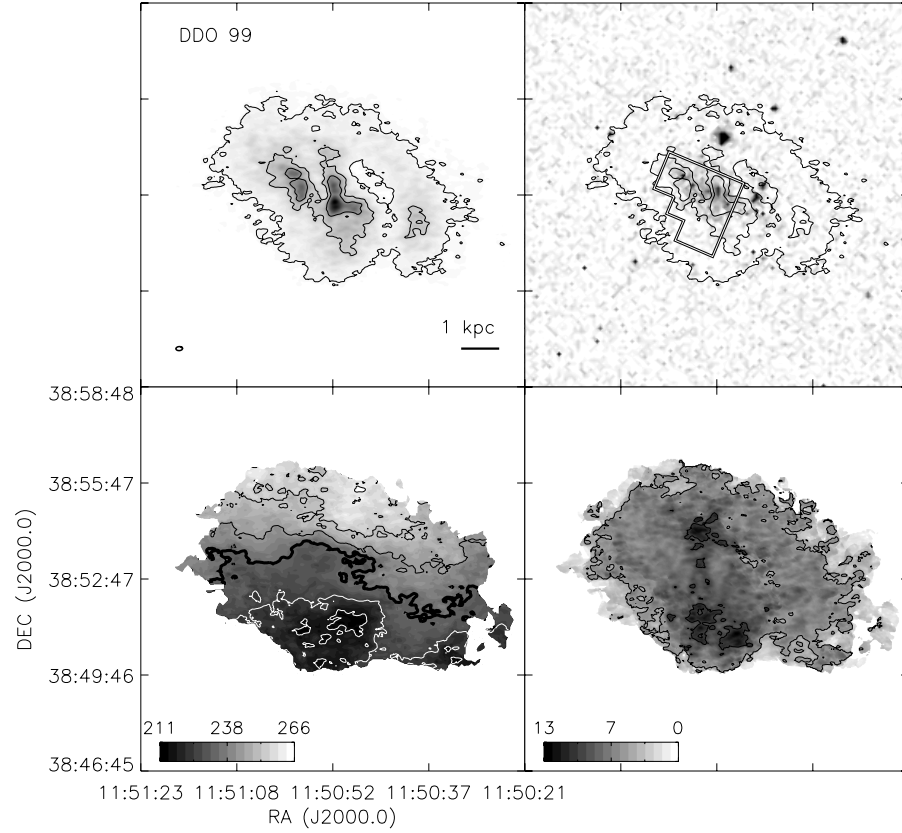


Figure 2.16b *Top left:* The integrated H I intensity map for DDO 99. The grayscale covers a range from 1×10^{19} to $2.6 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST WFPC2 footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 242.1 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

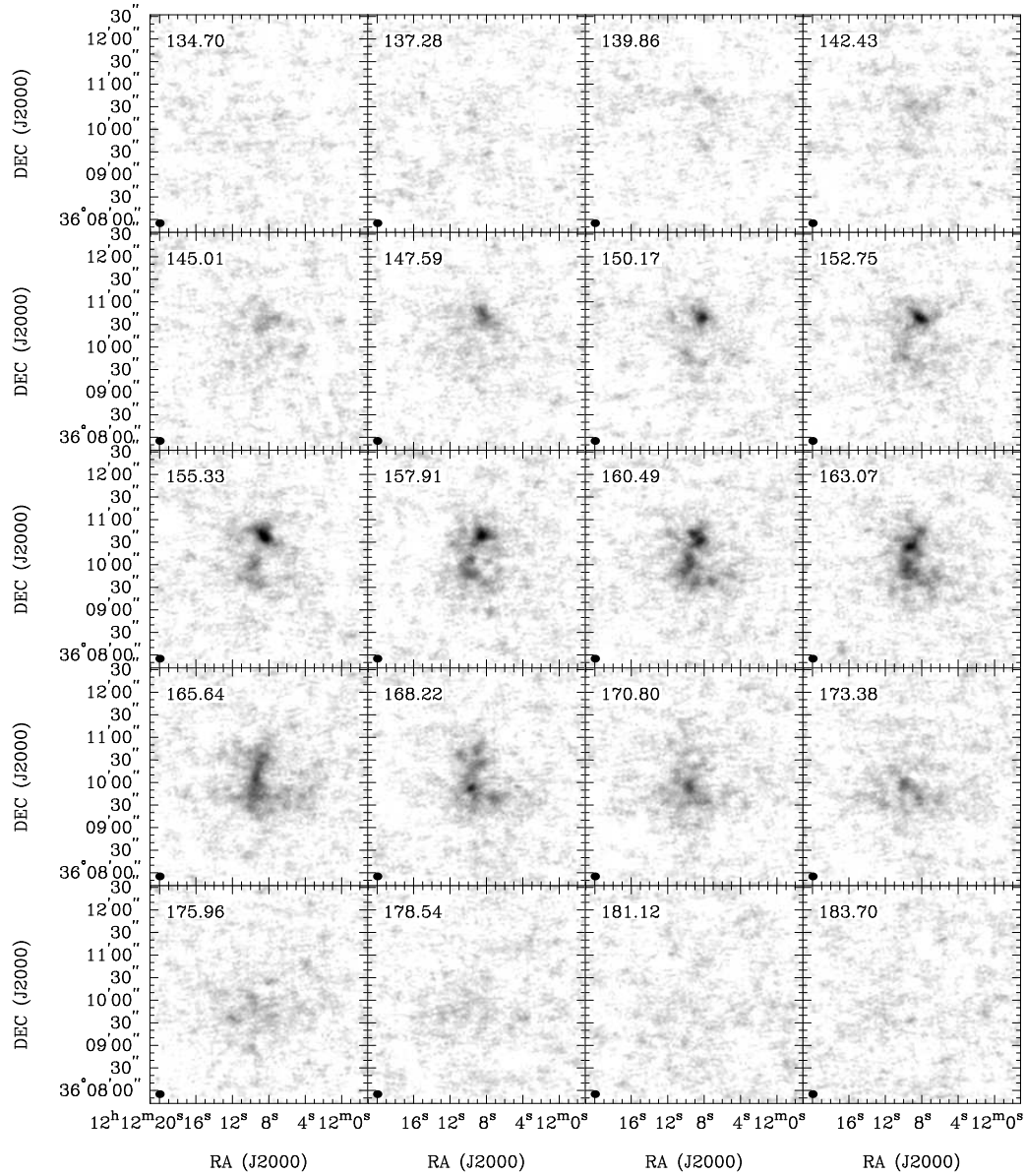


Figure 2.17a **NGC 4163**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $16.1 \text{ mJy beam}^{-1}$). Every third channel is shown (channel width 0.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

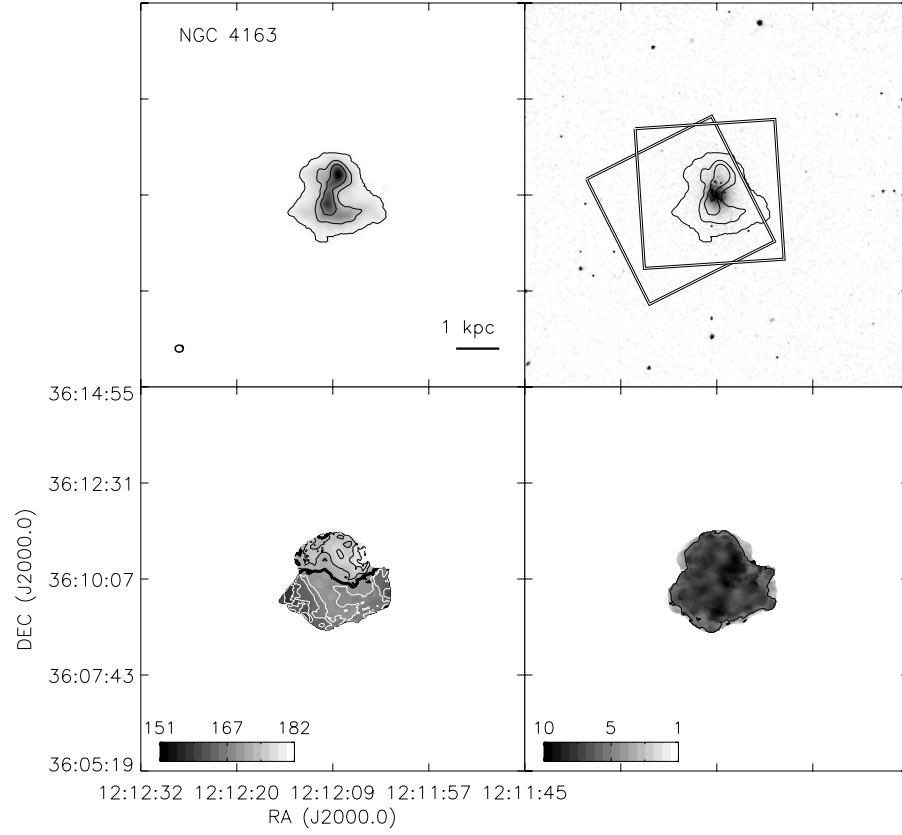


Figure 2.17b *Top left*: The integrated HI intensity map for NGC 4163. The grayscale covers a range from 1×10^{19} to $2.1 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right*: An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprints are the fields covered by the ANGST survey. *Bottom Left*: The HI velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 161.6 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 3 \text{ km s}^{-1}$. *Bottom Right*: The HI velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

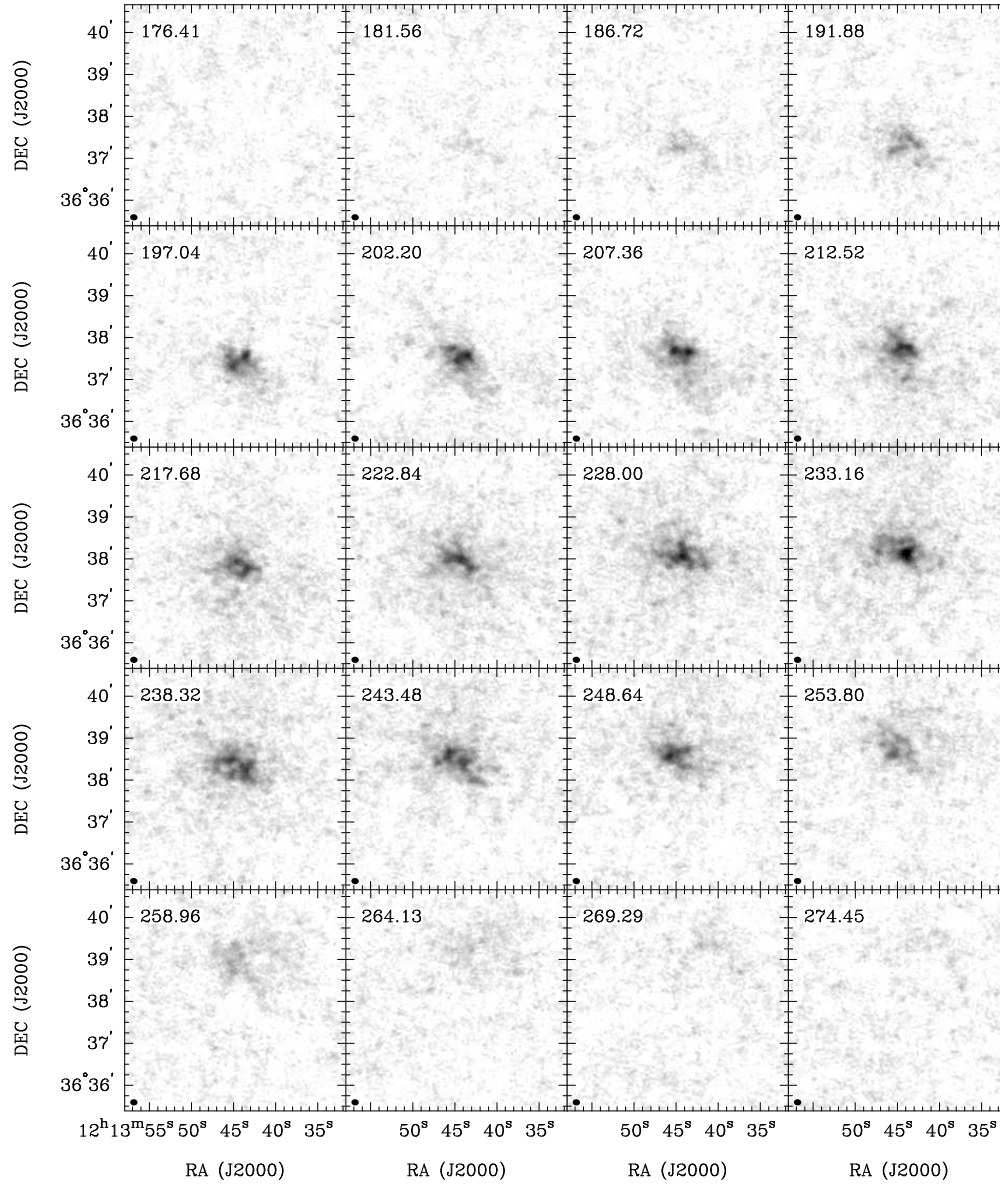


Figure 2.18a **NGC 4190**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $14.7 \text{ mJy beam}^{-1}$). Every third channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

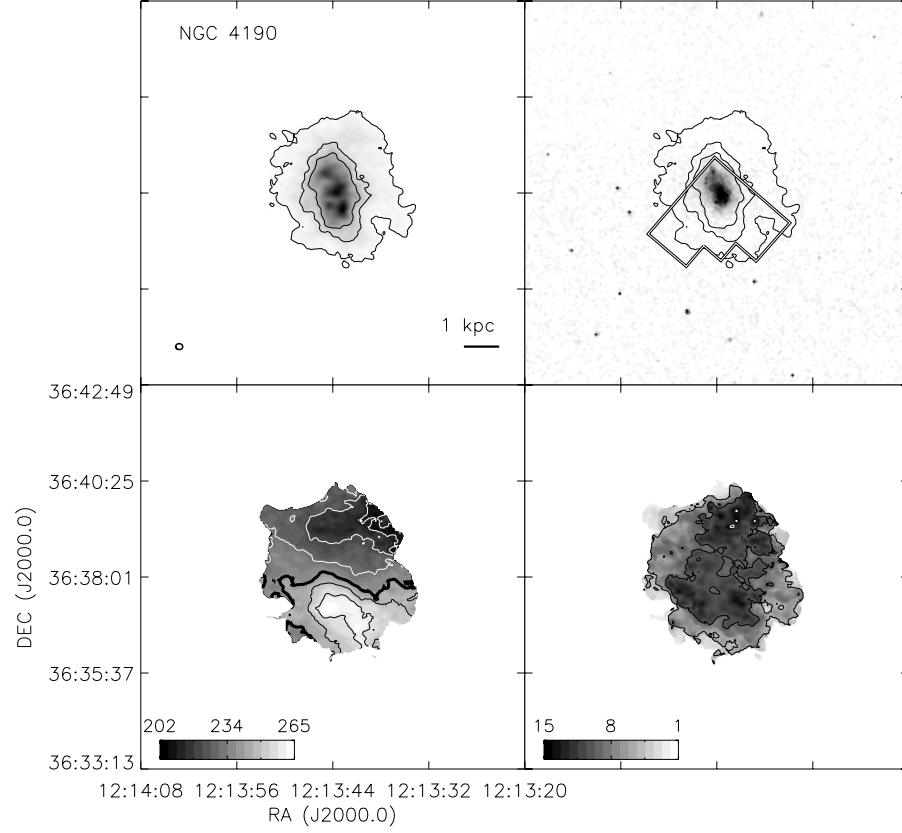


Figure 2.18b *Top left:* The integrated H I intensity map for NGC 4190. The grayscale covers a range from 1×10^{19} to $3.5 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST WFPC2 footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 227.0 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5, 10, and 15 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

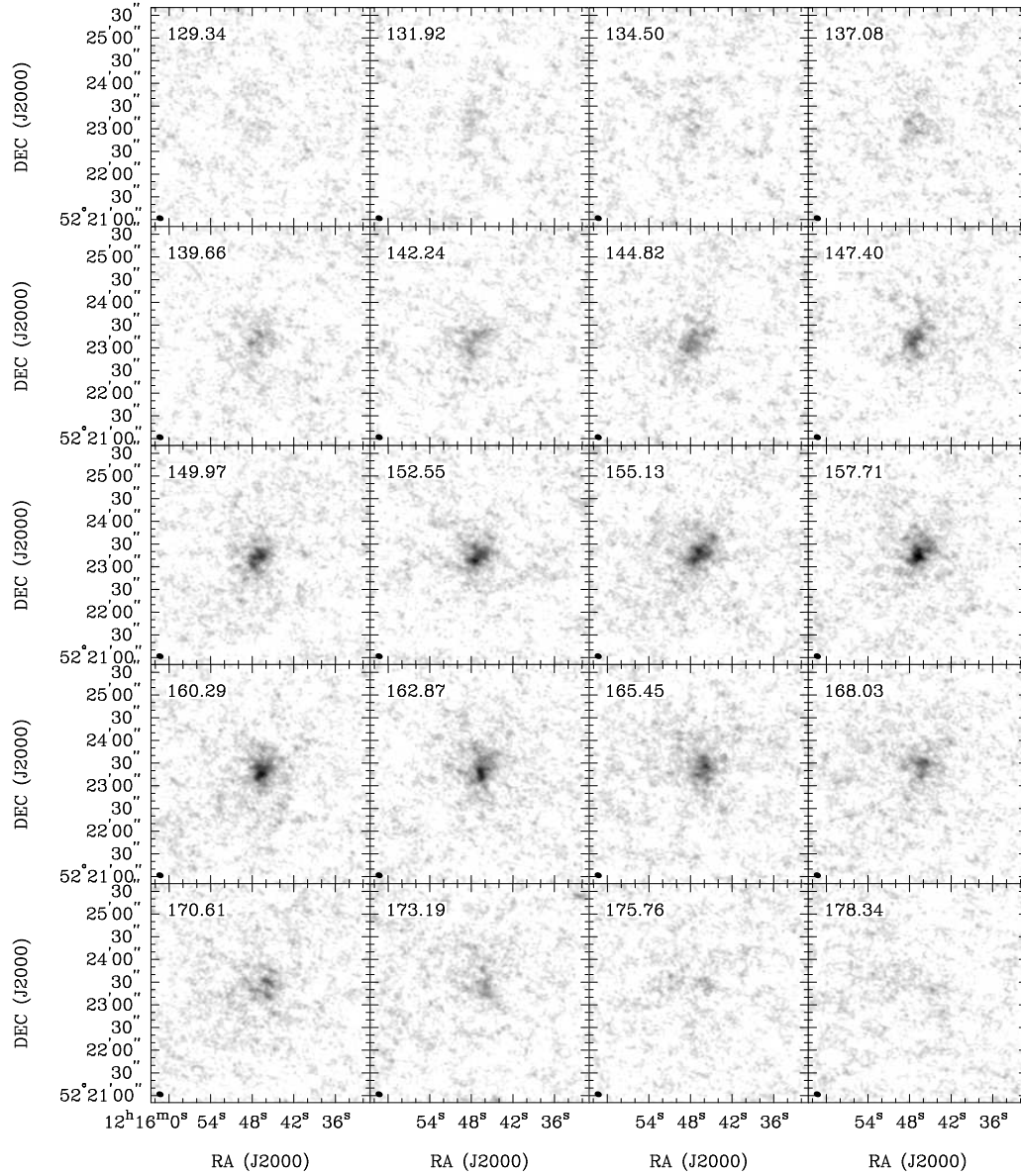


Figure 2.19a **MCG +09-20-131**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $12.3 \text{ mJy beam}^{-1}$). Every channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

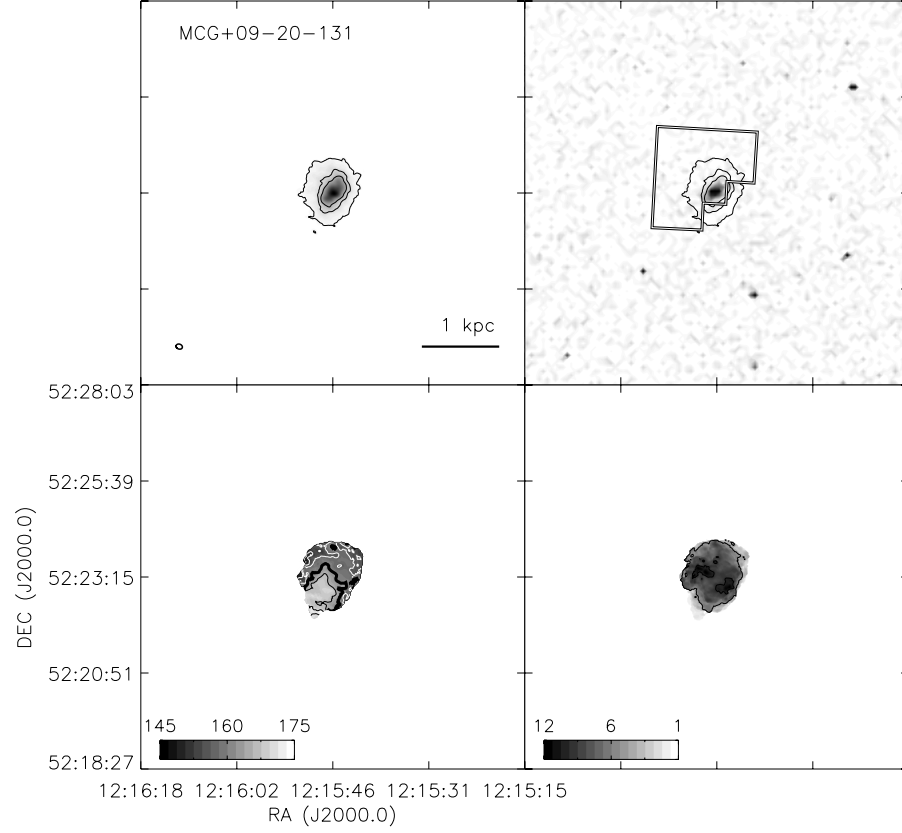


Figure 2.19b *Top left:* The integrated H I intensity map for MCG +09-20-131. The grayscale covers a range from 1×10^{19} to $3.3 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST WFPC2 footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 157.6 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 5 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

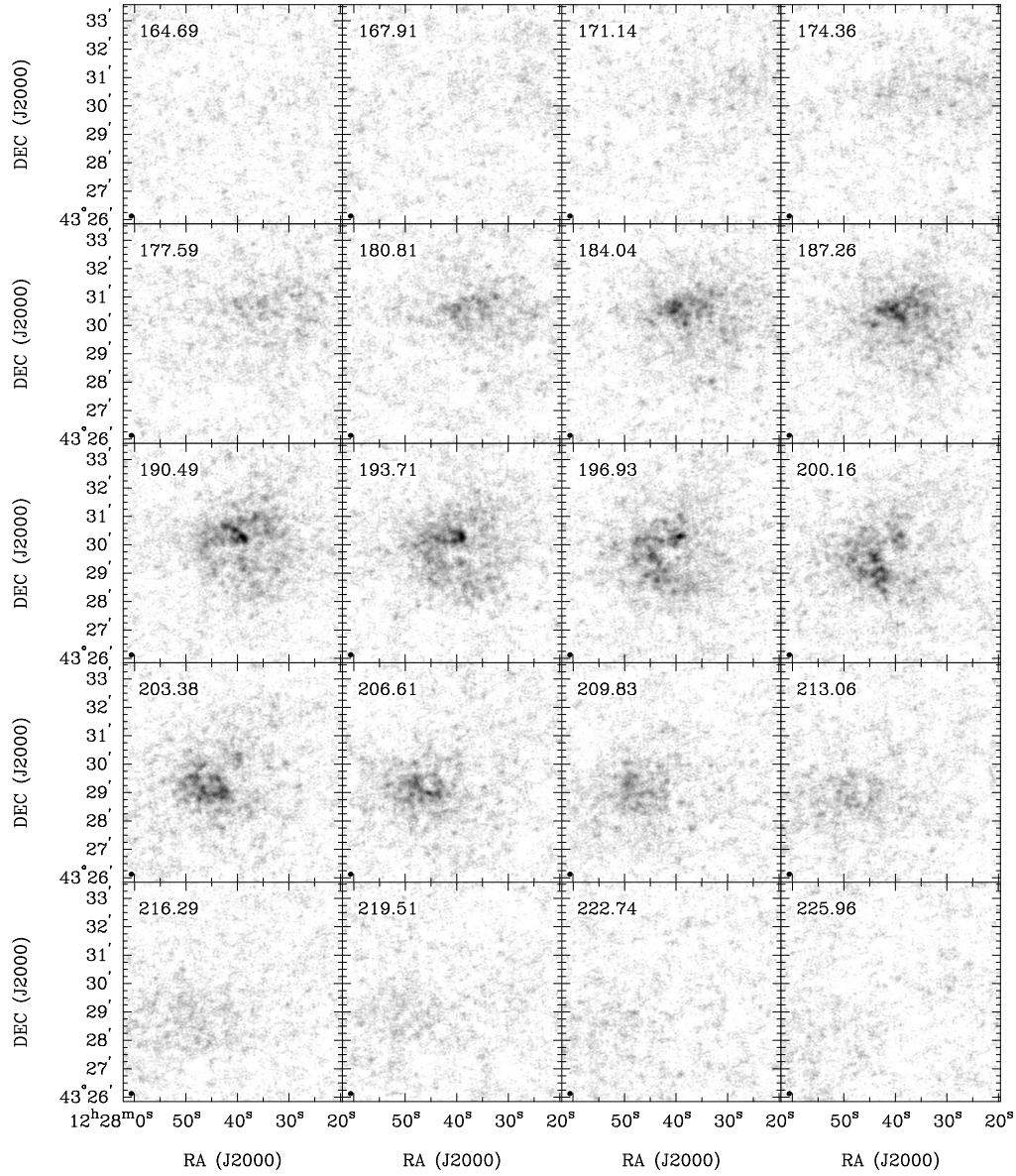


Figure 2.20a **DDO 125**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $16.0 \text{ mJy beam}^{-1}$). Every fourth channel is shown (channel width 0.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

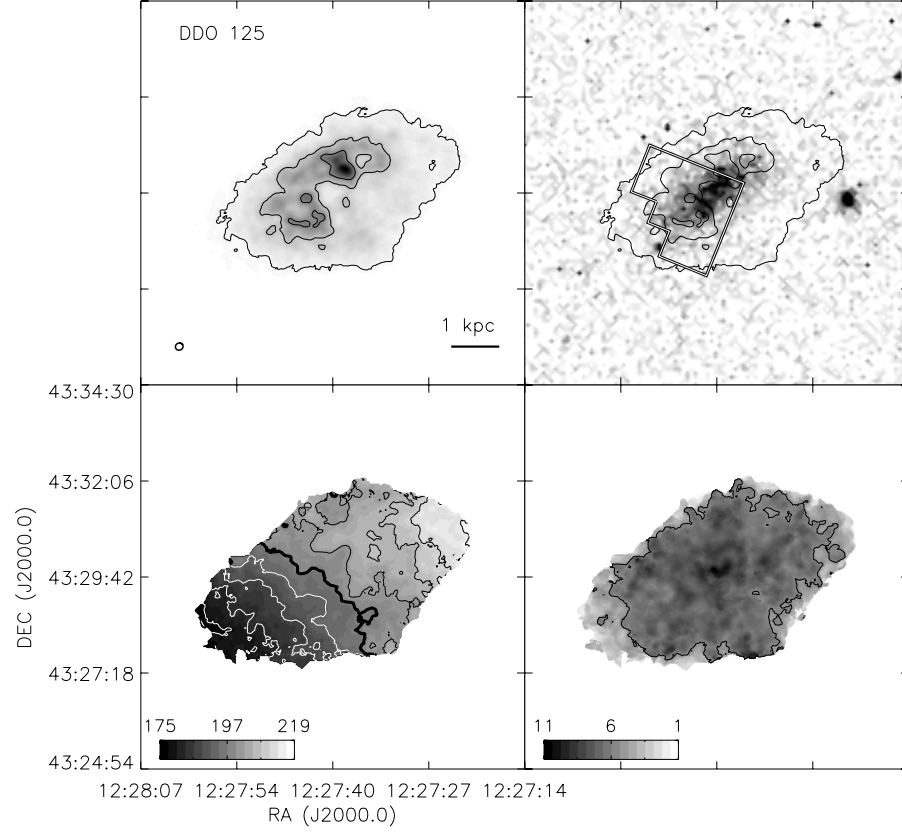


Figure 2.20b *Top left:* The integrated HI intensity map for DDO 125. The grayscale covers a range from 1×10^{19} to $2.1 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST WFPC2 footprint is the field covered by the ANGST survey. *Bottom Left:* The HI velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 196.1 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 5 \text{ km s}^{-1}$. *Bottom Right:* The HI velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

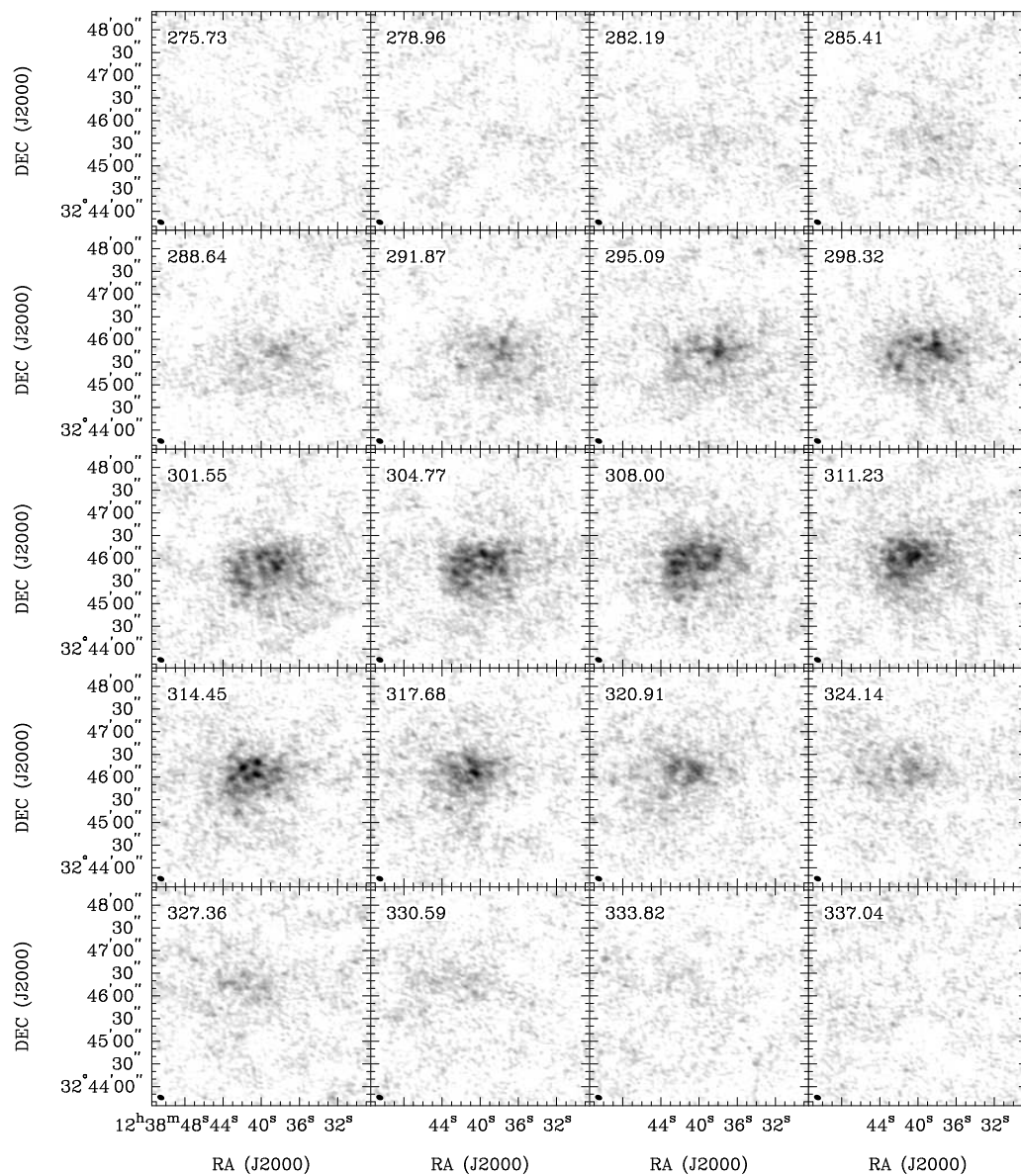


Figure 2.21a **UGCA 292**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $15.8 \text{ mJy beam}^{-1}$). Every fourth channel is shown (channel width 0.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

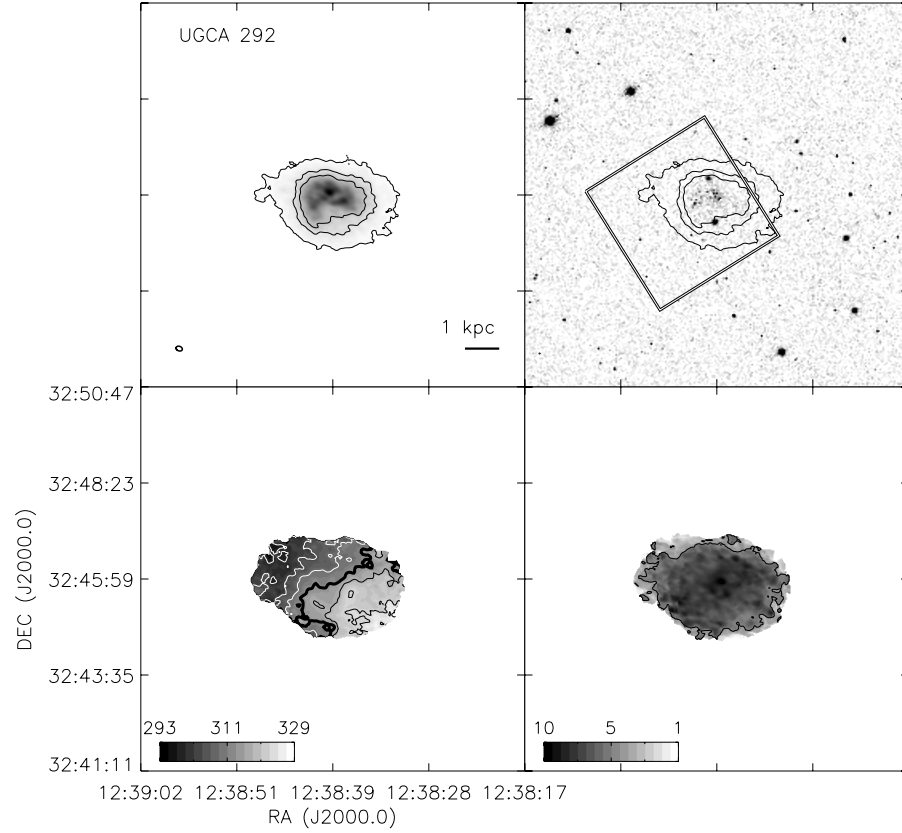


Figure 2.21b *Top left:* The integrated H I intensity map for UGCA 292. The grayscale covers a range from 1×10^{19} to $4.2 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 308.3 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 5 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

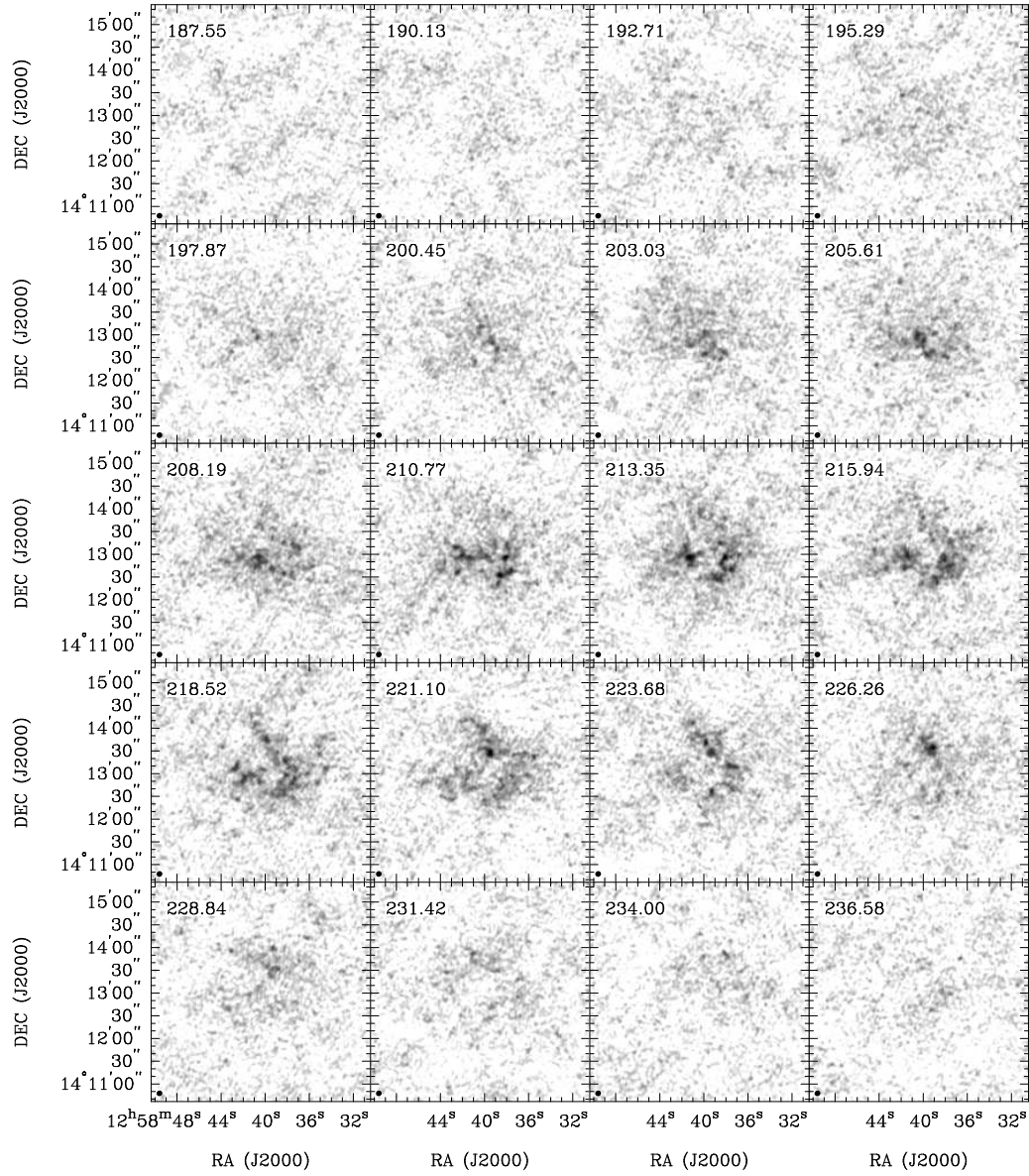


Figure 2.22a **GR 8**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $10.6 \text{ mJy beam}^{-1}$). Every third channel is shown (channel width 0.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

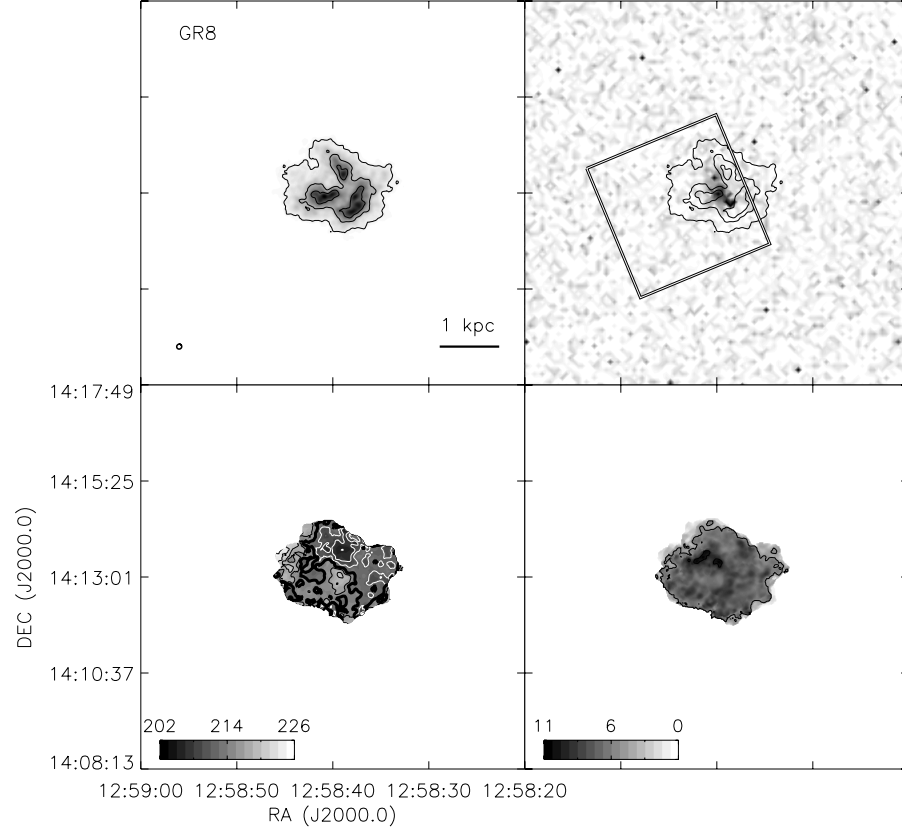


Figure 2.22b *Top left:* The integrated H I intensity map for GR8. The grayscale covers a range from 1×10^{19} to $1.7 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 213.7 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 3 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

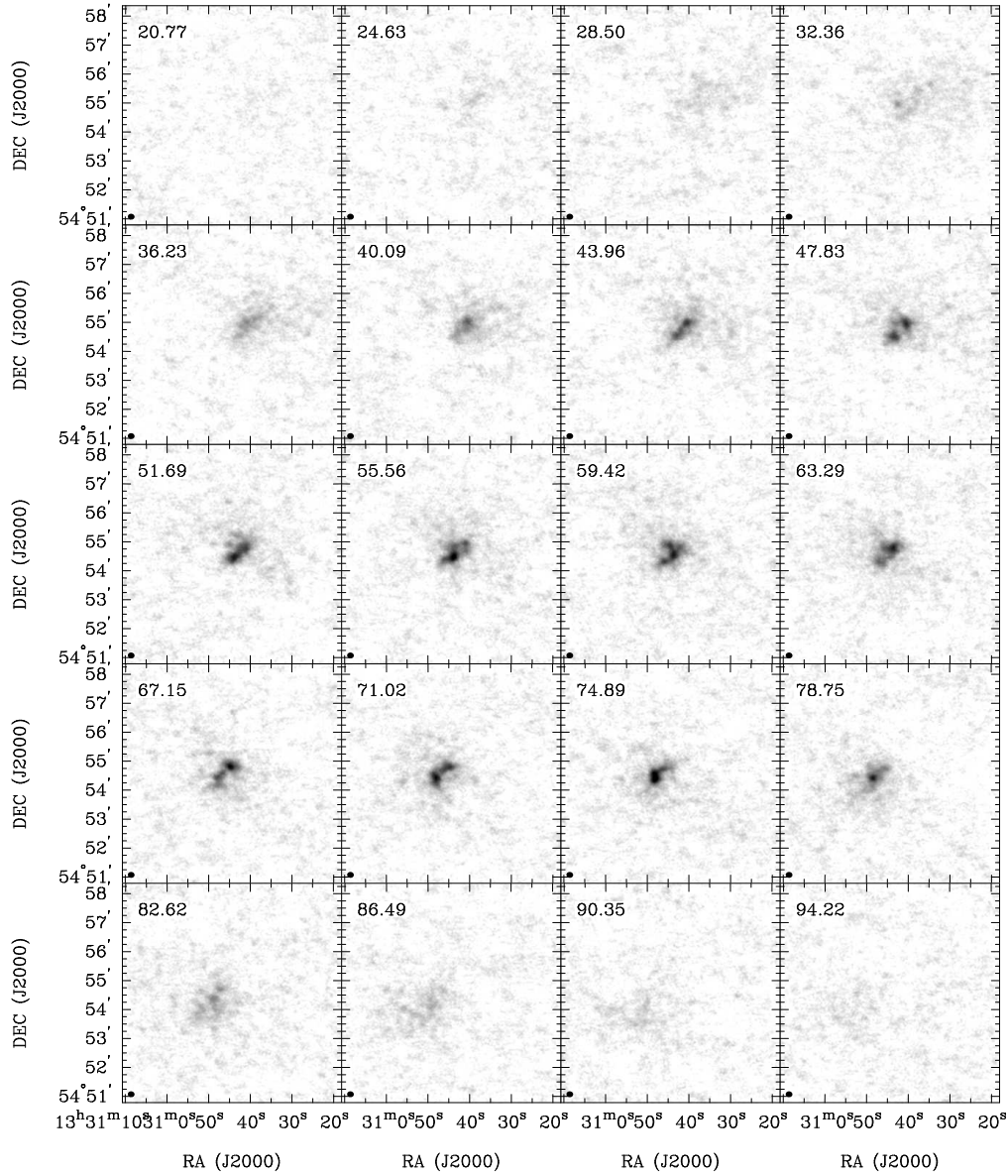


Figure 2.23a **UGC 8508**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $23.0 \text{ mJy beam}^{-1}$). Every fifth channel is shown (channel width 0.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

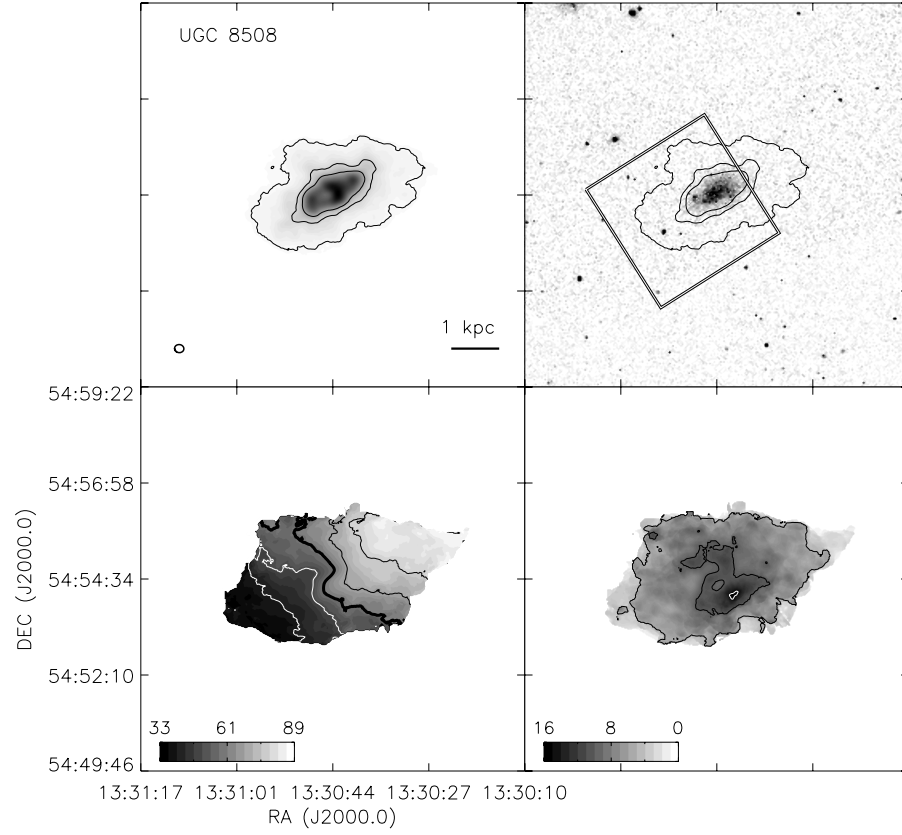


Figure 2.23b *Top left:* The integrated H I intensity map for UGC 8508. The grayscale covers a range from 1×10^{19} to $2.9 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 62.0 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5, 10, and 15 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

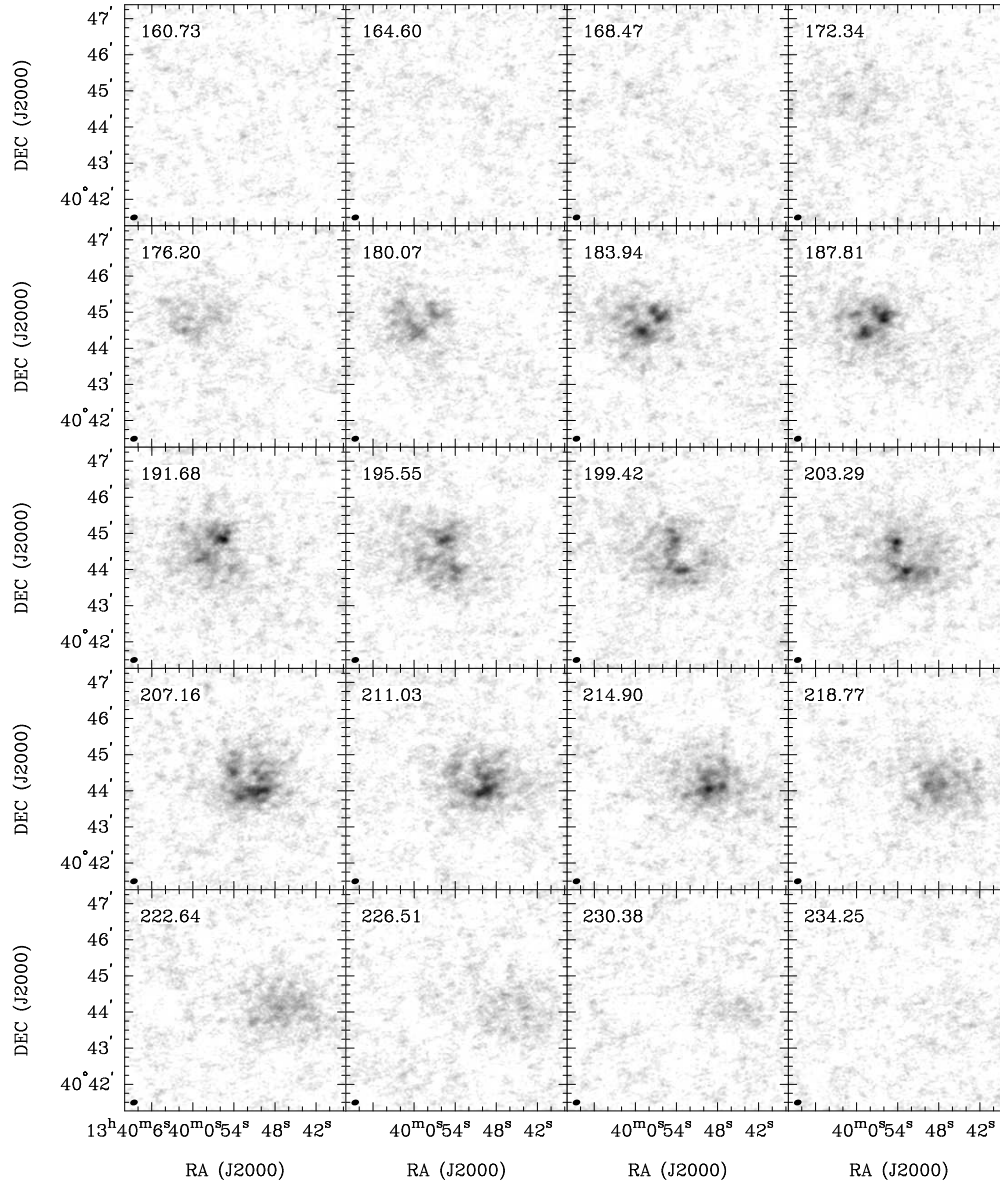


Figure 2.24a **DDO 181**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $13.9 \text{ mJy beam}^{-1}$). Every second channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

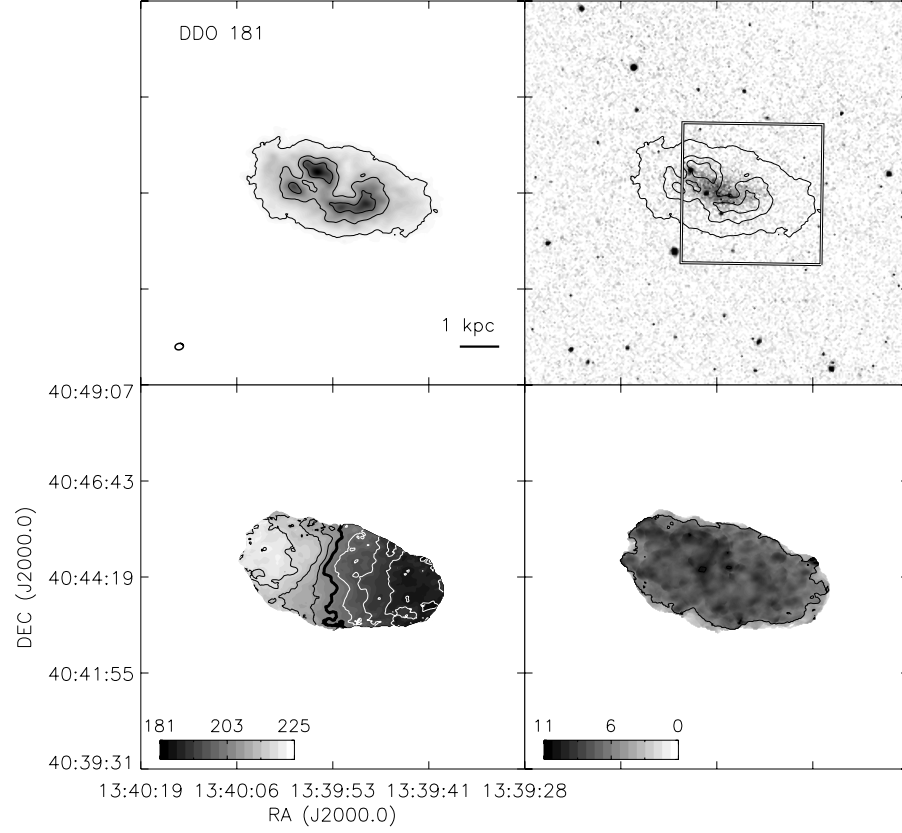


Figure 2.24b *Top left:* The integrated HI intensity map for DDO 181. The grayscale covers a range from 1×10^{19} to $1.7 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The HI velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 201.4 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 5 \text{ km s}^{-1}$. *Bottom Right:* The HI velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

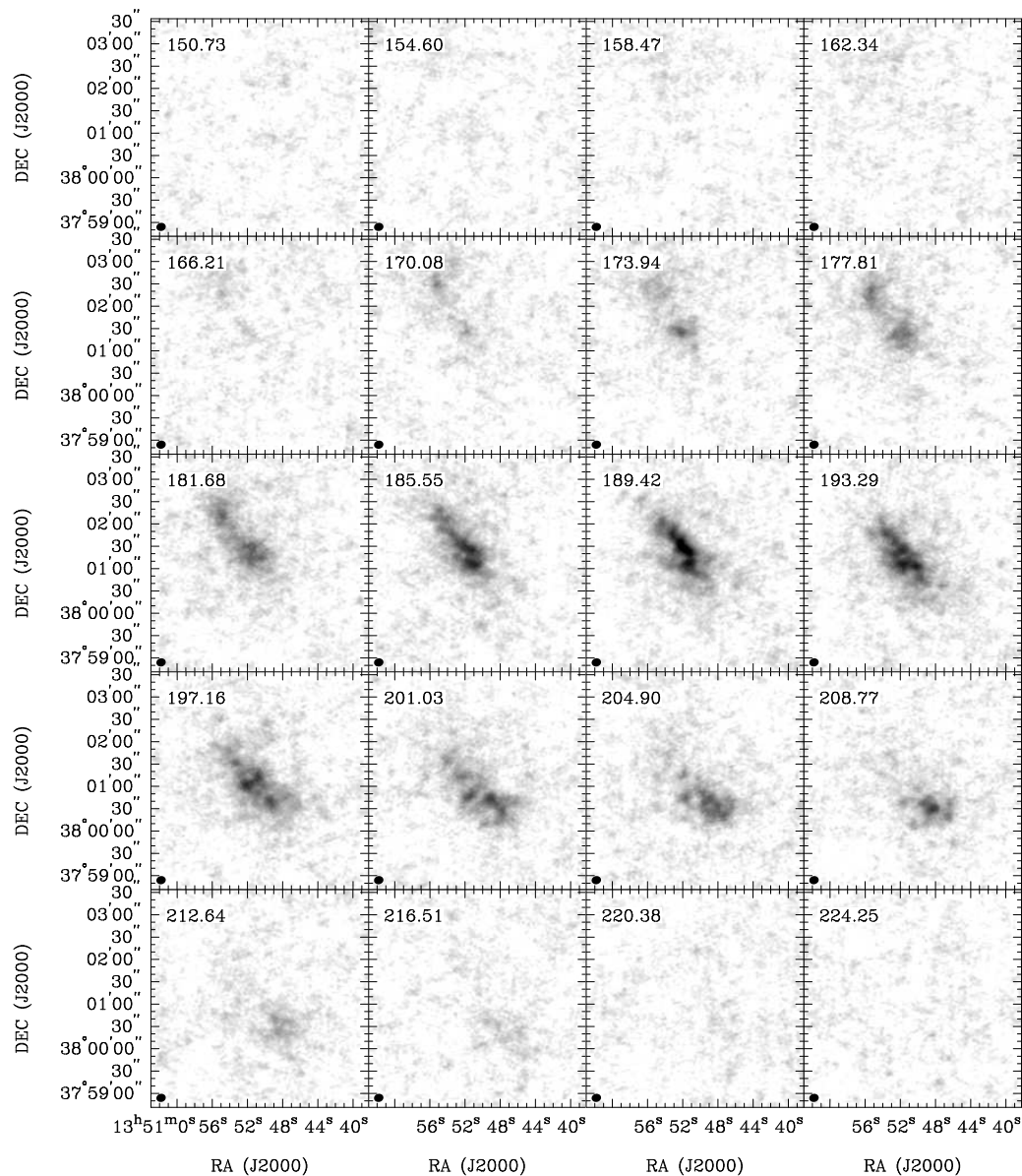


Figure 2.25a **DDO 183**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $15.7 \text{ mJy beam}^{-1}$). Every second channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

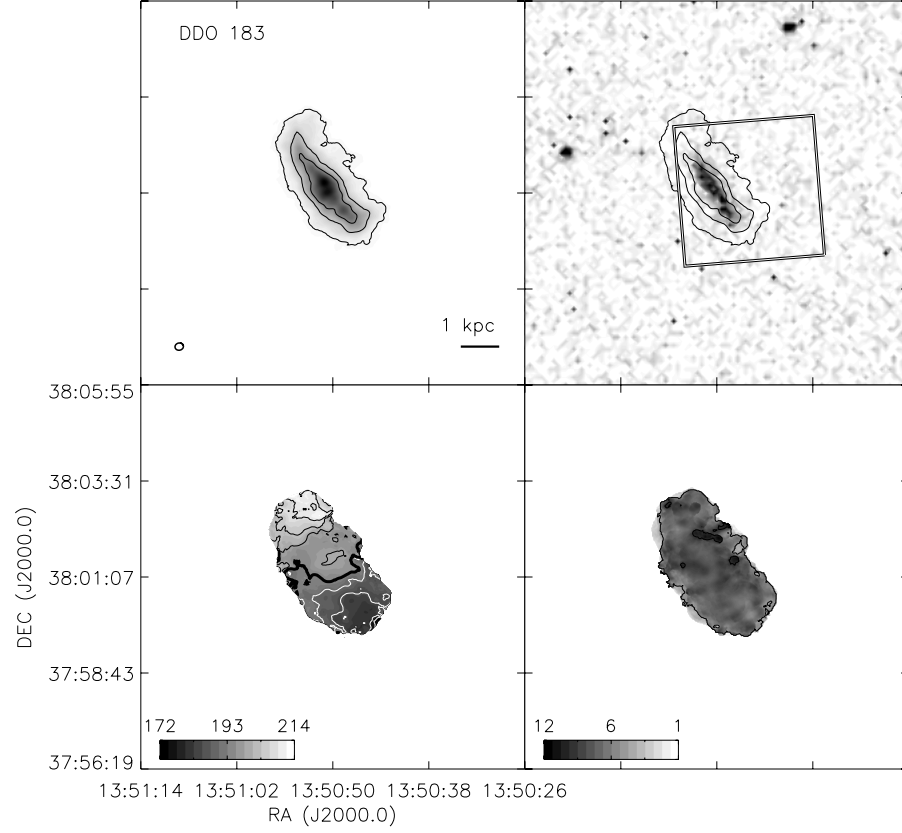


Figure 2.25b *Top left:* The integrated H I intensity map for DDO 183. The grayscale covers a range from 1×10^{19} to $2.2 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 191.2 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 5 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

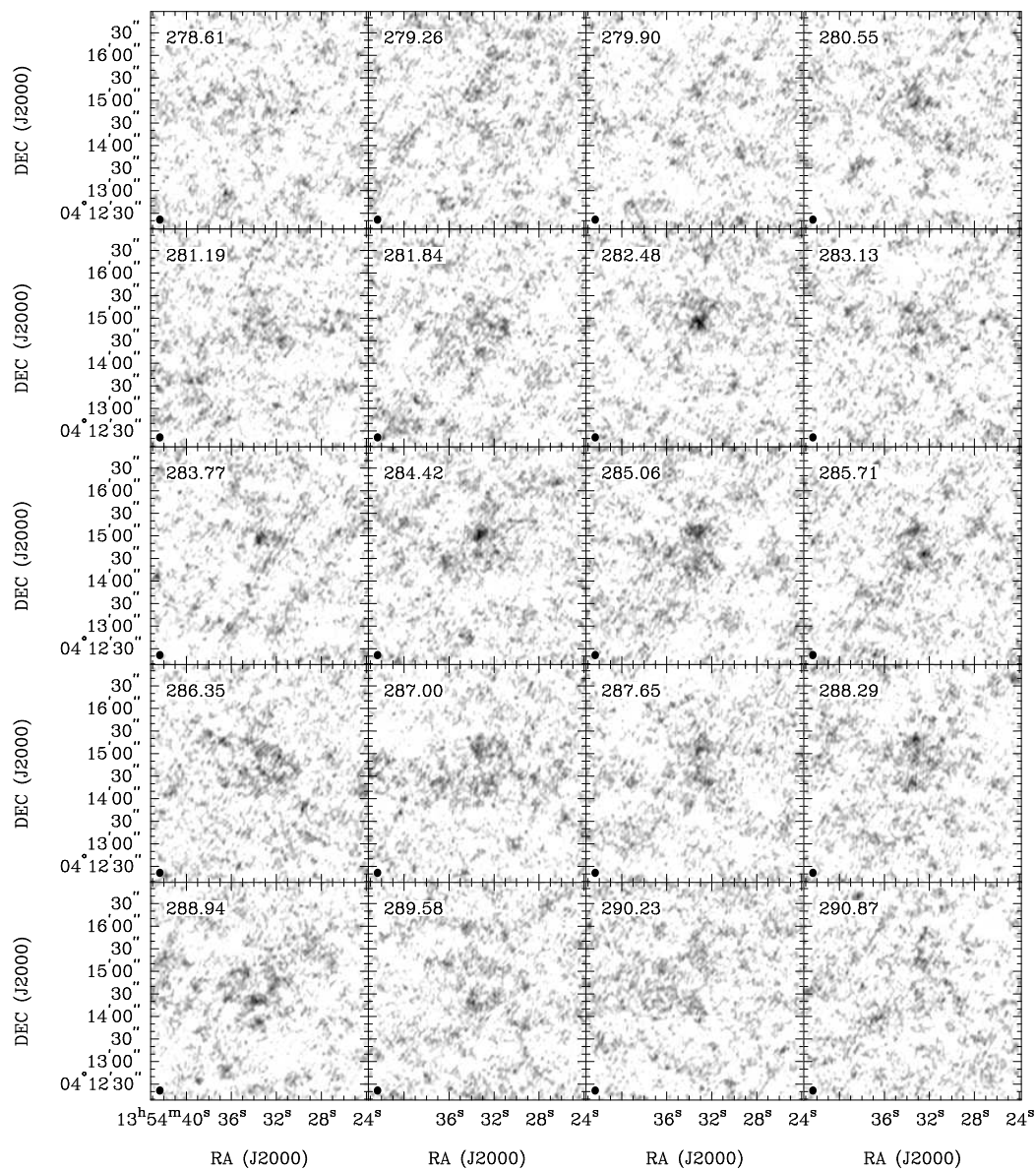


Figure 2.26a **KKH 86**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $7.7 \text{ mJy beam}^{-1}$). Every channel is shown (channel width 0.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

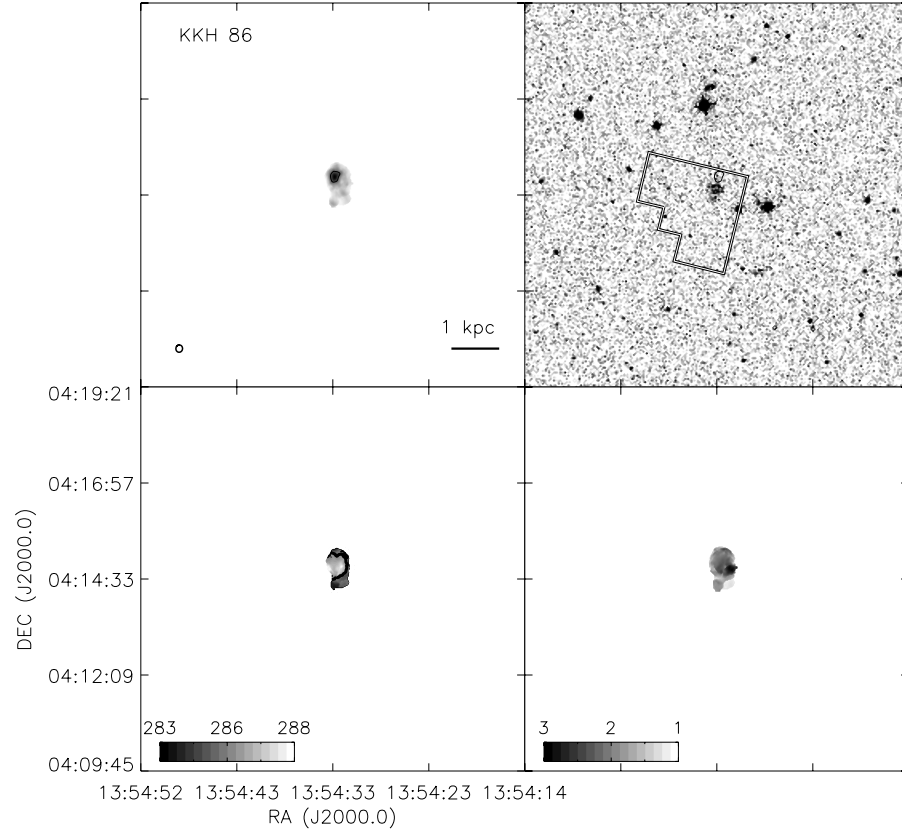


Figure 2.26b *Top left:* The integrated H I intensity map for KKH 86. The grayscale covers a range from 1×10^{19} to $1.5 \times 10^{20} \text{ cm}^{-2}$ with a contour of $1 \times 10^{20} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST WFPC2 footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 285.5 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

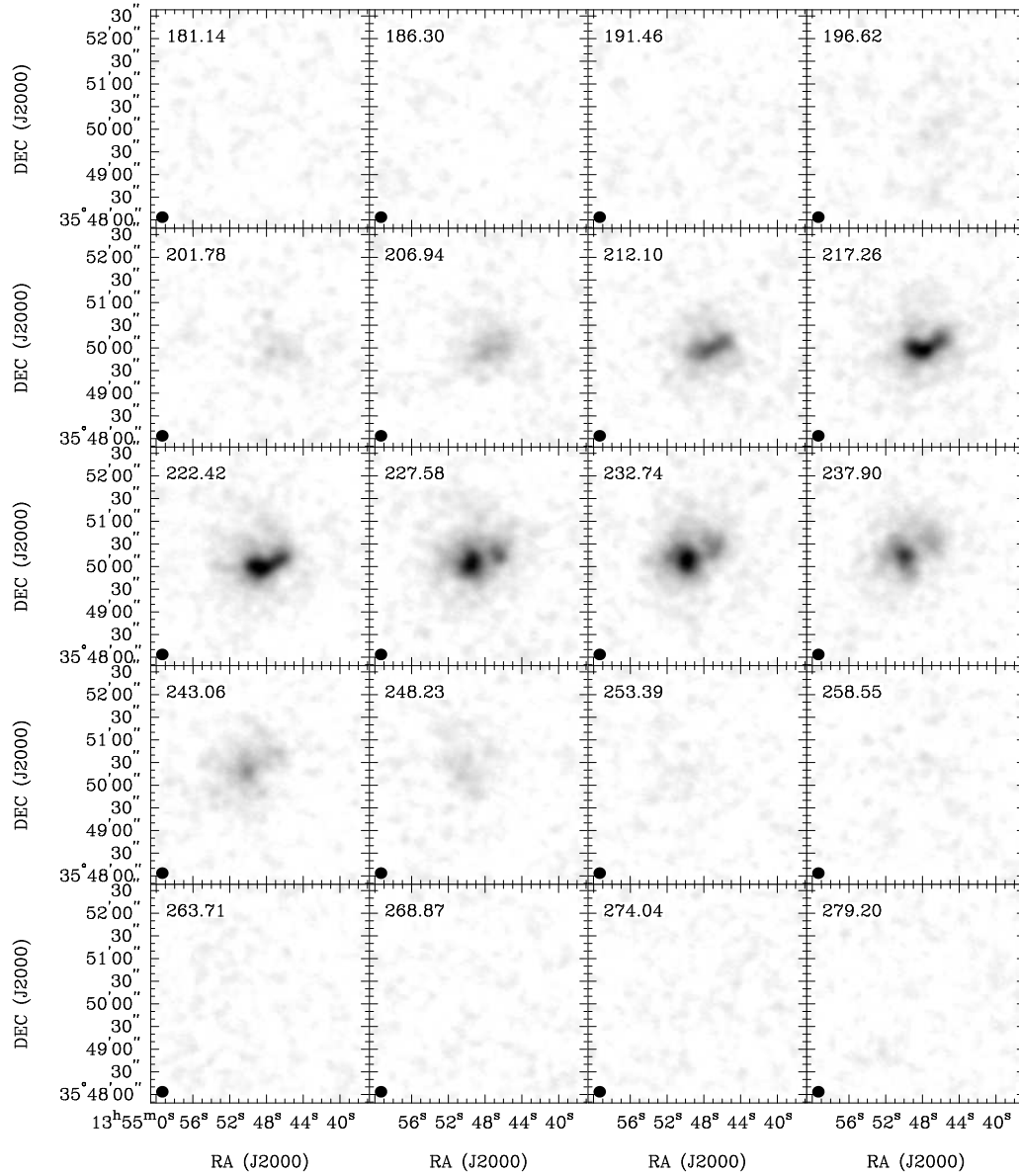


Figure 2.27a **UGC 8833**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $20.8 \text{ mJy beam}^{-1}$). Every channel is shown (channel width 2.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

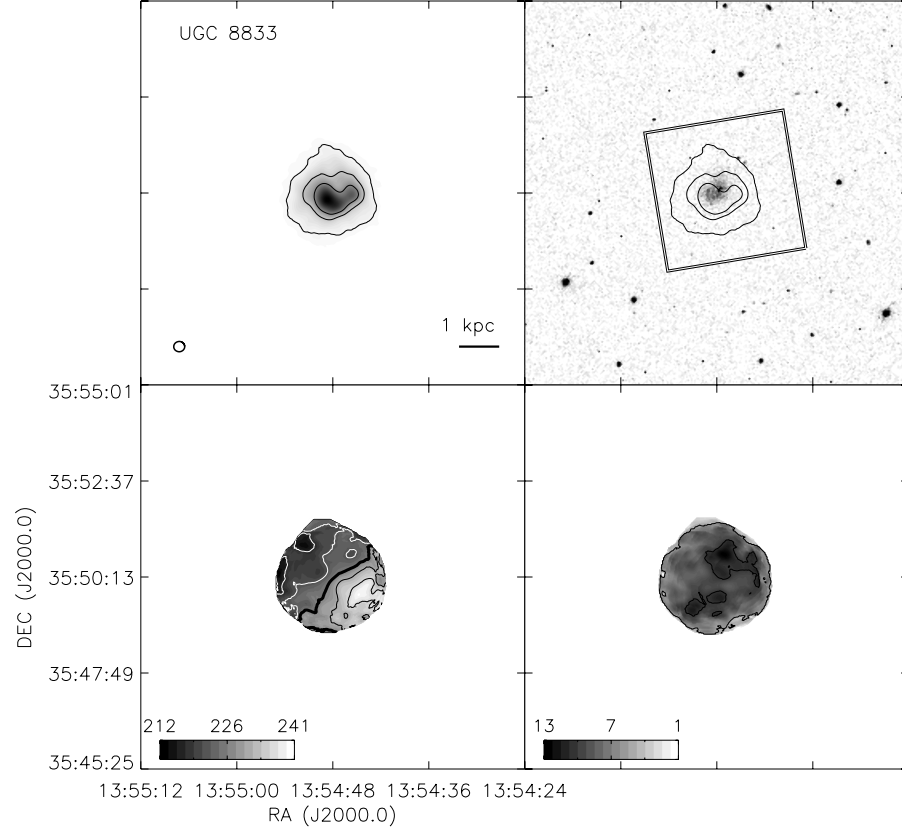


Figure 2.27b *Top left:* The integrated H I intensity map for UGC 8833. The grayscale covers a range from 1×10^{19} to $2.2 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 225.9 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 5 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

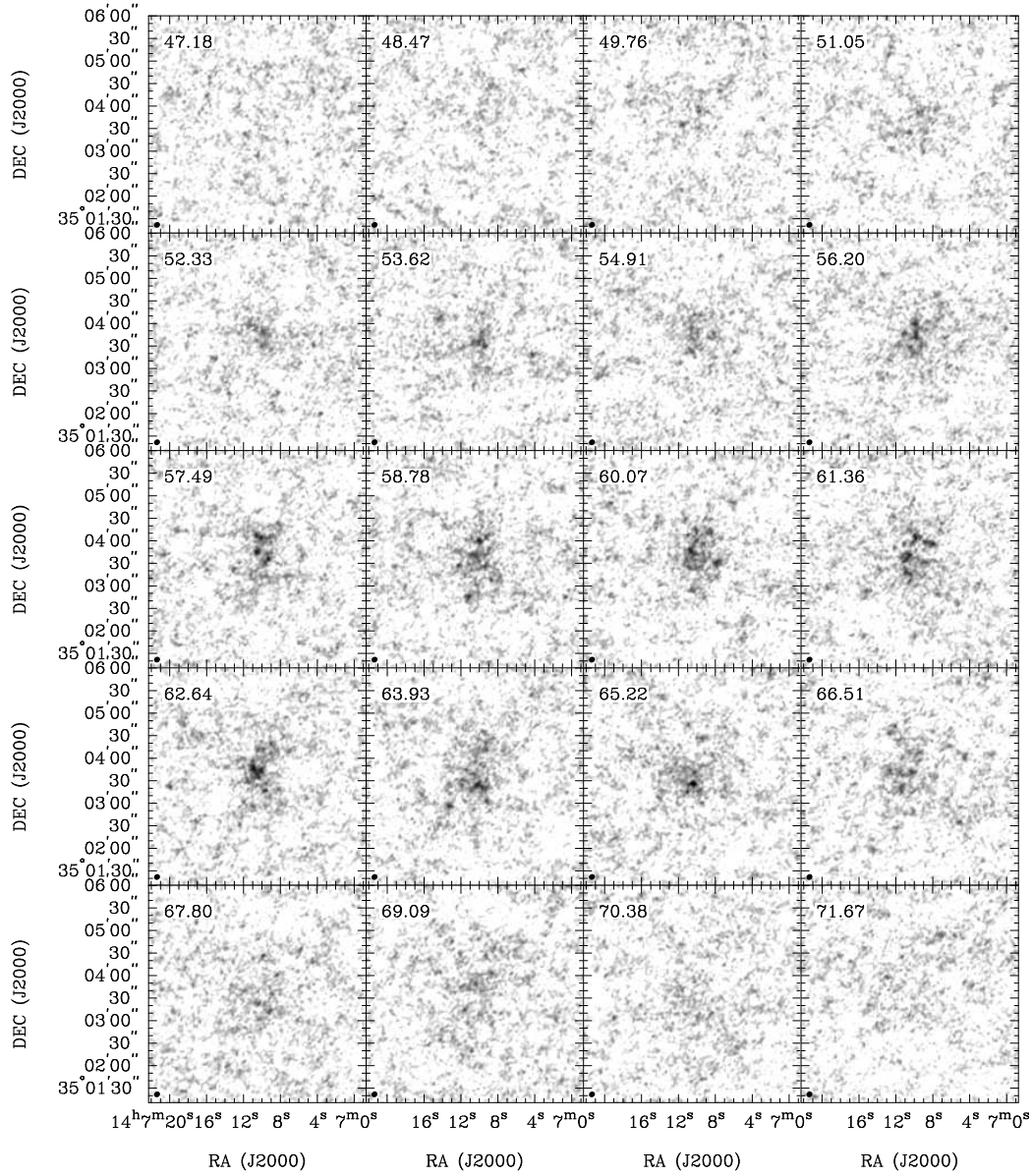


Figure 2.28a **KK 230**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $8.2 \text{ mJy beam}^{-1}$). Every channel is shown (channel width 0.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

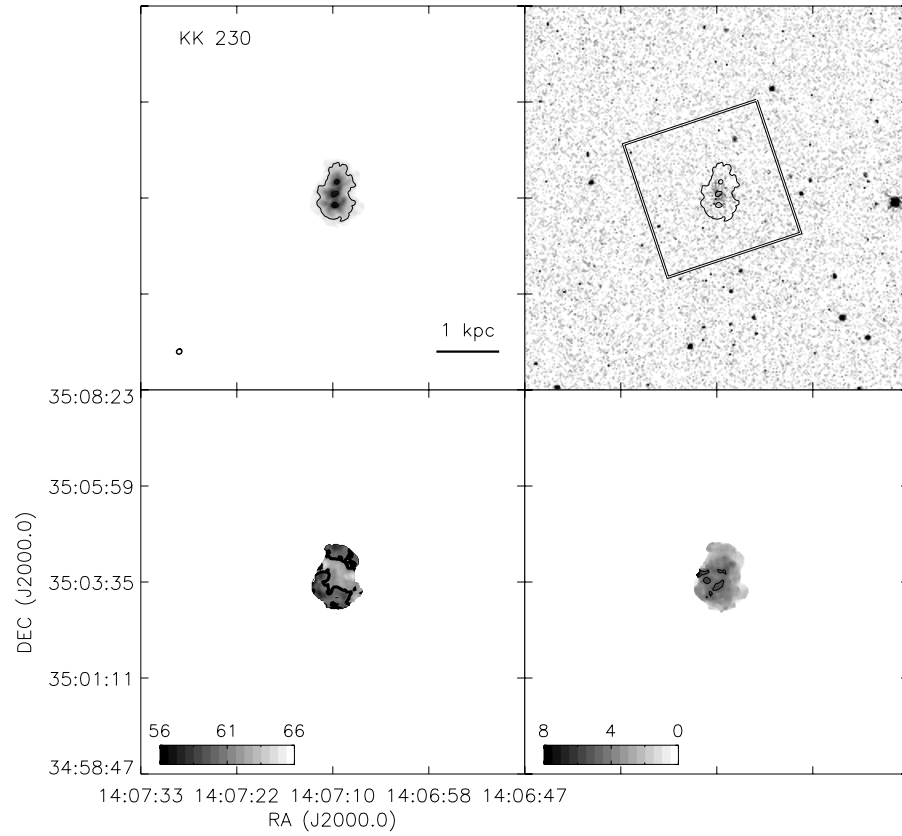


Figure 2.28b *Top left:* The integrated H I intensity map for KK 230. The grayscale covers a range from 1×10^{19} to $6.1 \times 10^{20} \text{ cm}^{-2}$ with contours of 1×10^{20} and $5 \times 10^{20} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 60.6 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 5 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. A contour is plotted at 5 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

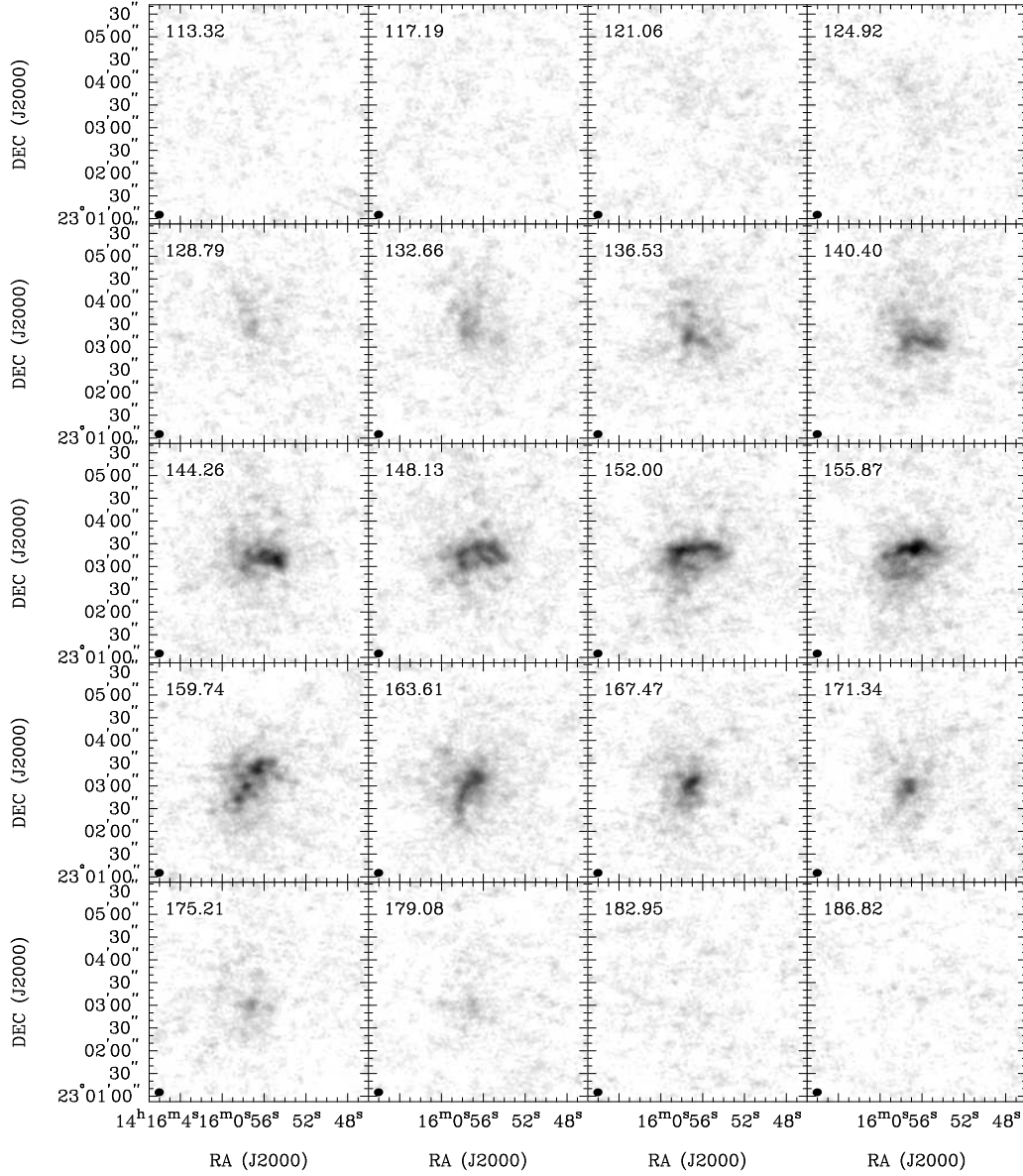


Figure 2.29a **DDO 187**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $17.1 \text{ mJy beam}^{-1}$). Every second channel is shown (channel width 1.3 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

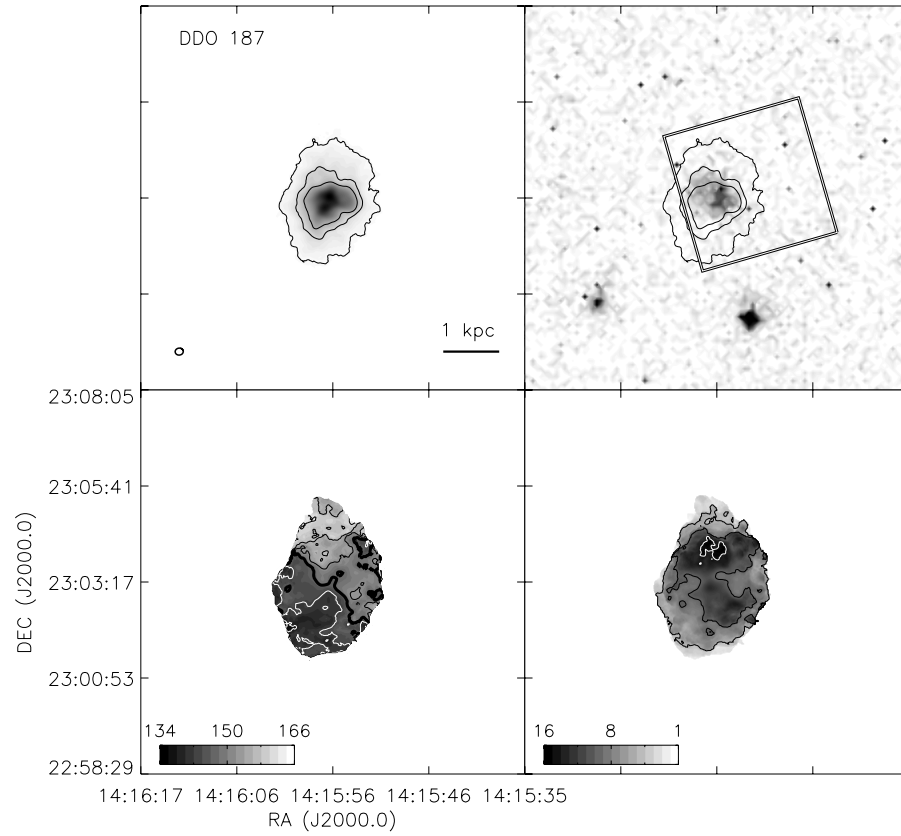


Figure 2.29b continued. *Top left:* The integrated H I intensity map for DDO 187. The grayscale covers a range from 1×10^{19} to $3.2 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 152.2 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 5 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5, 10, and 15 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

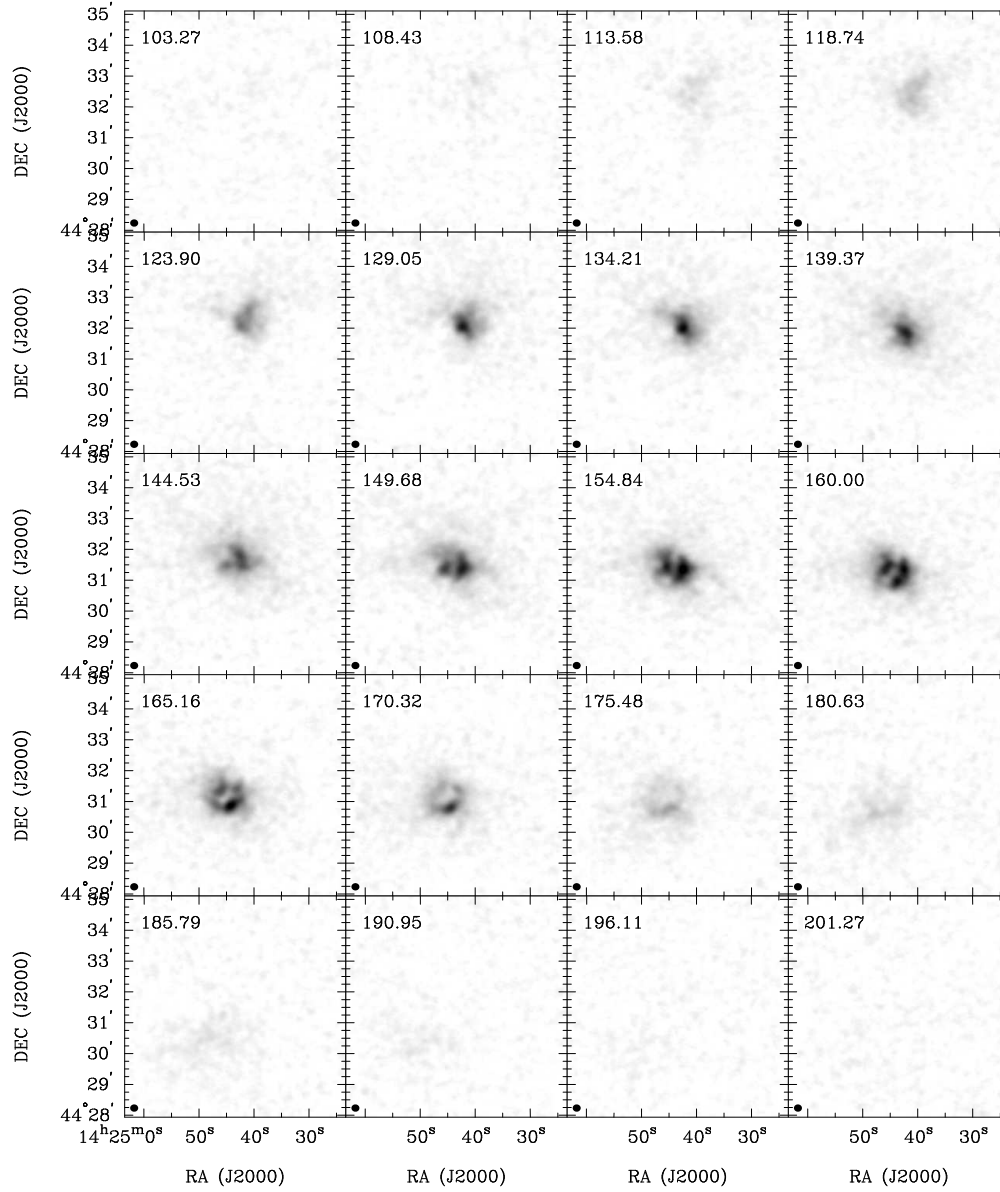


Figure 2.30a **DDO 190**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $27.5 \text{ mJy beam}^{-1}$). Every channel is shown (channel width 2.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

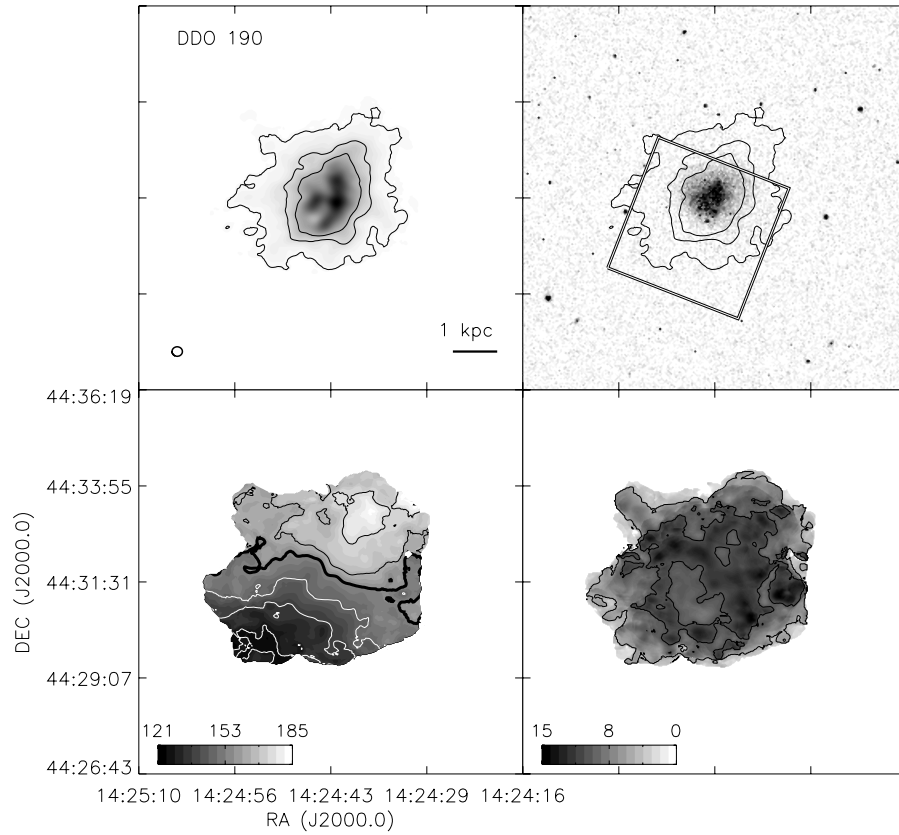


Figure 2.30b continued. *Top left:* The integrated H I intensity map for DDO 190. The grayscale covers a range from 1×10^{19} to $3.6 \times 10^{21} \text{ cm}^{-2}$ with contours of 1×10^{20} , 5×10^{20} , and $1 \times 10^{21} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The H I velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = 148.8 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 10 \text{ km s}^{-1}$. *Bottom Right:* The H I velocity dispersion. Contours are plotted at 5 and 10 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

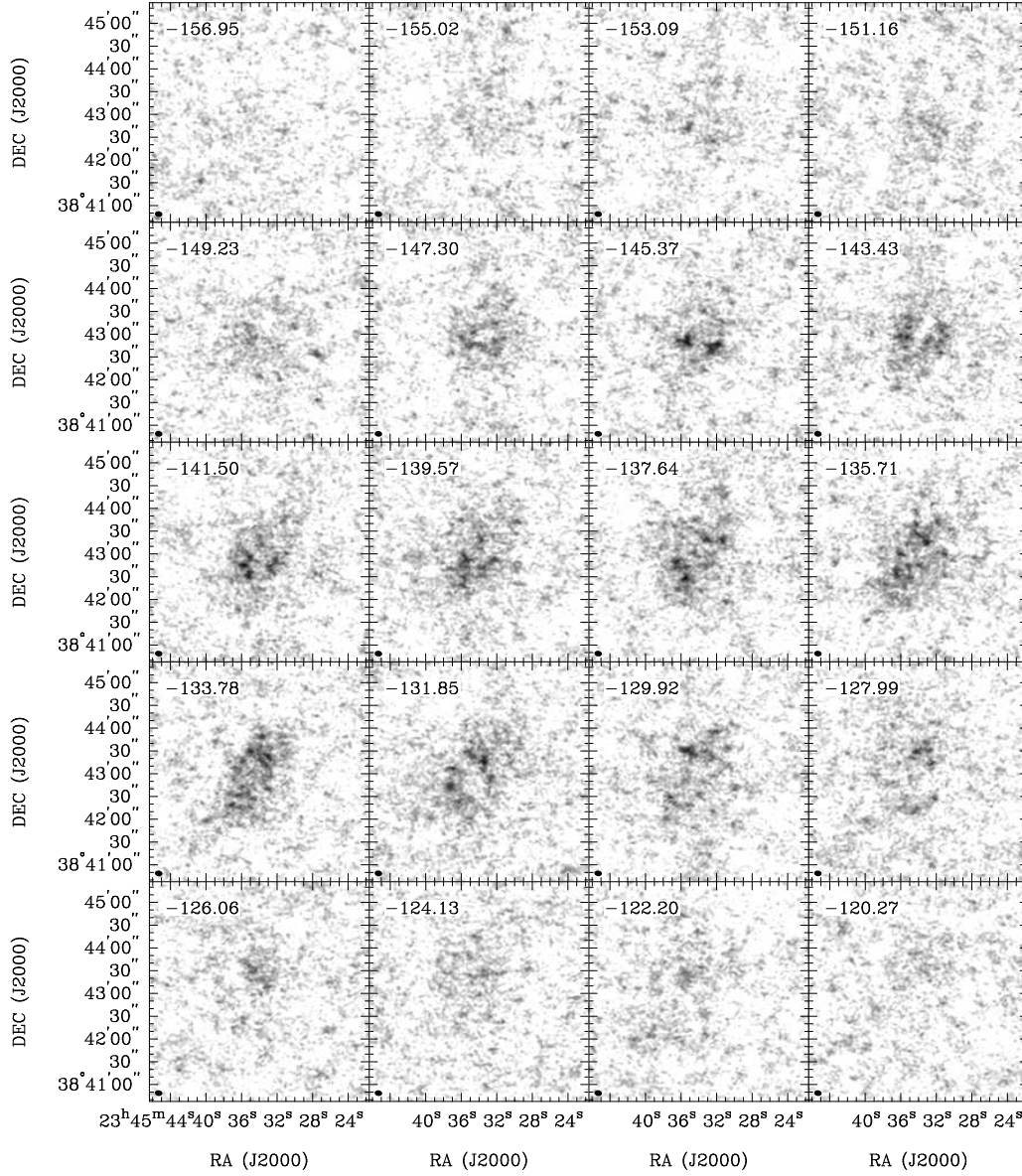


Figure 2.31a **KKH 98**: Channel maps based on the natural-weighted cube (grayscale range: -0.02 to $8.4 \text{ mJy beam}^{-1}$). Every second channel is shown (channel width 0.6 km s^{-1}) and each map has the same size as the moment maps in the following panels. *Reproduced from Ott et al. (2012).*

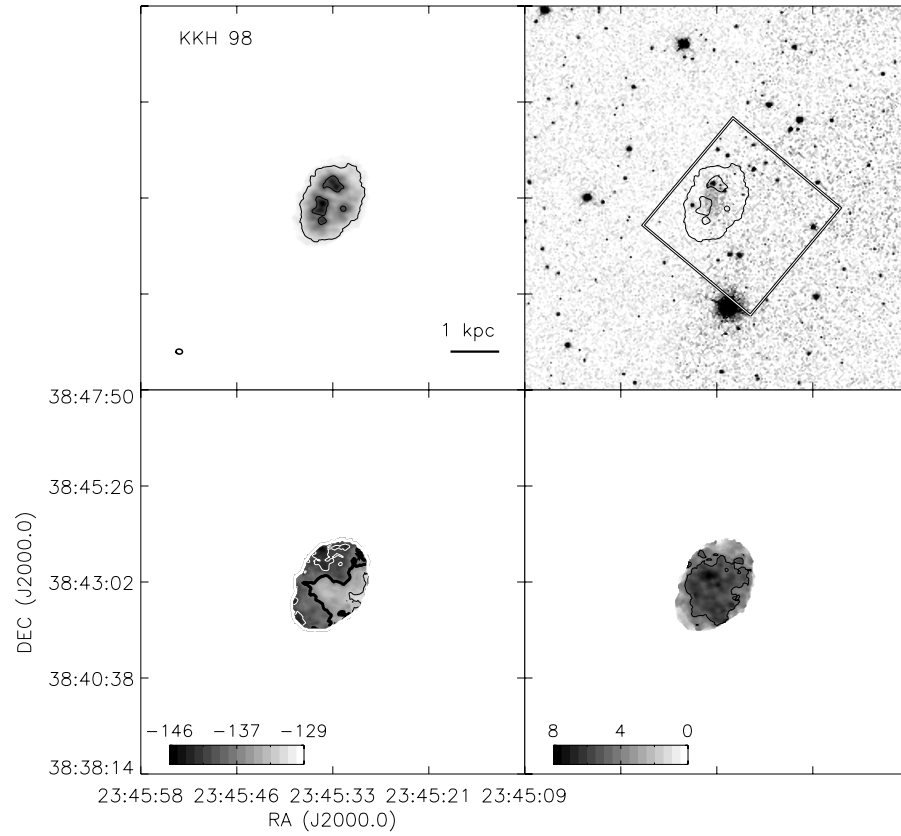


Figure 2.31b continued. *Top left:* The integrated HI intensity map for KKH 98. The grayscale covers a range from 1×10^{19} to $7.7 \times 10^{20} \text{ cm}^{-2}$ with contours of 1×10^{20} and $5 \times 10^{20} \text{ cm}^{-2}$. *Top Right:* An optical g-band image from the SDSS with the same column density contours overlaid. The HST ACS footprint is the field covered by the ANGST survey. *Bottom Left:* The HI velocity field. Black contours (lighter gray scale) indicate approaching emission, white contours (darker gray scale) receding emission. The thick black contour is the central velocity ($v_{cen} = -137.8 \text{ km s}^{-1}$) and the isovelocity contours are spaced by $\Delta v = 5 \text{ km s}^{-1}$. *Bottom Right:* The HI velocity dispersion. A contour is plotted at 5 km s^{-1} . Colorbars are in units of km s^{-1} . *Reproduced from Ott et al. (2012).*

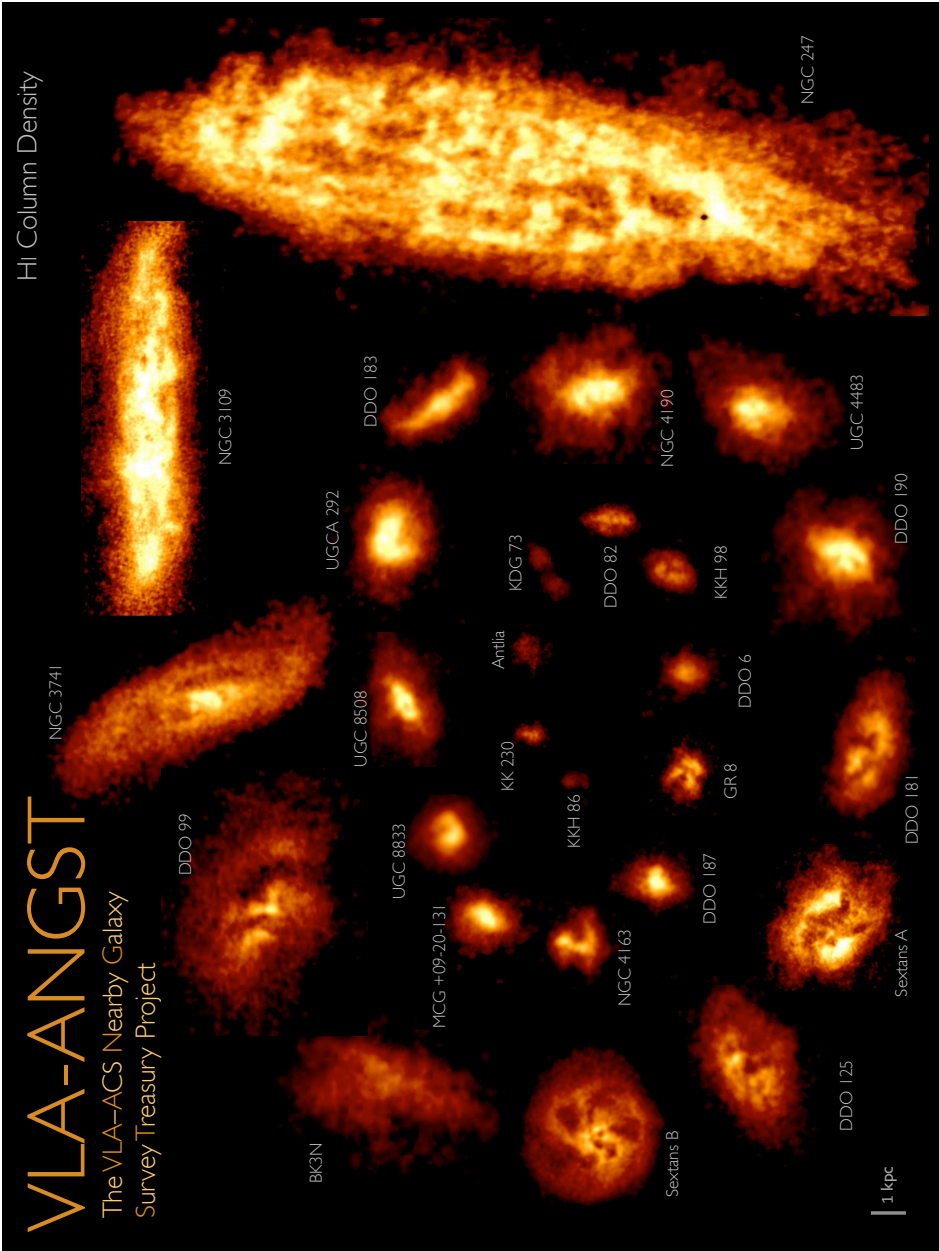


Figure 2.32 Overview of H I column density, N_{HI} , in VLA-ANGST galaxies. Galaxies are ordered by approximate physical size.

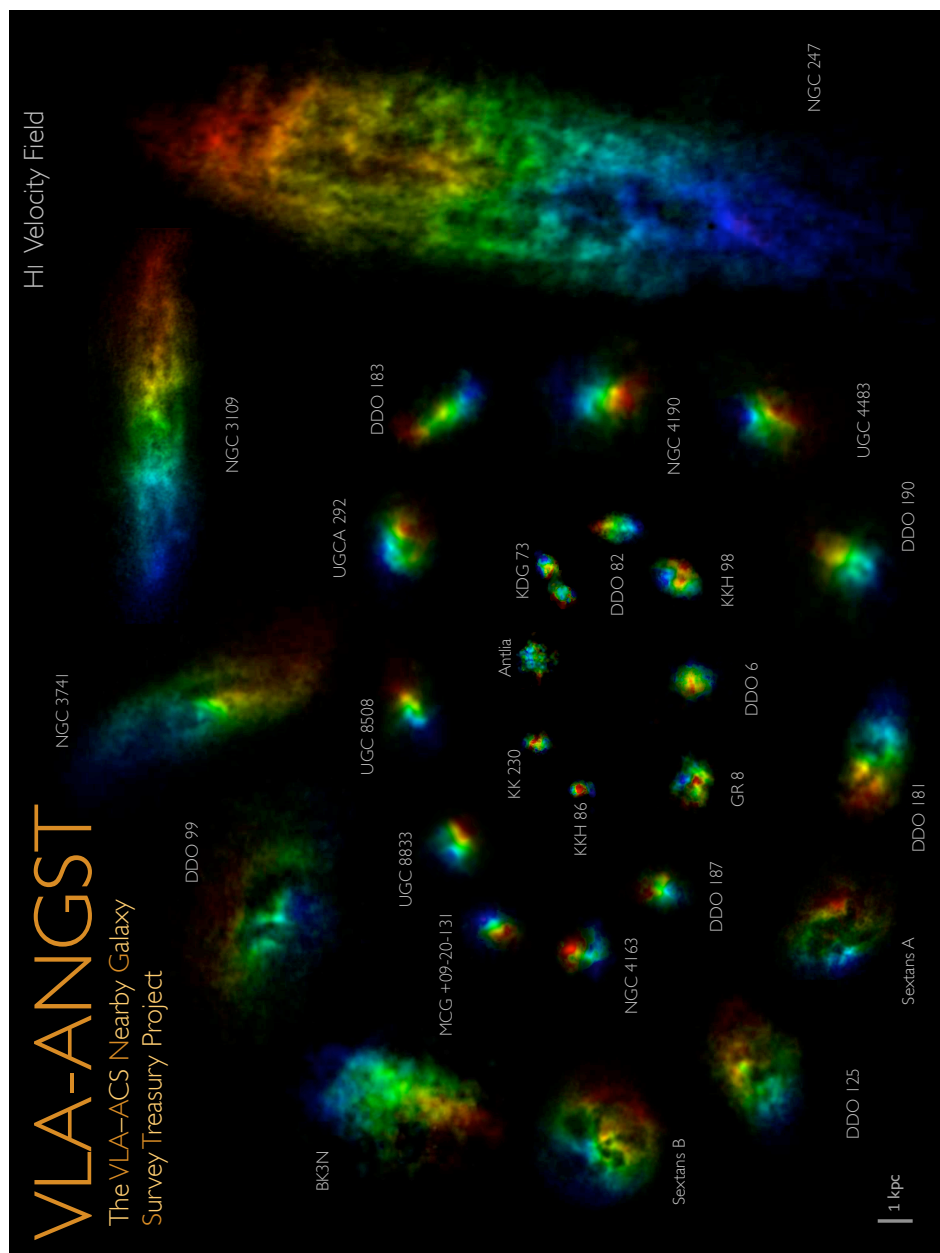


Figure 2.33 Overview of intensity-weighted mean velocity, $\langle v \rangle$, in VLA-ANGST galaxies. Galaxies are ordered by approximate physical size. The pixel color is set by the first moment value $\langle v \rangle$, chosen by hand (red to blue), and the brightness is set by the column density N_{HI} . Many of the smallest dwarfs show some rotational gradients across their disks.

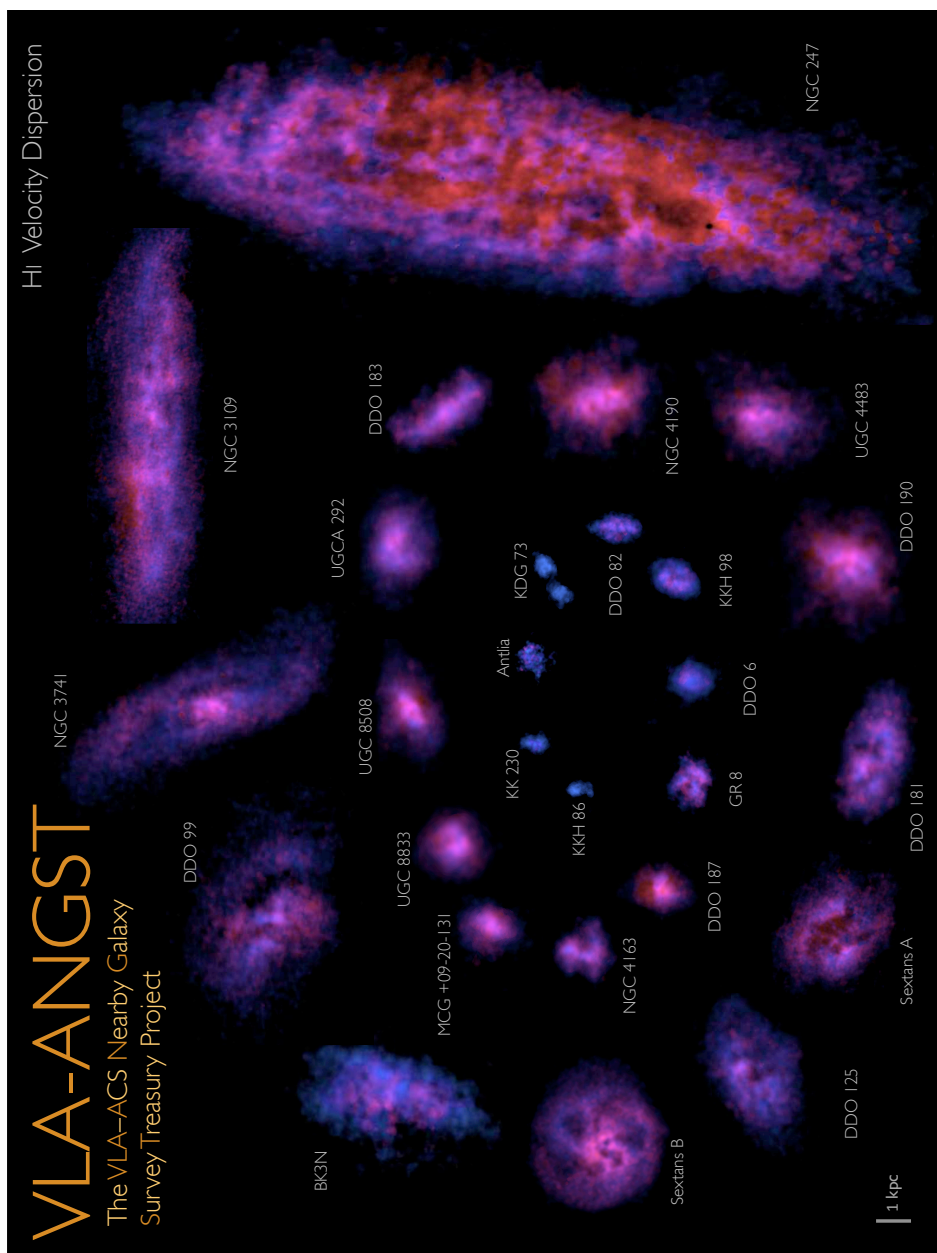


Figure 2.34 Overview of second moment, σ^2 , in VLA-ANGST galaxies. Galaxies are ordered by approximate physical size. The pixel color is set by the second moment value σ^2 from 4 to 16 km s⁻¹ (blue to red), and the brightness is set by the column density N_{HI} . The second moment is remarkably constant across the wide range of galaxy types in the VLA-ANGST sample.

Chapter 3

GLOBAL H I KINEMATICS IN DWARF GALAXIES

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H I line widths are typically interpreted as a measure of ISM turbulence, which is potentially driven by star formation. In an effort to better understand the possible connections between line widths and star formation, we have characterized H I kinematics in a sample of nearby dwarf galaxies by co-adding line-of-sight spectra after removing the rotational velocity to produce an average, global H I line profile. These “superprofiles” are composed of a central narrow peak ($\sim 6 - 10 \text{ km s}^{-1}$) with higher-velocity wings to either side that contain $\sim 10 - 15\%$ of the total flux. The superprofiles are all very similar, indicating a universal global H I profile for dwarf galaxies. We compare characteristics of the superprofile to various galaxy properties, such as mass and measures of star formation (SF), with the assumption that the superprofile represents a turbulent peak with energetic wings to either side. We use these quantities to derive average scale heights for the sample galaxies. When comparing to physical properties, we find that the velocity dispersion of the central peak is correlated with $\langle \Sigma_{\text{HI}} \rangle$. The fraction of mass and characteristic velocity of the high velocity wings are correlated with measures of SF, consistent with the picture that SF drives surrounding H I to higher velocities. While gravitational instabilities provide too little energy, the SF in the sample galaxies does provide enough energy through supernova, with realistic estimates of the coupling efficiency, to produce the observed superprofiles.

3.1 Introduction

The neutral hydrogen (H I) component of the interstellar medium (ISM) is an ideal tracer of kinematics in disk galaxies. H I is observable in some galaxy disks far beyond optical

emission, making it a superb tool for probing large-scale kinematics speeds. On smaller scales, the H I velocity dispersions offer a way to measure the random turbulence velocities on scales of $10 - 200$ pc. By connecting the H I velocity dispersion with possible drivers of turbulence, we can study the sources of energy in the ISM.

H I velocity dispersions typically vary between $5 - 15 \text{ km s}^{-1}$ across a wide range of disk galaxy types, and generally decrease in the outskirts of galaxies to $\sim 6 - 10 \text{ km s}^{-1}$ (e.g., Tamburro et al., 2009). Generally, these line widths are thought to be due to turbulent velocities rather than thermal broadening. For example, Wolfire et al. (1995) found two stable temperatures for H I gas: $\sim 150 \text{ K}$ for the cold neutral medium (CNM) and $\sim 7000 \text{ K}$ for the warm neutral medium (WNM). These temperatures correspond to velocity dispersions of $\sim 1 \text{ km s}^{-1}$ and $\sim 7 \text{ km s}^{-1}$ at typical ISM pressures, which is often smaller than the observed line widths in nearby galaxies. This mismatch suggests that the line widths are set primarily by turbulence. However, the time scale for dissipating turbulent energy is $\sim 10^7 \text{ yr}$ (Mac Low, 1999). Energy must therefore be continually injected in order to maintain the H I line widths we see in galaxies.

The sources of energy that drive turbulence are still debated. A number of studies have suggested that star formation can provide the necessary energy to generate H I turbulence in the inner regions of galaxies (e.g., Kim et al., 1998; Tamburro et al., 2009; Joung et al., 2009). However, H I velocity dispersions are still substantial at large radii, whereas the majority of star formation in galaxies is contained within r_{25} , defined as the radius where the B-band surface brightness drops below $25 \text{ mag arcsec}^{-2}$ (e.g., Kennicutt, 1989; Bigiel et al., 2010). Beyond r_{25} , the star formation rate (SFR) falls off much more quickly than the H I velocity dispersion, implying that it cannot be the only contribution to the H I velocity dispersion in disk galaxies.

Other proposed drivers of turbulence are the magneto-rotational instability (MRI; Sellwood & Balbus, 1999), shear from rotation curves (e.g., Schaye, 2004), or gravitational instabilities (e.g., Wada et al., 2002). One can potentially distinguish among these various mechanisms by comparing the observed energy in turbulence to the energy available from the possible drivers. Many of these processes should be effective in spiral galaxies, which have spiral arms and exhibit differential rotation, but should be less strong in their

lower mass dwarf counterparts, which lack spiral structure and show solid-body rotation. However, the observed H I velocity dispersions of spirals are surprisingly similar to those of dwarfs.

In this paper we take a different approach to study the global behavior of the H I velocity dispersion and its relationship to possible drivers of turbulence. By working on global scales, we can not only increase the signal-to-noise of individual spatially-resolved line-of-sight spectra but also remove the assumption that input energy must necessarily couple to H I in the same spatial region. Our work extends the many previous studies of turbulence in the ISM but uses better data over a wider baseline in galaxy mass. We also improve the characterization of the average velocity dispersion. In contrast, most earlier papers typically use the intensity-weighted second velocity moment as a proxy for intrinsic H I velocity dispersion (e.g., Tamburro et al., 2009), fit single Gaussians to line-of-sight spectra (e.g., Dickey et al., 1990; Petric & Rupen, 2007), or both (e.g., van Zee & Bryant, 1999). However, the second moment can be artificially increased by gas with anomalous velocities, such as bulk inward or outward flows or expanding H I, while single Gaussian fits are unable to represent asymmetric line-of-sight spectra. In addition, most literature studies of H I turbulence have not used a uniform sample of observations, as few such samples have been available until recently. Instead, studies focused on a single galaxies (e.g., Petric & Rupen, 2007) or worked at the instrumental resolution for each galaxy (e.g., Tamburro et al., 2009). The combination of such studies means that H I turbulence is sampled on different physical scales in each galaxy. Since turbulence is larger on larger physical scales (e.g., Zhang et al., 2012), this mismatch in spatial resolution makes galaxy-to-galaxy comparisons dubious.

A better, uniform measurement of the typical underlying H I turbulence is necessary to accurately constrain the detailed kinematics of the ISM. By co-adding H I line-of-sight spectra after removal of the rotational velocity, we can obtain an average measurement of H I turbulent velocities. A small number of previous studies have followed a similar approach as we undertake here. Dickey et al. (1990) found relatively constant Gaussian line widths in the face-on spiral NGC 1058, with median profiles at some radii exhibiting wings larger than expected from a simple Gaussian profile. These high-velocity wings were shown to exist in the average line profiles regardless of the average FWHM of the contributing line-of-sight

profiles (Petric & Rupen, 2007). Similar results were found by Boulanger & Viallefond (1992) and Kamphuis & Sancisi (1993) in NGC 6946. Braun (1997) also found H I gas at higher velocities compared to the average central H I line width in a number of other spirals by studying average H I line profile shapes. However, the existence of high-velocity wings superimposed on a Gaussian center may not be ubiquitous; no evidence of such wings is seen in NGC 5457 (Rownd et al., 1994) or the outer regions of NGC 1232 (van Zee & Bryant, 1999). Unfortunately, the majority of the studies of average H I line profiles had poor velocity resolution ($\geq 5.2 \text{ km s}^{-1}$; Braun, 1997), coarse spatial resolution ($\gtrsim 1 \text{ kpc}$; Dickey et al., 1990; Petric & Rupen, 2007; van Zee & Bryant, 1999), or both (Boulanger & Viallefond, 1992; Rownd et al., 1994). A recent study by Ianjamasimanana et al. (2012, hereafter I2012), generated average H I profiles (“superprofiles”) using a similar approach as this paper, but for a number of more massive spirals within $D \sim 10 \text{ Mpc}$. They found the same basic line profile structure as we see here, and proposed that they may be comprised of emission from the CNM and WNM.

Recently, a number of H I synthesis observation surveys of nearby galaxies have greatly improved the available data. Compared with the numerous published H I studies of single galaxies, these surveys can provide better spatial and spectral resolution as well as a uniform observing setup. The H I Nearby Galaxy Survey (THINGS; Walter et al., 2008) pioneered this new era of high-resolution H I surveys by observing 34 nearby spiral galaxies with high spatial ($6 - 10''$) and spectral ($1.3 - 5.2 \text{ km s}^{-1}$) resolution. The Very Large Array ACS Nearby Galaxy Survey Treasury Project (VLA-ANGST; Ott et al., 2012) followed in its footsteps, extending THINGS to smaller galaxy masses at a similar sensitivity and better spectral resolution ($0.6 - 2.6 \text{ km s}^{-1}$). Other surveys, such as FIGGS (“Faint Irregular Galaxy GMRT Survey”; Begum et al., 2008) and LITTLE THINGS (“Local Irregulars That Trace Luminosity Extremes-THINGS”; Hunter et al., 2012) have also sought to provide a uniform sample of H I observations of dwarfs with similar observing setups.

In this paper we focus on the global measurements of H I kinematics in a wide range of dwarf galaxies chosen from VLA-ANGST and THINGS. We present a method to measure the intrinsic H I kinematics in low-mass disk galaxies by co-adding flux-weighted H I line profiles after removal of the rotational velocity. The combined sample covers a wide range

of galaxy properties, allowing us to examine the overall H I kinematics in a broader range of environments than previously studied. In § 3.2 we describe the data we use to determine galaxy global properties. We next explain our method of characterizing the global H I gas kinematics in § 3.3. We then discuss our parameterization and the physical interpretation of these superprofiles in § 3.4. In § 3.5, we investigate significant correlations between superprofile parameters and galaxy physical properties. In § 3.6 we discuss the potential physical cause behind correlations with each parameter; give energy estimates for driving kinematics in the different components; assess limits on H I scale heights; and examine the possibility of a universal H I velocity profile for dwarfs. Finally, we summarize our results in § 3.7 .

3.2 Sample and Data

In the following sections, we briefly describe the H I data available from VLA-ANGST and THINGS as well as our sample selection criteria. We then discuss our conversion from the data to the physical properties of our sample galaxies. If available, we use the ANGST TRGB distance from Dalcanton et al. (2009). Otherwise, we use the distances compiled in Karachentsev et al. (2004). When necessary, we correct all published quantities to our adopted distances, and we include published or estimated distance uncertainties in the uncertainties for all our calculated quantities. In § 3.2.1.3 we discuss the criteria that we use to select the galaxies for our sample.

The 9 galaxies from THINGS and 14 galaxies from VLA-ANGST in our sample are listed in Table 3.1 in order of decreasing baryonic mass along with their basic physical properties. We list (1) the galaxy name; (2) alternate names; (3) H I survey (VLA-ANGST or THINGS); (4-5) right ascension and declination; (6) distance; (7) inclination i , (see § 3.2.3.1); (8) total H I mass taken from Walter et al. (2008) or Ott et al. (2012); (9) r_{25} , from Karachentsev et al. (2004); (10) inclination-corrected width at 20% of the total line profile, w_{20} , from Walter et al. (2008) or Ott et al. (2012) and corrected using i as listed in this table; and (11) de Vaucouleurs T-type. If necessary, previously-published quantities such as mass are corrected for the adopted distance.

Table 3.1: The sample. (1) Galaxy name. (2) Alternative names. (3) H I survey. (4-5) position in J200 coordinates taken from Walter et al. (2008) for THINGS galaxies or Ott et al. (2012) for VLA-ANGST galaxies. (6) Distance from Dalcanton et al. (2009) unless marked with [†] indicating Karachentsev et al. (2004). (7) Inclination, references below. (8) $M_{\text{HI,tot}}$ in $M_{\odot}$ from Walter et al. (2008) for THINGS galaxies or Ott et al. (2012) for VLA-ANGST galaxies, updated for distances given in this table. (9) B -band r_{25} from Dalcanton et al. (2009) unless marked with [†] indicating Walter et al. (2008). (10) inclination-corrected w_{20} , taken from Walter et al. (2008) for THINGS galaxies or Ott et al. (2012) for VLA-ANGST galaxies. (11) de Vaucouleurs T-type taken from Walter et al. (2008) or Ott et al. (2012).

1	2	3	4	5	6	7	8	9	10	11
Galaxy	Alt. Name	Survey	RA (hh:mm:ss)	Dec (dd:mm:ss)	Distance (Mpc)	i ($^{\circ}$)	$M_{\text{HI,tot}}$ ($\log M_{\odot}$)	r_{25} (kpc)	w_{20} (km s^{-1})	Type
NGC 7793		THINGS	23:57:49.7	-32:35:28	3.90 [†]	50 ^a	8.9	5.9 [†]	249	7
IC 2574	UGC 5666; DDO 81	THINGS	10:28:27.7	+68:24:59	3.79	55 ^b	9.1	7.1 [†]	160	9
NGC 4214	UGC 7278	THINGS	12:15:39.2	+36:19:37	3.04	44 ^c	8.6	3.0 [†]	129	10
Ho II	UGC 4305	THINGS	08:19:05.0	+70:43:12	3.38	49 ^b	8.8	3.2 [†]	94	10
NGC 2366	UGC 3851	THINGS	07:28:53.4	+69:12:51	3.21	63 ^b	8.8	2.0 [†]	130	10
DDO 154	UGC 8024	THINGS	12:54:05.9	+27:09:10	4.30 [†]	66 ^b	8.6	1.2 [†]	115	10
Ho I	UGC 5139; DDO 63	THINGS	09:40:32.3	+71:10:56	3.90	13 ^b	8.2	1.9 [†]	184	10
NGC 4190	UGC 7232	VLA-ANGST	12:13:44.6	+36:38:00	3.50 [†]	41 [*]	7.7	0.9	113	10

Continued on next page

Table 3.1, continued

NGC 3741	UGC 6572	VLA-ANGST	11:36:06.4	+45:17:07	3.24	64 ^d	7.9	0.9	95	10
Sextans A	DDO75; UGCA 205	VLA-ANGST	10:11:00.8	-04:41:34	1.38	36 ^e	7.8	1.1	103	10
DDO 53	UGC 4459	THINGS	08:34:07.2	+66:10:54	3.61	27 ^b	7.8	0.4 [†]	101	10
DDO 190	UGC 9240	VLA-ANGST	14:24:43.5	+44:31:33	2.79	30 [*]	7.6	0.7	126	10
DDO 125	UGC 7577	VLA-ANGST	12:27:41.8	+43:29:38	2.58	63 ^f	7.5	1.6	48	10
Sextans B	DDO70; UGC 5373	VLA-ANGST	10:00:00.1	+05:19:56	1.39	52 [*]	7.6	1.0	77	10
DDO 99	UGC 6817	VLA-ANGST	11:50:53.0	+38:52:50	2.59	60 [*]	7.7	1.5	62	10
M81 DwB	UGC 5423	THINGS	10:05:30.6	+70:21:52	5.30 [†]	44 ^b	7.4	0.9 [†]	84	10
UGCA 292	Cvnl-DwA	VLA-ANGST	12:38:40.0	+32:46:00	3.62	16 [*]	7.6	0.5	140	10
NGC 4163	UGC 7199	VLA-ANGST	12:12:09.1	+36:10:09	2.86	45 [*]	7.0	0.8	51	10
UGC 4483		VLA-ANGST	08:37:03.0	+69:46:31	3.41	42 [*]	7.5	0.6	74	10
DDO 181	UGC 8651	VLA-ANGST	13:39:53.8	+40:44:21	3.14	50 [*]	7.4	1.1	70	10
UGC 8833		VLA-ANGST	13:54:48.7	+35:50:15	3.08	33 [*]	7.1	0.4	75	10
DDO 187	UGC 9128	VLA-ANGST	14:15:56.5	+23:03:19	2.21	55 [*]	7.1	0.5	59	10
GR 8	DDO155; UGC 8091	VLA-ANGST	12:58:40.4	+14:13:03	2.08	33 [*]	6.8	0.3	61	10

* Derived from LVL 3.6 μ m images^a de Blok et al. (2008)^b Oh et al. (2011)^c Walter et al. (2008)^d Begum et al. (2005)^e Skillman et al. (1988)^f Swaters et al. (2009)

3.2.1 HI Data

We use a combination of NRAO Very Large Array (VLA) H I data from both THINGS and VLA-ANGST for our analysis. The two surveys provide complementary information, as THINGS targets are primarily large spiral galaxies while VLA-ANGST probes gas-rich galaxies at lower mass scales. Our final sample is composed primarily of dwarfs that span a wide range of galaxy properties, including absolute magnitude; stellar, gas, and baryonic masses; SFRs; and rotation speeds.

We use the robust-weighted data cubes published in Ott et al. (2012) and Walter et al. (2008) from VLA-ANGST and THINGS, respectively. This weighting scheme offers $\sim 30\%$ better spatial resolution and a well-behaved synthesized beam with only a moderate decrease in sensitivity. Both VLA-ANGST and THINGS provide two sets of robust-weighted data cubes, the standard and flux-rescaled cubes. Standard data cubes have uniform noise properties but incorrect fluxes, while the flux-rescaled cube has been scaled to have correct fluxes in exchange for more complicated noise properties. Because we use both cubes in our analysis, we specify which cube we are using in each step. To ensure that we are sampling the same physical scales in the galaxies' ISM, we work at a common physical resolution of 200 pc as discussed in §3.2.2.

The parameters of the H I observations are listed in Table 3.2. We list (1) the galaxy name; (2) velocity resolution, Δv ; (3) FWHM beam corresponding to 200 pc physical resolution, $\theta_{200\text{pc}}$; and (4) *rms* noise in a single channel of the 200 pc convolved standard cube, σ_{chan} .

3.2.1.1 VLA-ANGST

The ACS Nearby Galaxy Survey Treasury (ANGST) Program obtained multi-color HST photometry of a volume limited sample of galaxies within 4 Mpc, excluding the Local Group, and provides spatially-resolved star formation histories for its sample (Dalcanton et al., 2009). As a followup, the VLA-ANGST survey targeted all galaxies in ANGST that were visible with the VLA ($\delta \gtrsim -30^\circ$), showed signs of having observable H I reservoirs, and lacked adequate previous H I observations. Many of the galaxies in the sample of 35

Table 3.2: Observation parameters. (1) Galaxy name. (2) Channel spacing. (3) Circular beam in " that corresponds to 200 pc. (4) *rms* noise in mJy beam⁻¹ in the convolved, standard cube.

1	2	3	4
Galaxy	Δv	$\theta_{200\text{pc}}$	σ_{chan}
	km s ⁻¹	(")	(mJy beam ⁻¹)
NGC 7793	2.6	10.58	1.19
IC 2574	2.6	10.88	0.91
NGC 4214	1.3	13.57	1.08
Ho II	2.6	12.21	1.54
NGC 2366	2.6	12.85	1.00
DDO 154	2.6	9.59	0.60
Ho I	2.6	10.58	1.23
NGC 4190	1.3	11.79	1.50
NGC 3741	1.3	12.73	1.90
Sextans A	1.3	29.89	4.06
DDO 53	2.6	11.43	0.76
DDO 190	2.6	14.69	0.62
DDO 125	0.6	15.99	3.07
Sextans B	1.3	29.68	1.90
DDO 99	1.3	15.93	1.97
M81 DwB	2.6	7.78	0.64
UGCA 292	0.6	11.40	2.13
NGC 4163	0.6	14.42	2.16
UGC 4483	2.6	12.10	0.80
DDO 181	1.3	13.14	1.52
UGC 8833	2.6	13.39	0.59
DDO 187	1.3	18.67	2.12
GR 8	0.6	19.83	4.15

are therefore low-mass, low-luminosity dwarfs.

The velocity resolution of the survey is $0.6 - 2.6 \text{ km s}^{-1}$, which is necessary to study the detailed H I line profiles in galaxies with the low peak rotation speeds characteristic of the sample (e.g., Warren et al., 2012). The typical instrumental spatial resolutions at the median galaxy distance is $\sim 7''$, corresponding to $\sim 100 \text{ pc}$ at the median distance of 2.8 Mpc.

3.2.1.2 *THINGS*

THINGS provides a complementary sample of 34 large, gas-rich spirals chosen mainly from the Spitzer Infrared Nearby Galaxy Survey (SINGS). Since THINGS galaxies have characteristically higher masses and rotation speeds, larger velocity resolutions were often required to fully cover the H I emission. Therefore, the velocity resolution is often coarser than VLA-ANGST, and the majority of THINGS observations have velocity resolutions of either 2.6 or 5.2 km s^{-1} . THINGS resolves spatial scales of $\sim 7''$, corresponding to $\sim 200 \text{ pc}$ at the median distance of $\sim 6 \text{ Mpc}$.

3.2.1.3 *Sample Selection*

To increase the robustness of our results, we select a high-quality subset of the 63 detected galaxies in VLA-ANGST and THINGS surveys for our analysis. We consider only disk-dominated galaxies (de Vaucouleurs T-type > 3) to avoid confusion with the bulge; all selected galaxies are $7 \leq T \leq 10$.

We further exclude galaxies that suffer from one or more of the following problems, with the number of galaxies eliminated due to each criterion given in parentheses.

1. Instrumental physical resolution larger than our working resolution of 200 pc (18 galaxies).
2. Velocity resolution $\Delta v \geq 5.2 \text{ km s}^{-1}$, which complicates determination of the peak velocity and approaches the width of turbulent regions in these galaxies (16 galaxies).

3. Inclinations $> 70^\circ$, which could lead to artificially broadened line profiles due to beam smearing (7 galaxies).
4. Noticeable contamination from the Milky Way or from a companion, which would hinder separation of the galaxy H I emission from its companion (8 galaxies).
5. Fewer than 10 independent beams above the signal-to-noise threshold where we can accurately measure v_{peak} ($S/N > 5$; see § 3.3.2) at our working resolution. Galaxies with fewer independent beams show very noisy co-added profiles and have more than 50% of H I flux in pixels below our S/N threshold (8 galaxies).
6. A lack of ancillary far-ultraviolet (FUV) imaging, needed to determine the current average star formation rate (10 galaxies).

These cuts eliminate 40 potential galaxies from our sample; the majority of these were cut because they failed item (1) or (2) of the above criteria, and a number of galaxies failed more than one of the criteria. The final sample for analysis has 23 galaxies, with 14 from VLA-ANGST and 9 from THINGS.

3.2.2 H I Data Preparation

To provide the best galaxy-to-galaxy comparison of H I kinematics, we must take the spatial resolution into account. Since the velocity dispersion is typically larger on larger spatial scales (e.g., Zhang et al., 2012), we must ensure that we are sampling the H I kinematics on the same spatial scale in our sample galaxies. Since the instrumental angular resolution is roughly the same but the galaxies are at different distances, we must apply spatial smoothing to some of the cubes to ensure that the same spatial resolution is sampled from galaxy to galaxy. This is essentially equivalent to placing all galaxies at the same distance.

We choose a spatial resolution of 200 pc to match that used by Warren et al. (2012), allowing for future comparison of our results. This resolution is also a good compromise between potential sample size and physical resolution at the distance of each galaxy, which

is limited primarily by galaxy distance. It also matches results from Joung et al. (2009), who find that most turbulence is contained on spatial scales of 200 pc or less.

To apply the spatial smoothing to the data cubes, we first calculate the beam size that yields 200 pc resolution at each galaxy’s distance. We produce spatially-smoothed versions of both the standard and flux-rescaled data cubes at 200 pc resolution using the AIPS task CONVL, which accounts for the original beam major axis, minor axis, and position angle.

To generate a mask for these 200 pc data cubes, we first convolve the original standard cube to $45''$ resolution (CONVL). Next, we measure $\sigma_{\text{chan},45''}$, the *rms* noise in the $45''$ cube, and mask all emission below $3\sigma_{\text{chan},45''}$ using the AIPS task BLANK. Finally, we remove any remaining non-emission regions by hand. To regenerate the moment maps for the 200 pc resolution data, we blank the convolved, flux-rescaled data cube in regions outside of the mask. We then use the AIPS task XMOM to produce zeroth, first, and second moment maps. For the remainder of the paper, all mention of data cubes or moment maps refer to the 200 pc data sets described in this section, unless otherwise specified.

We note that convolution to a circular beam means that inclined galaxies have slightly larger physical resolution along their minor axis than along their major axis. However, the uncertainty of inclinations and position angles for the majority of galaxies in our sample makes it difficult to correct. Therefore, we choose to use the simplest option of a circular beam.

Finally, we include in our final analysis only line-of-sight spectra with a signal-to-noise (S/N) > 5 , where S/N is defined as the ratio between our fits to the peak divided by the *rms* noise in the line-free channels of the data cube. The reasons for this choice are discussed further in § 3.3.2.

3.2.3 Converting Data to Physical Quantities

In this section we describe the methods we use to measure the physical quantities discussed in the paper so that we are able to compare them to the H I superprofile properties of the sample. For many of the quantities, such as the star formation rate (SFR) or the H I surface density Σ_{HI} , we calculate the global properties using only the pixels whose H I line-of-sight

spectra contribute to the superprofile ($S/N > 5$). This choice provides a matched aperture measurement that allows us to consider only regions that are able to directly affect the H I measured by the superprofiles. A notable exception is the total baryonic mass of the galaxy, $M_{\text{baryon,tot}}$, which we use as a proxy for halo mass (§ 3.2.3.2). In this case, including only pixels above the S/N threshold would artificially underestimate the total baryonic mass, and therefore the halo mass, of galaxies in the low signal-to-noise regime. The halo mass is not expected to directly influence H I velocity dispersions, but it is useful to first characterize how the H I superprofile properties behave as a function of total halo mass before exploring their connection with other physical properties.

We list our derived quantities in Table 3.3. We give these quantities, followed by the relevant section: (1) the galaxy name; (2) $M_{\text{baryon,tot}}$, § 3.2.3.2; (3) H I mass, M_{HI} , § 3.2.3.3; (4) stellar mass, M_{star} , § 3.2.3.7; (5) SFR, § 3.2.3.5; (6) SFR / M_{HI} , § 3.2.3.6; (7) average star formation rate surface density, $\langle \Sigma_{\text{SFR}} \rangle$, § 3.2.3.5; and (8) $\langle \Sigma_{\text{HI}} \rangle$, § 3.2.3.3. We measure the quantities listed in columns 3 – 7 using only pixels above our S/N threshold.

3.2.3.1 Galaxy Inclination

For disk galaxies, the best inclination is usually the one inferred from tilted ring model fits to the H I velocity fields. Inclinations derived this way are available for 12 galaxies in our sample from a variety of sources in the literature (e.g., Skillman et al., 1988; Begum et al., 2005; de Blok et al., 2008; Swaters et al., 2009; Oh et al., 2011); we use these inclinations if available. We note that for strictly solid body rotation, as is common in dwarfs, the velocity field does not contain any information about the inclination angle of the disk.

However, 11 galaxies in our sample do not have previously-derived rotation curves and are therefore lacking these inclination estimates. In the absence of velocity field analysis, the traditional method is to measure ellipticity from B-band observations and then to derive an inclination after assuming an intrinsic disk thickness. This method often fails dramatically in dwarf galaxies, since it relies on the assumption that the intrinsic disk structure is well-traced by the B-band surface brightness. Unfortunately, SFRs in dwarf galaxies are much lower than in spiral galaxies, such that the massive stars that dominate the B-band surface

Table 3.3: Derived physical properties for the sample. (1) Galaxy name. (2) Total baryonic mass (§ 3.2.3.2). (3) Aperture-matched H I mass (§ 3.2.3.3). (4) Aperture-matched stellar mass (§ 3.2.3.7). (5) Aperture-matched SFR (§ 3.2.3.5). (6) Aperture-matched SFR / M_{HI} (§ 3.2.3.6). (7) Aperture-matched average star formation rate surface density (§ 3.2.3.5). (8) Aperture-matched average H I surface density (§ 3.2.3.3).

1	2	3	4	5	6	7	8
Galaxy	$M_{\text{baryon,tot}}$ (log $M_{\odot}$)	M_{HI} (log $M_{\odot}$)	$M_{\star}$ (log $M_{\odot}$)	SFR ($10^{-3} M_{\odot} \text{ yr}^{-1}$)	SFR / M_{HI} (10^{-10} yr^{-1})	$\langle \Sigma_{\text{SFR}} \rangle$ ($M_{\odot} \text{ kpc}^{-2}$)	$\langle \Sigma_{\text{HI}} \rangle$
NGC 7793	9.7	8.7	9.4	193.7	4.01	3.020	7.53
IC 2574	9.4	9.0	8.8	62.7	0.66	0.325	4.91
NGC 4214	9.2	8.5	8.9	122.6	3.66	1.250	3.41
Ho II	9.0	8.6	8.3	35.1	0.98	0.549	5.62
NGC 2366	9.0	8.7	8.3	55.9	1.17	0.628	5.39
DDO 154	8.7	8.4	7.8	6.6	0.29	0.087	3.01
Ho I	8.4	7.8	7.4	4.9	0.70	0.654	9.39
NGC 4190	8.1	7.4	7.7	4.8	1.80	1.770	9.84
NGC 3741	8.1	7.6	7.2	2.8	0.72	0.240	3.32
Sextans A	8.0	7.8	7.4	5.8	0.94	0.478	5.11
DDO 53	8.0	7.6	7.2	4.1	1.04	0.871	8.35
DDO 190	8.0	7.5	7.5	2.7	0.84	0.674	8.06
DDO 125	7.9	7.2	7.4	1.5	1.01	0.274	2.70
Sextans B	7.9	7.6	7.7	1.7	0.46	0.091	1.98

Continued on next page

Table 3.3, continued

DDO 99	7.9	7.4	7.2	2.0	0.87	0.237	2.72
M81 DwB	7.9	7.1	7.3	2.1	1.66	1.676	10.08
UGCA 292	7.8	7.5	6.8	1.1	0.40	0.536	13.31
NGC 4163	7.7	6.7	7.3	1.4	2.84	1.558	5.49
UGC 4483	7.7	7.4	7.0	2.1	0.93	0.630	6.80
DDO 181	7.7	7.2	7.1	1.4	0.96	0.375	3.90
UGC 8833	7.4	7.0	6.8	0.6	0.58	0.356	6.09
DDO 187	7.3	7.0	6.7	0.4	0.46	0.230	5.01
GR 8	7.1	6.6	6.6	1.0	2.29	1.050	4.59

brightness are formed stochastically across the disk. Since their light does not smoothly trace the galactic disk, we must turn to another indicator to measure the projected galactic disk.

As opposed to B-band observations, near-infrared observations are dominated by flux from the older stars and should therefore provide a better measurement of the projected shape of a galaxy’s disk. All sample galaxies without inclinations derived from rotation curves are part of the Local Volume Legacy survey (LVL; Dale et al., 2009), which provides photometric infrared observations of galaxies within 11 Mpc. For these galaxies, we fit ellipses to isophotes in the LVL $3.6\mu\text{m}$ Spitzer images. We then calculate inclination by assuming:

$$\sin^2 i = \frac{1 - (b/a)^2}{1 - q_0^2}, \quad (3.1)$$

where (b/a) is the measured axial ratio and q_0 is the intrinsic disk thickness. We use the values for q_0 provided in Karachentsev et al. (2004) for different galaxy types, which range between $0.12 - 0.2$. The derived inclinations only change by $\lesssim 5^\circ$ when we increase q_0 to a fixed value of 0.3 . We estimate an uncertainty $\Delta b/a \sim 0.05$ from repeated measurements of “best-fit by eye” ellipses to the $3.6\mu\text{m}$ surface brightness distribution, which leads to uncertainties in the inclination of $\sim 5^\circ$. When we compare inclinations derived using this method to those of galaxies with tilted ring inclinations, we find that the inclinations typically differ by less than 10° . The inclinations derived using H I morphology (Begum et al., 2008) for the five galaxies that overlap both samples are within 5° , with the exception of DDO 187. We therefore estimate our total uncertainty on the inclination as $\sigma_i \sim 10^\circ$.

We denote the galaxies whose inclinations have been derived using this method with * in column 7 of Table 3.1.

3.2.3.2 Halo Mass

In large spiral galaxies, the inclination-corrected widths of the H I integrated line profile at 20% or 50% of the peak (w_{20} and w_{50}) are good tracers of the total halo mass, as the rotation curve flattens to approximately the circular velocity (e.g., Verheijen, 2001). In low-mass dwarf galaxies, however, rotation curves often continue rising past the extent of

the observable H I, so any measured velocity provides only a lower limit on the circular velocity of the halo. Second, the global profiles are generally Gaussian and, due to the small rotational velocities, are more affected by turbulent motions (Begum et al., 2006). The ability to derive the intrinsic velocity width also requires an accurate knowledge of the galaxy inclination, which is uncertain for many of the low-mass dwarfs in our sample.

However, detailed studies of the baryonic Tully-Fisher relation in dwarf galaxies (e.g., Geha et al., 2006; Stark et al., 2009) indicate a strong correlation between baryonic mass, as measured with gas and stars, and halo mass, as measured with either w_{20} or w_{50} when inclinations are well-known. This correlation is expected if all halos in our sample have approximately the same baryon fraction. In the absence of reliable inclination-corrected w_{20} measurements, however, it is preferable to use the baryonic mass as a proxy for halo mass in dwarf galaxies. We therefore use $M_{\text{baryon,tot}}$ to indirectly measure halo mass in our sample.

Unlike the other measurements described in this section, we use the total baryonic mass instead of only the mass contained in the same pixels as we use to derive the superprofiles. Because this measurement is simply a proxy for halo mass and does not have a direct causal connection to the H I properties, we include the entire baryonic mass for each galaxy. Including only pixels above our S/N threshold would underestimate the baryonic mass, and therefore the halo mass, of galaxies in the low signal-to-noise regime.

We calculate $M_{\text{baryon,tot}} = 1.36M_{\text{HI,tot}} + M_{\star,\text{tot}}$, using listed values for $M_{\text{HI,tot}}$ from Walter et al. (2008) and Ott et al. (2012); and $L_{3.6}$ values from Dale et al. (2009) and then apply the $L_{3.6} \rightarrow M_{\star}$ conversion in §3.2.3.7. The factor of 1.36 accounts for helium; we neglect metals as the low metallicities of our sample imply that $< 1\%$ of the gas is composed of metals (see § 3.2.3.4). In most cases, $M_{\text{baryon,tot}}$ is higher than the aperture-matched measurement of M_{baryon} , primarily due to H I in low S/N pixels that do not contribute to the superprofiles.

3.2.3.3 H I Mass

We calculate the average H I surface density, $\langle \Sigma_{\text{HI}} \rangle$, and H I mass, M_{HI} , from the convolved H I total intensity maps. We first convert this map to a de-projected surface density in $M_{\odot} \text{ pc}^{-2}$:

$$\Sigma_{\text{HI}} (M_{\odot} \text{ pc}^{-2}) = 12.14 \frac{S\Delta v}{\text{FWHM}_{\text{maj}} \text{FWHM}_{\text{min}}} \cos i \quad (3.2)$$

where $S\Delta v$ is the H I surface brightness in $\text{Jy beam}^{-1} \text{ km s}^{-1}$, FWHM_{maj} and FWHM_{min} are the beam major and minor axes in arcsec, and i is the inclination.

To calculate the average $\langle \Sigma_{\text{HI}} \rangle$ for each galaxy, we average the Σ_{HI} map using all the pixels above our S/N threshold (see § 3.3.2). We then calculate M_{HI} by summing Σ_{HI} times the de-projected physical area of each pixel. We note that the mass we calculate in this step is less than the total H I mass of each galaxy given in Table 3.1 due to our S/N threshold.

3.2.3.4 Gas Mass

We calculate the gas mass by assuming $M_{\text{gas}} = 1.36 M_{\text{HI}}$. We include the factor of 1.36 to account for the presence of helium. As most of our galaxies are dwarfs with currently-undetectable H_2 , we neglect possible contributions from molecular gas. Only two galaxies in our sample have detected H_2 , and in both cases the molecular gas contributes $< 10\%$ to the gas mass. We also do not correct for metals, since the metallicities of our sample are likely to be low; the $4.5\mu\text{m}$ luminosity-metallicity relations given in Berg et al. (2012) imply metallicities of $12 + \log (\text{O}/\text{H}) < 8$ for all but two galaxies (NGC 4214 and NGC 7793). Corrections for the masses of heavy elements in the ISM are therefore less than 1% for all of our galaxies, and thus much less than the uncertainties in the gas masses.

3.2.3.5 FUV + $24\mu\text{m}$ Star Formation Rate

We measure the SFR by combining *GALEX* FUV and *Spitzer* $24\mu\text{m}$ luminosities following the prescription from Leroy et al. (2008). FUV emission primarily traces unobscured star formation that has occurred within the past $\sim 10 - 100$ Myr, while the $24\mu\text{m}$ emission traces warm gas that has been heated by embedded star formation on timescales of $3 - 10$

Myr (Calzetti et al., 2007). Therefore, the combination of FUV with $24\mu\text{m}$ provides a measurement of both the embedded and the unobscured recent star formation.

We generate pixel-by-pixel maps of SFR following the formalism described in Leroy et al. (2008). The empirically-calibrated relationship between FUV emission, $24\mu\text{m}$ emission, and SFR is given by:

$$\Sigma_{\text{SFR}} = (8.1 \times 10^{-2} I_{\text{FUV}} + 3.2 \times 10^{-3} I_{24}) \cos i, \quad (3.3)$$

where Σ_{SFR} is in $\text{M}_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$ and the FUV and $24\mu\text{m}$ intensities are in MJy ster^{-1} . The conversion assumes a Kroupa (2001) IMF with a maximum mass of $120 \text{ M}_{\odot}$ as implemented in STARBURST99 (Leitherer et al., 1999). The measured SFRs are smaller by a factor of 1.59 compared to a Salpeter (1955) IMF with a mass range of $0.1 - 100 \text{ M}_{\odot}$ when normalized for the same number of ionizing photons. At $\Sigma_{\text{SFR}} < 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, the $24\mu\text{m}$ emission is an upper limit to the SFR due to the diffuse dust component of the disk. However, only two of our galaxies have average $\langle \Sigma_{\text{SFR}} \rangle < 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, and in these cases, over 90% of the SFR is determined by the FUV component alone. The $24\mu\text{m}$ tracer contributes less than 20% of the total SFR in all but four galaxies (DDO 53, NGC 2366, NGC 4214, and NGC 7793).

We start with publicly available FUV and $24\mu\text{m}$ images from LVL (Dale et al., 2009). These maps have resolutions of $\sim 5''$ and $\sim 1.6''$, respectively. For the FUV images, we subtract a small sky background and correct for Galactic extinction using the dust maps from Schlegel et al. (1998) and $A_{\text{FUV}}/E(B - V) = 8.376$. We mask foreground stars, identified by pixels that have NUV / FUV flux ratios > 15 . The $24\mu\text{m}$ maps have already been background-subtracted, so no additional correction is applied. We then convolve both the $24\mu\text{m}$ and FUV data to our working resolution, place both maps on the astrometric grid defined by the H I data, and apply Equation 3.3.

To calculate the global SFR for each galaxy, we sum the Σ_{SFR} contribution from only the pixels above our H I S/N threshold multiplied by the de-projected physical area of each pixel. To estimate $\langle \Sigma_{\text{SFR}} \rangle$, we divide the SFR by the de-projected physical area covered by pixels above our S/N threshold.

We have attempted to calculate H α -based star formation rates using LVL H α maps, as

they trace star formation on timescales ~ 10 Myr, shorter than the FUV+24 μ m measurement. However, the Σ_{SFR} values implied by H α observations are often below the $10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ level where H α maps are no longer reliable (e.g., Leroy et al., 2012). Additionally, at the low SFR typical of our sample, FUV tracers of SFR appear to be more robust than H α tracers (e.g., Lee et al., 2011; Leroy et al., 2012). We therefore use the FUV+24 μ m as our only SFR tracer.

3.2.3.6 Star Formation Rate per M_{HI}

The star formation rate per unit M_{gas} is often taken to be the star formation efficiency (SFE). However, such an interpretation can be problematic in dwarf galaxies. The H_2 component of the total gas mass is notoriously difficult to measure in dwarfs but must exist if our current understanding of star formation is correct (although see Krumholz, 2012). Using dust as a proxy for H_2 , Bolatto et al. (2011) find molecular gas fractions of $\Sigma_{\text{H}_2}/\Sigma_{\text{HI}} \sim 0.1$ on 200 pc scales in the SMC. However, the typical Kennicutt-Schmidt relation for standard spirals tends to overpredict the star formation rate for a given total gas mass even on a pixel-by-pixel basis (e.g., Leroy et al., 2008; Bolatto et al., 2011). Such observations could be explained if dwarf galaxies have a fundamentally different SFE, or if the HI surface density in dwarfs is simply less directly connected to star formation than in larger spirals. Since the $\Sigma_{\text{SFR}}\text{-}\Sigma_{\text{H}_2}$ relation is comparable to that found in larger spirals, the latter is likely the case. Therefore, our $\text{SFR} / M_{\text{HI}}$ measurement more likely traces the ability of recent star formation to affect the HI gas than any true SFE effects.

To calculate the global average $\langle \text{SFR} / M_{\text{HI}} \rangle$, we simply calculate:

$$\langle \text{SFR} / M_{\text{HI}} \rangle = \frac{\text{SFR}}{M_{\text{HI}}}, \quad (3.4)$$

where SFR and M_{HI} are the star formation rate and HI mass from contributing pixels as derived in § 3.2.3.5 and § 3.2.3.3.

3.2.3.7 Stellar Mass

We use 3.6 μ m Spitzer data from LVL to estimate the stellar mass, using the method in Appendix C of Leroy et al. (2008). This band primarily traces the light from older stellar

populations. In more massive galaxies, the $3.6\mu\text{m}$ band can also contain emission from hot dust and polycyclic aromatic hydrocarbons (PAHs). However, dwarf galaxies show reduced PAH emission compared to larger galaxies of the same color (e.g., Hogg et al., 2005; Engelbracht et al., 2005; Madden et al., 2006; Rosenberg et al., 2006; Jackson et al., 2006). Since our sample is primarily composed of dwarfs, we do not account for PAH emission when converting from $3.6\mu\text{m}$ intensity to stellar mass.

We use the empirically-derived conversion from Leroy et al. (2008):

$$\Sigma_{\star} = \Upsilon_{\star, \text{K}} \langle \frac{I_K}{I_{3.6}} \rangle I_{3.6} \cos i = 280 I_{3.6} \cos i, \quad (3.5)$$

where $\Upsilon_{\star, \text{K}} \sim 0.5$ is the mass-to-light ratio in the K-band, $\Sigma_{\star}$ is in $\text{M}_{\odot} \text{pc}^{-2}$, $I_{3.6}$ is the $3.6\mu\text{m}$ intensity in MJy ster^{-1} and $\langle I_K/I_{3.6} \rangle \sim 1.81$ is the $3.6\mu\text{m}$ -to-K-band conversion as derived by Leroy et al. (2008). The conversion assumes a Kroupa (2001) IMF. The mass-to-light ratio has a scatter of ~ 0.1 dex. Further discussion of the conversion is given in Leroy et al. (2008).

We start with the LVL point-subtracted $3.6\mu\text{m}$ maps from Dale et al. (2009). In a few cases we have extended the point-subtracted mask to the outskirts of the galaxy, as the H I covers a larger area than the LVL aperture in which point-subtraction was initially performed. We place the maps on the same astrometric grid as the H I data and convolve to our 200 pc resolution.

To calculate the total stellar mass, M_{star} , we sum the contribution from only the $\Sigma_{\star}$ pixels above our H I S/N threshold and multiply by the de-projected physical area of a single pixel. To calculate the global average $\langle \Sigma_{\star} \rangle$, we divide $M_{\star}$ by the de-projected area covered by pixels above our S/N threshold.

3.2.3.8 Baryonic Mass and Surface Density

We combine our Σ_{gas} maps with the $\Sigma_{\star}$ maps to find the total baryonic surface density, $\Sigma_{\text{baryon}} = 1.36 \Sigma_{\text{HI}} + \Sigma_{\star}$. We calculate the aperture-matched baryonic mass, M_{baryon} , by summing only the pixels above our H I S/N threshold times the de-projected area of a single pixel. We note that this mass is typically smaller than the $M_{\text{baryon, tot}}$ used as a proxy for halo mass in § 3.2.3.2 due to eliminating low S/N pixels in this measurement. The global

average $\langle \Sigma_{\text{baryon}} \rangle$ is calculated by dividing M_{baryon} by the de-projected area covered by pixels above our S/N threshold.

3.2.3.9 Global H I Second Velocity Moment

To facilitate comparisons with velocity dispersions in the literature, which often use the second moment map as a proxy, we use the intensity-weighted H I velocity dispersion (second moment) maps to calculate a global second moment for the entire galaxy:

$$\langle \sigma_{m_2} \rangle = \frac{\sum_{i,j} \Sigma_{\text{HI},i,j} \sigma_{m_2,i,j}}{\sum_{i,j} \Sigma_{\text{HI},i,j}}. \quad (3.6)$$

for every pixel (i, j) above our H I S/N threshold. We weight each pixel's second moment value, $\sigma_{m_2,i,j}$, by the H I surface density $\Sigma_{\text{HI},i,j}$. We include flux weighting in this calculation because the co-added profiles discussed in § 3.3 are also flux-weighted. It therefore allows for a more meaningful comparison between the velocity dispersions derived from the superprofiles presented in this paper and those derived from the second moment maps as in the literature.

3.2.3.10 Correlations between properties

A number of the above physical properties are correlated with each other. As discussed further in § 3.5, we use the Spearman rank correlation coefficient, r_s , to determine whether two properties are correlated. This statistic also yields p_s , the probability of a random sample having an r_s value that is equal or more extreme than the measured r_s value. We choose $p_s \leq 0.01$ as a conservative threshold for correlation.

In Figure 3.1, we show the correlations between many of the above physical properties. Within one panel, each point represents the globally-averaged properties for a single galaxy. These points are then colored either black if the two properties are significantly correlated or grey if they are uncorrelated. The correlation coefficient, r_s , is shown in each panel. It is immediately clear that many of the mass tracers (M_{HI} , M_{star} , M_{baryon} , w_{20}) are correlated, as expected. The total SFR is also strongly correlated with mass for the reason that more

massive disk galaxies simply tend to have more material for star formation. We also see correlations among many of the more local surface density quantities. The correlation between $\langle \Sigma_{\text{SFR}} \rangle$ and $\langle \Sigma_{\text{HI}} \rangle$ is expected due to the Kennicutt-Schmidt relation, although this relation begins to break down in dwarf galaxies for gas masses measured only using H I (e.g., Bolatto et al., 2011). The baryonic surface density $\langle \Sigma_{\text{baryon}} \rangle$ also correlates with these quantities; given that the galaxies are gas rich with a median gas fraction of $f_{\text{gas}} = 0.74$, $\langle \Sigma_{\text{HI}} \rangle$ makes a large contribution to $\langle \Sigma_{\text{baryon}} \rangle$.

3.3 Global H I Superprofiles

The global properties of the H I velocity dispersion are not necessarily well-characterized by H I second moment maps, as the second moment can be artificially increased by bulk motions of small amounts of gas at anomalous velocities. Instead, we co-add individual line-of-sight profiles after removal of the rotational velocity. This method produces an average, high S/N H I line spectrum, which allows us to characterize the average velocity structure of the ISM.

The basic outline of the procedure is as follows. We first measure the rotational line-of-sight velocity from each profile using the standard, 200 pc resolution data cube (§ 3.3.1). After applying a S/N cut (§ 3.3.2), we recenter each line-of-sight profile in the flux-rescaled data cube so that the peak is at zero and then sum all recentered line-of-sight profiles into a single, global superprofile (§ 3.3.3).

3.3.1 Determining the Peak Velocity

To calculate the H I superprofiles, we must first find the velocity by which to shift each line-of-sight spectrum in the data cube. For undisturbed, idealized H I line-of-sight profiles, this velocity is simply the velocity where the spectrum reaches its maximum. However, non-circular motions and instrumental effects can influence the location of the peak. Initially, Braun (1997) determined this velocity by simply finding the velocity at which the line profile reached its maximum. In the comparatively higher S/N regime of Braun’s data, the peak is unlikely to be strongly affected by noise. The peak position is also affected by the velocity resolution, such that observations with coarse velocity resolution cannot be used

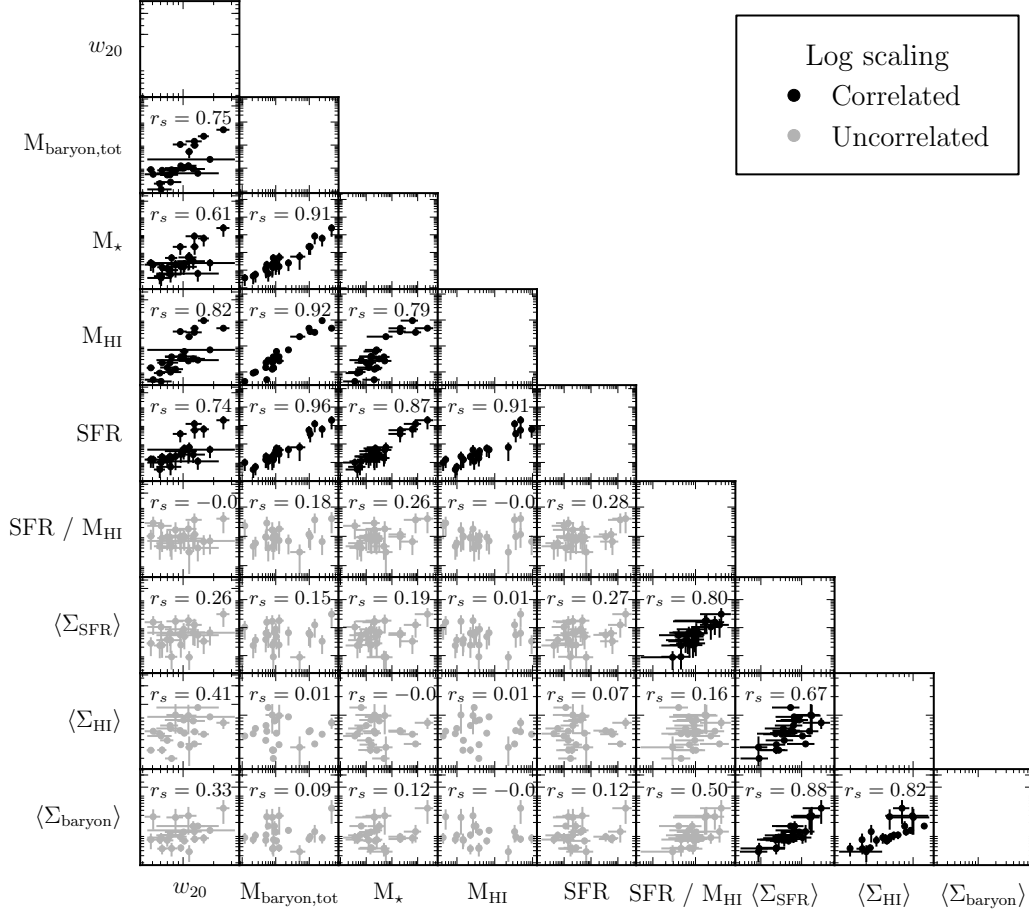


Figure 3.1 Correlations between the globally-averaged physical properties for our sample. Each panel shows the correlation between two different properties. Within each panel, each point represents the globally-averaged value for a single galaxy. Points are colored black if the two properties are significantly correlated ($p_s \leq 0.01$, or $r_s \gtrsim 0.53$) or grey if they are uncorrelated.

to identify the peak to better than the velocity resolution. In lower S/N spectra with high velocity resolution, however, the peak of observed profiles can be artificially shifted either to neighboring channels or even to a completely arbitrary value by noise spikes. Other median line profile studies used the velocity field derived from the first moment map (e.g., Dickey et al., 1990; Boulanger & Viallefond, 1992) or from single Gaussian fitting (Kamphuis & Sancisi, 1993; Rownd et al., 1994) to determine the velocity shift. These velocity fields, however, are often affected by asymmetric H I line-of-sight profiles. Because any offset in velocity can introduce artificial broadening into the superprofile, we must find a more robust method for determining v_{peak} by using information from the entire line-of-sight spectrum.

Toward this goal, de Blok et al. (2008) tested a variety of methods to determine v_{peak} for rotation curve calculation: the intensity-weighted mean velocity; the velocity of the peak flux; a single or a multiple Gaussian fit; and a Gauss-Hermite polynomial fit (e.g., van der Marel & Franx, 1993). They concluded that the most robust function in the low S/N regime is a Gauss-Hermite polynomial that includes an h_3 term. This method has already been used to generate velocity fields used in rotation curve analysis for a number of galaxies (e.g., Noordermeer et al., 2007; de Blok et al., 2008). Double Gaussian functions also tend to accurately fit line-of-sight spectra, but must be subjected to stringent parameter and S/N constraints to avoid fitting noise spikes (e.g., Warren et al., 2012).

In individual line-of-sight spectra, we find that the first moment, single Gaussian fits, and the velocity of the peak can be strongly influenced by asymmetries or noise, as result similar to that found by de Blok et al. (2008). We show a comparison of these various peak-determining methods for two individual line-of-sight spectra in Figure 3.2. Both line-of-sight spectra show clear asymmetries, and the Gauss-Hermite polynomial best approximates the peak of the line-of-sight spectra. In comparison, the single Gaussian fit and the first moment value are both shifted due to the asymmetry. Because we are interested only in determining v_{peak} and not the detailed underlying structure of each individual line-of-sight spectrum, we adopt Gauss-Hermite polynomials when deriving v_{peak} .

We use the unmasked, standard data cube to generate v_{peak} maps for each galaxy. This cube provides the correct, uniform noise properties necessary for Gauss-Hermite fitting, even though the fluxes are not accurate. Nonetheless, we expect v_{peak} to be the same in both the

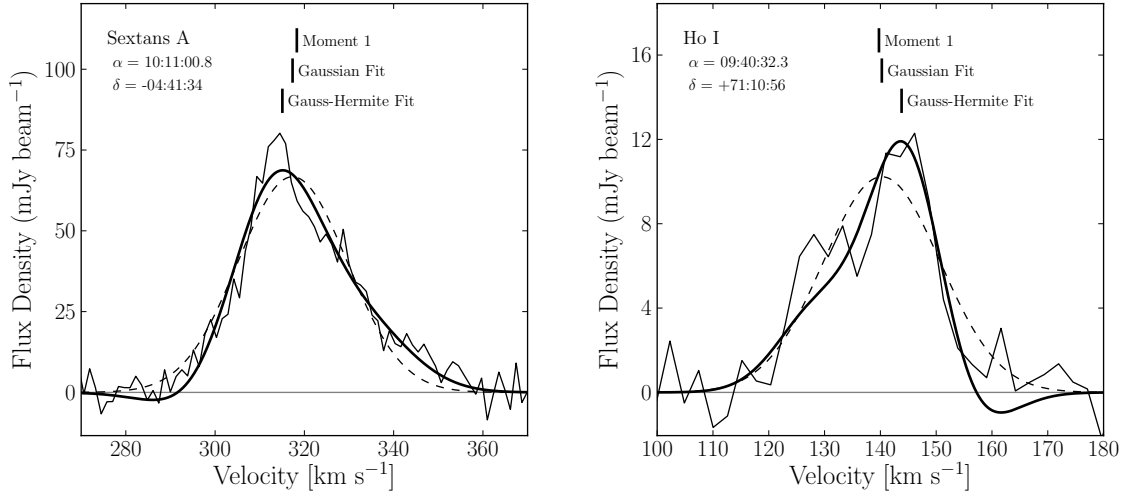


Figure 3.2 Two observed line-of-sight spectra from standard cubes with v_{peak} methods: the first moment map, a Gaussian fit, and a Gauss-Hermite fit. The upper panels show the spectra and various fits, while the lower panels are the residuals. The thin black line in the spectrum, the dashed line is the Gaussian fit, and the thick black line is the Gauss-Hermite fit. The plotted H I profiles are for line-of-sight spectra with higher than average S/N ratios, to better show the adopted functional form. The Gauss-Hermite polynomials are primarily to find v_{peak} and are not meant to characterize the detailed line profile structure. Left: Sextans A, for a line-of-sight spectrum with $S/N = 16.9$. Right: Holmberg I, for a line-of-sight spectrum with $S/N = 9.7$.

standard cube and the flux-rescaled cube. As explained in Ott et al. (2012) and Walter et al. (2008), and references therein, the correction applied to the flux-rescaled cube rescales the intensity of the residuals of deconvolution to the same beam area as the intensity measured from the clean components. However, the H I emission in channels near the peak of the profile is primarily in the clean components and is not rescaled. The low level of flux in the residuals should not affect the location of the highest intensity emission that determines v_{peak} .

To generate the v_{peak} maps for each galaxy, we fit a Gauss-Hermite polynomial with an h_3 term to each pixel in the unmasked, standard data cube as given by:

$$\phi(v) = Ae^{-y^2/2} \left[1 + \frac{h_3}{\sqrt{6}} \left(2\sqrt{2}y^3 - 3\sqrt{2}y \right) \right] \quad (3.7)$$

where $y \equiv (v - \mu)/\sigma_{\text{GH}}$ and the h_3 component measures an asymmetric deviation from a Gaussian with amplitude A , offset μ , and standard deviation σ_{GH} (van der Marel & Franx, 1993). We note that the value of σ_{GH} is not necessarily the same as the standard deviation of a best-fit Gaussian without the h_3 term. The Gauss-Hermite polynomial fits are not intended to be a representation of the underlying H I distribution, and we attach no physical significance to the parameters other than the determination of v_{peak} .

For the fitting process itself, we use a Python implementation of the Levenberg-Marquardt fitting algorithm¹ with uniform weight given by $1/\sigma_{\text{chan}}$ on each channel. We require that the peak velocity be within $\pm 20 \text{ km s}^{-1}$ of the first moment to ensure that the peak falls in the range of true H I emission. The width of the profile is forced to be greater than the velocity resolution to prevent the algorithm from fitting individual noise spikes. While individual line-of-sight profiles can show double peaks indicative of expanding structures, recent studies of spectra in these galaxies have shown that they comprise only a small fraction of all spectra (Warren et al., 2012); thus, they do not contribute large amounts of flux to the superprofiles. We assess the accuracy of our v_{peak} measurements in § 3.3.2. We further discuss the effects of v_{peak} uncertainties on our results in § 3.3.5.1.

As an example, the final v_{peak} map for Sextans A is shown in the upper panel of Figure 3.3. The middle and lower panels illustrate the differences between the Gauss-Hermite

¹mpfit.py; available at <http://code.google.com/p/astrolibpy/>

determination of v_{peak} and what would have been determined by fitting a single Gaussian (middle panel) or using the first moment map (lower panel). In each map, we have overlaid a line to indicate where $S/N > 5$. The absolute differences between the Gauss-Hermite velocity field and the first moment and Gaussian velocity fields are small in a global sense (i.e. $\sim 4 \text{ km s}^{-1}$). However, the differences are often only a factor of two smaller than the second moment values themselves, which could lead to spurious broadening of the global superprofiles if we use either the first moment map or a single Gaussian fit to determine v_{peak} .

3.3.2 Signal-to-Noise Threshold Selection

To ensure that we have accurately measured v_{peak} for each line-of-sight spectrum we include in the superprofile, we select only pixels for which the peak of the profile fit in Equation 3.7 is above a specific S/N threshold. For each pixel, we define S/N as the ratio between the maximum of the Gauss-Hermite polynomial fit and σ_{chan} . Figures 3.4 and 3.5 show a number of individual line profiles with various S/N from NGC 2366 and Sextans A, with the Gauss-Hermite fits overlaid in red. It is qualitatively clear that the Gauss-Hermite polynomials provide better fits as the S/N increases. For spectra with $S/N > 5$, the fitting routine does a good job at identifying the peak. For spectra with $3 < S/N < 5$, the fitting routine does a reasonable job, and spectra with $S/N < 3$ have decidedly questionable fits.

To quantify this behavior, we run Monte Carlo (MC) simulations for four representative galaxies that span the range in velocity resolution and S/N (GR 8, Sextans A, UGC 4483, and NGC 2366). We create a simulated data cube from the Gauss-Hermite polynomial fits to the data, add noise at the appropriate level, and run our v_{peak} -finding algorithm. We then repeat this process 100 times. While the Gauss-Hermite fits are not necessarily representative of the underlying HI distribution, they provide a known input for our tests. The output v_{peak} maps from all the MC realizations allow us to calculate the average uncertainty in measuring v_{peak} as a function of S/N . In Figure 3.6, we show the standard deviation of MC v_{peak} offsets versus S/N for the four test galaxies. Each point represents the standard deviation around the input v_{peak} of the 100 repeated v_{peak} measurements for a

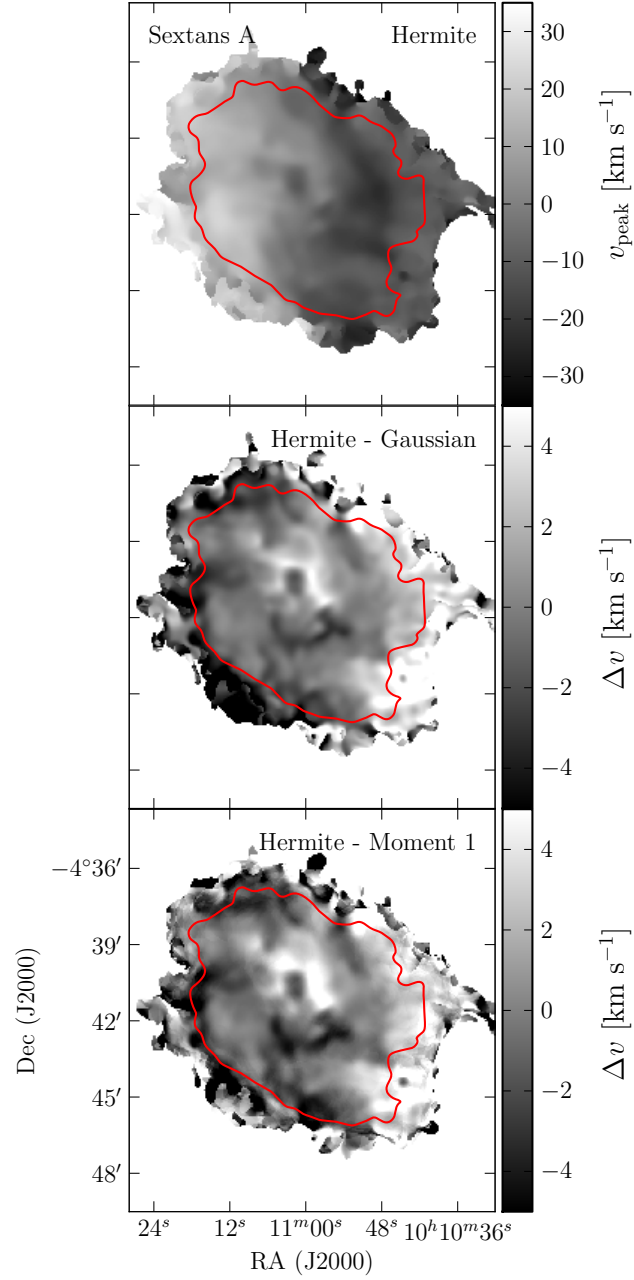


Figure 3.3 The v_{peak} map generated from the Gauss-Hermite fits with the systemic velocity removed (top) and differences from both a single Gaussian fit (middle) and the first moment map (bottom). The red contour line shows regions with $S/N > 5$.

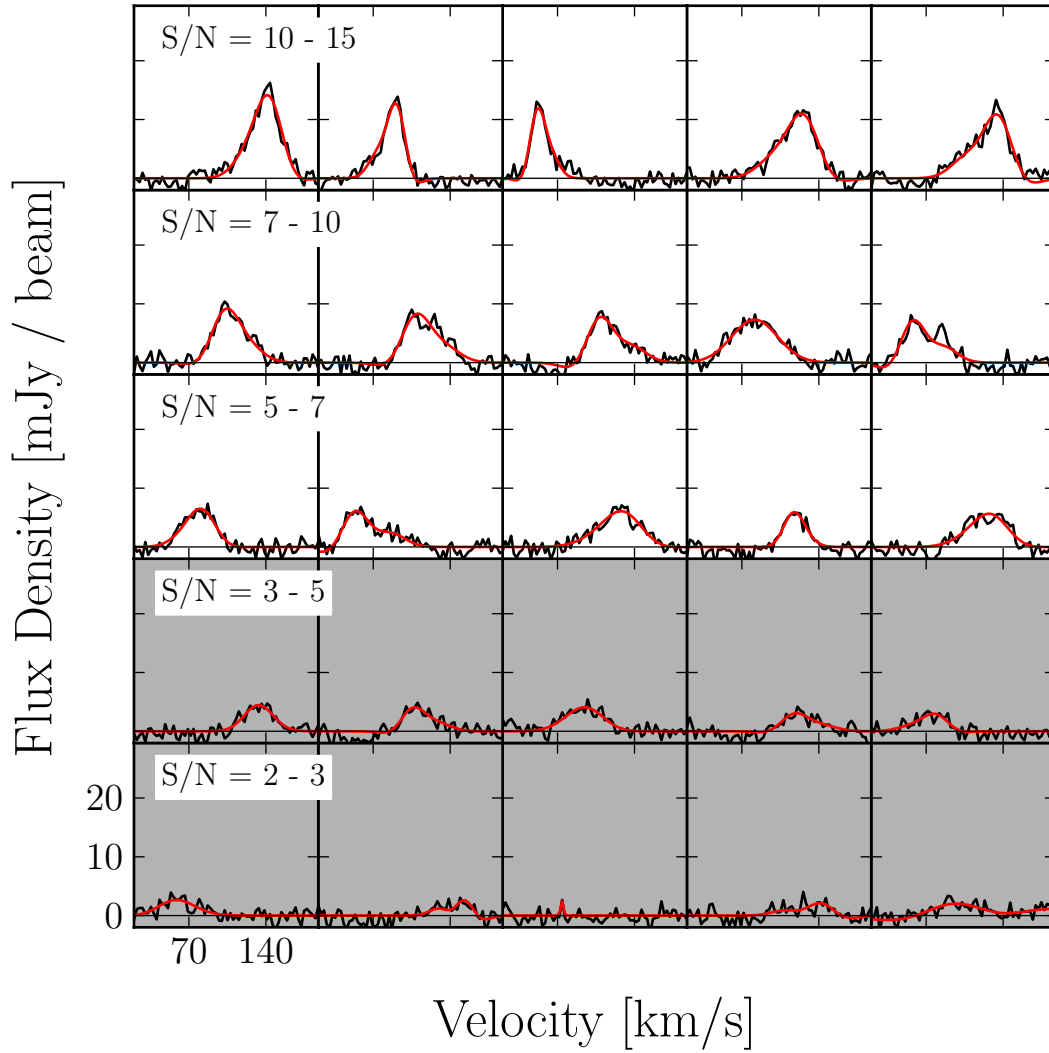


Figure 3.4 Example Gauss-Hermite polynomial fits to various H I line-of-sight spectra for NGC 2366, a galaxy with a velocity resolution of 2.6 km s^{-1} . The line-of-sight profiles are sorted into rows based on their S/N ; spectra with $S/N < 5$ have grey backgrounds. The general asymmetry of the line-of-sight spectra is readily apparent. For spectra with $S/N > 5$, the Gauss-Hermite polynomials generally do a good job at finding the peak. At lower S/N , the peak is more difficult to determine and may even be due solely to noise spikes. In our analysis, we only use pixels with $S/N > 5$.

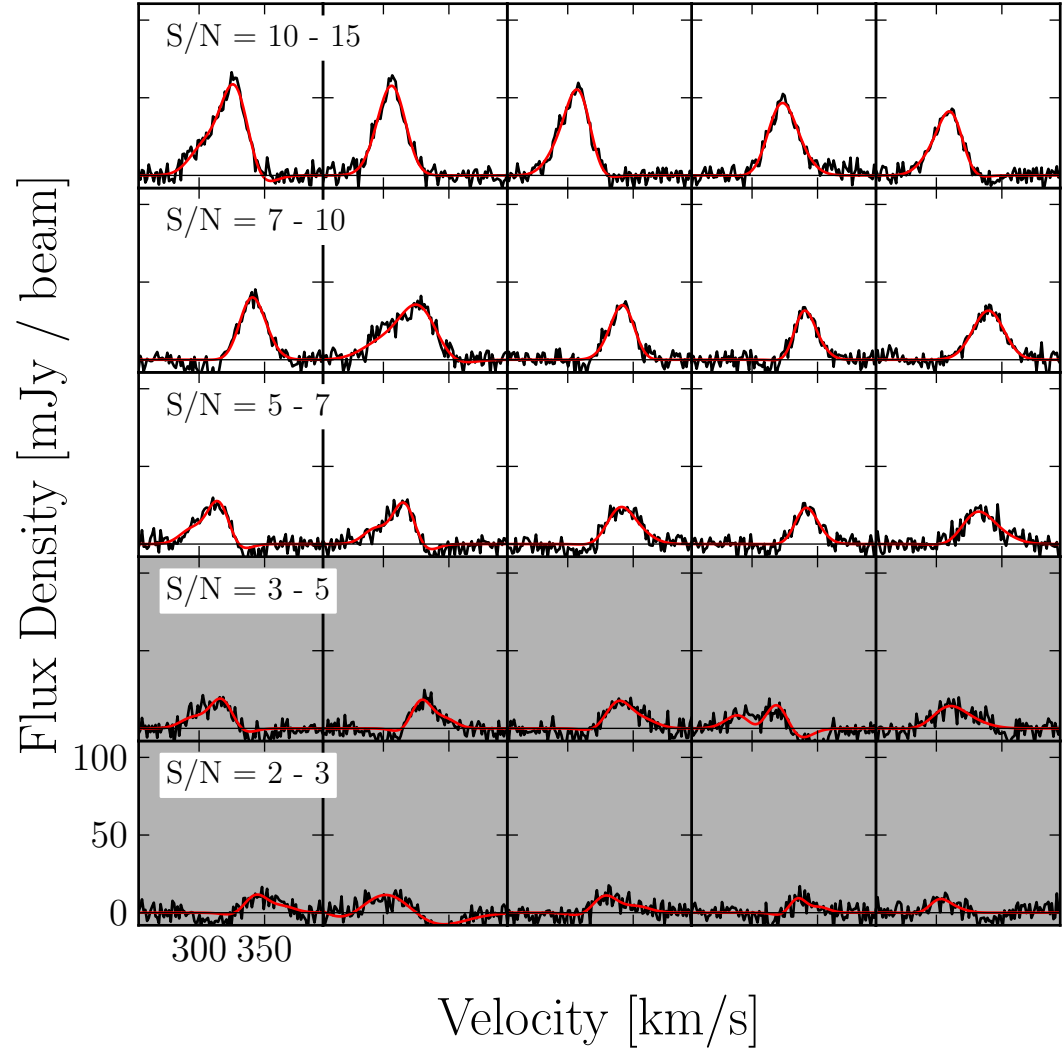


Figure 3.5 Same as Figure 3.4, for Sextans A, a galaxy with a velocity resolution of 1.3 km s^{-1} .

single pixel. For clarity, only 5000 random points are shown for each galaxy. Regions below the cube’s velocity resolution Δv are shown in grey.

At smaller velocity resolutions, we are better able to determine v_{peak} , for a fixed S/N . We overlay a vertical dashed line at $S/N = 5$, where the standard deviations of the coarsest velocity resolution data (2.6 km s^{-1}) start to flatten. In all cases, we reproduce the input v_{peak} with an error of $< 2 \text{ km s}^{-1}$. Based on these tests, we adopt $S/N > 5$ as our threshold.

3.3.3 Co-addition of Line-of-Sight Spectra

We use the flux-rescaled cubes to generate the final global superprofiles. These cubes provide correct flux properties and have been corrected for primary beam attenuation. The advantages of using the flux-rescaled cubes is that they allow us to calculate accurate estimates of H I mass and energy, at the cost of having more complicated noise properties than superprofiles generated from standard cubes.

We apply a mask to the data cubes so that only channels with real H I emission contribute. We use the $45''$ resolution masks described in § 3.2.2 for each galaxy but extend them by 15 km s^{-1} on either side in velocity. This extension includes any low-level H I emission from gas in the surrounding channels that is below our masking threshold, but mostly eliminates spurious signals from instrumental effects such as sidelobes and clean bowls, which often occur further from the true H I emission in velocity space. The final superprofiles are not strongly changed when using unmasked spectra in data cubes that do not show detectable instrumental artifacts such as sidelobes or negative bowls due to missing short spacings.

To create the final global line profile from the masked, flux-rescaled data cubes, we first recenter the selected ($S/N > 5$) individual line-of-sight spectra such that v_{peak} is at zero. Because v_{peak} is often located in the middle of a channel, simply shifting all profiles by an integer number of channels and then summing can artificially broaden the final global line profile. Instead, we linearly interpolate across each line-of-sight profile by a factor of 10 before shifting in velocity space. Finally, we co-add the shifted line-of-sight profiles with equal weight to obtain the intensity-weighted H I superprofile.

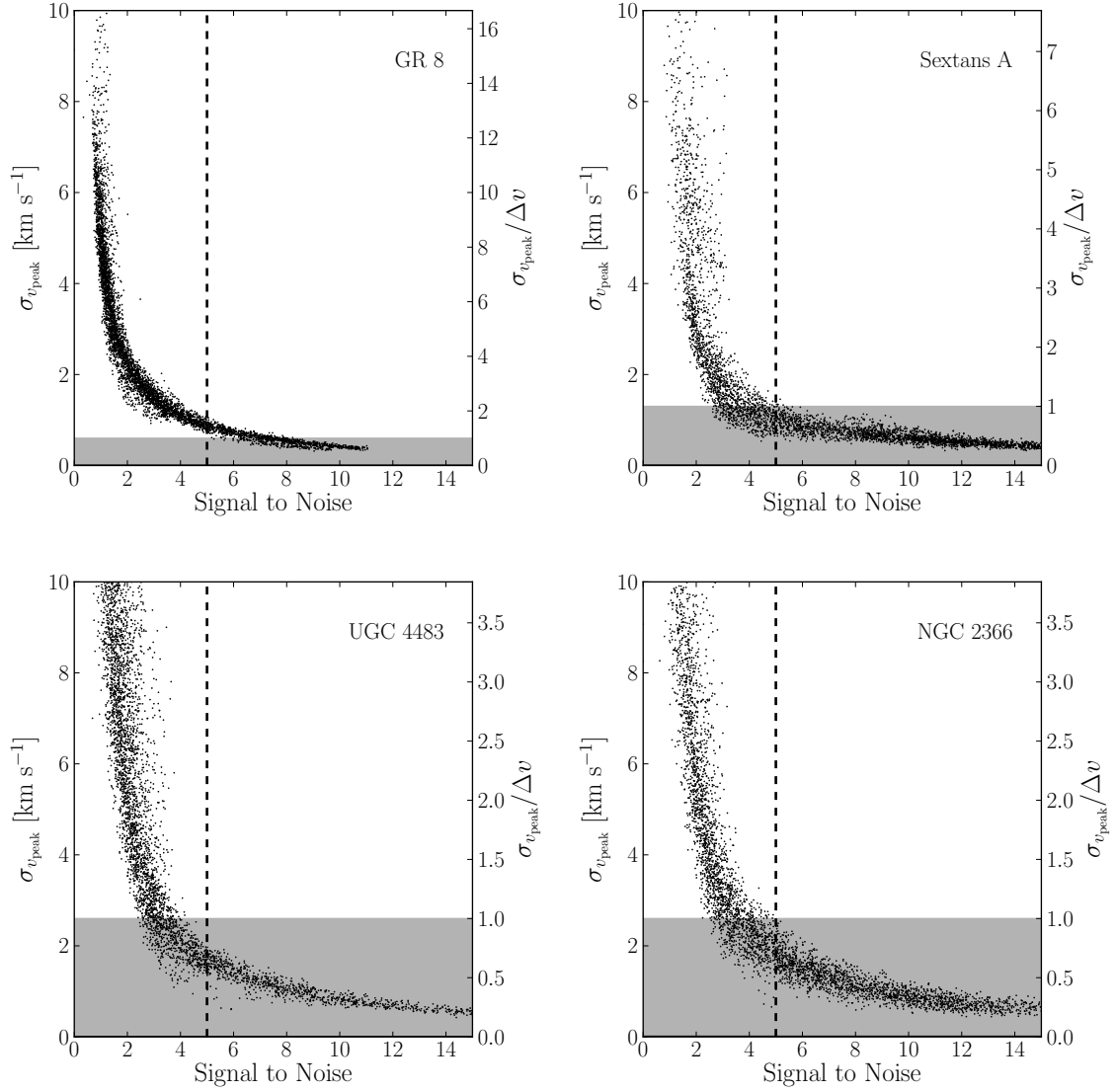


Figure 3.6 The average error on finding v_{peak} ($\sigma_{v_{\text{peak}}}$) as a function of S/N for three different simulated galaxy data cubes with three different velocity resolutions. The grey box indicates regions where $\sigma_{v_{\text{peak}}}$ is below the observation's velocity resolution. The dashed black line is our adopted $S/N = 5$ threshold. At our S/N threshold, we find an average uncertainty of $\lesssim 1 \text{ km s}^{-1}$ for $\Delta v = 0.6 \text{ km s}^{-1}$ (GR 8), $\lesssim 1$ for $\Delta v = 1.3 \text{ km s}^{-1}$ (Sextans A), and $\lesssim 1.5$ for $\Delta v = 2.6 \text{ km s}^{-1}$ (UGC 4483).

The final global line profiles are shown in Figure 3.7a, ordered by decreasing $M_{\text{baryon,tot}}$. They will be discussed in detail in § 3.4.1.

3.3.4 Uncertainties

We define the noise on each point of the superprofile, σ_{SP} , as:

$$\sigma_{\text{SP}} = \sigma_{\text{chan}} \times \sqrt{N_{\text{pix}}/N_{\text{pix/beam}}} \times \frac{F_{\text{rescaled}}}{F_{\text{standard}}}. \quad (3.8)$$

Here, σ_{chan} is the *rms* noise in a single channel. N_{pix} is the number of channels contributing to a superprofile point, and $N_{\text{pix/beam}}$ is the number of pixels per resolution element; this term represents the approximate number of independent profiles contributing to each superprofile point. We count each interpolated point contributing to a single superprofile point as one pixel. The $F_{\text{rescaled}}/F_{\text{standard}}$ term is the flux ratio between the total measured flux in the superprofile generated from the rescaled cube to that from the standard cube. It is included to approximate the rescaling process, and maintains the same fractional noise between the standard cube and the rescaled cube. Typical values for $F_{\text{rescaled}}/F_{\text{standard}}$ are 0.4 ± 0.13 . We discuss the details of this estimate further in § 3.3.4.1.

The noise for each superprofile is shown in Figure 3.7a as the grey shaded region around each measured superprofile. In some cases, the S/N of the final superprofile is high enough that the uncertainties are smaller than the black line showing the superprofile itself.

3.3.4.1 Noise Rescaling for Flux-Rescaled Data Cubes

The flux rescaling process is important for interferometric data because it provides an accurate measurement of the true H I flux of each galaxy. Since this process only rescales the residuals, the noise properties of the rescaled data cube are complicated. While the highest noise peaks can show up in the clean components of the rescaled data cube, the majority of the noise is still in the residuals. Traditional estimates of noise therefore provide an overestimate of the noise for superprofiles generated from rescaled data cubes.

The noise on a single point of a superprofile generated from a *standard* cube can be approximated as:

$$\sigma_{\text{SP}} = \sigma_{\text{chan}} \times \sqrt{N_{\text{pix}}/N_{\text{pix/beam}}}, \quad (3.9)$$

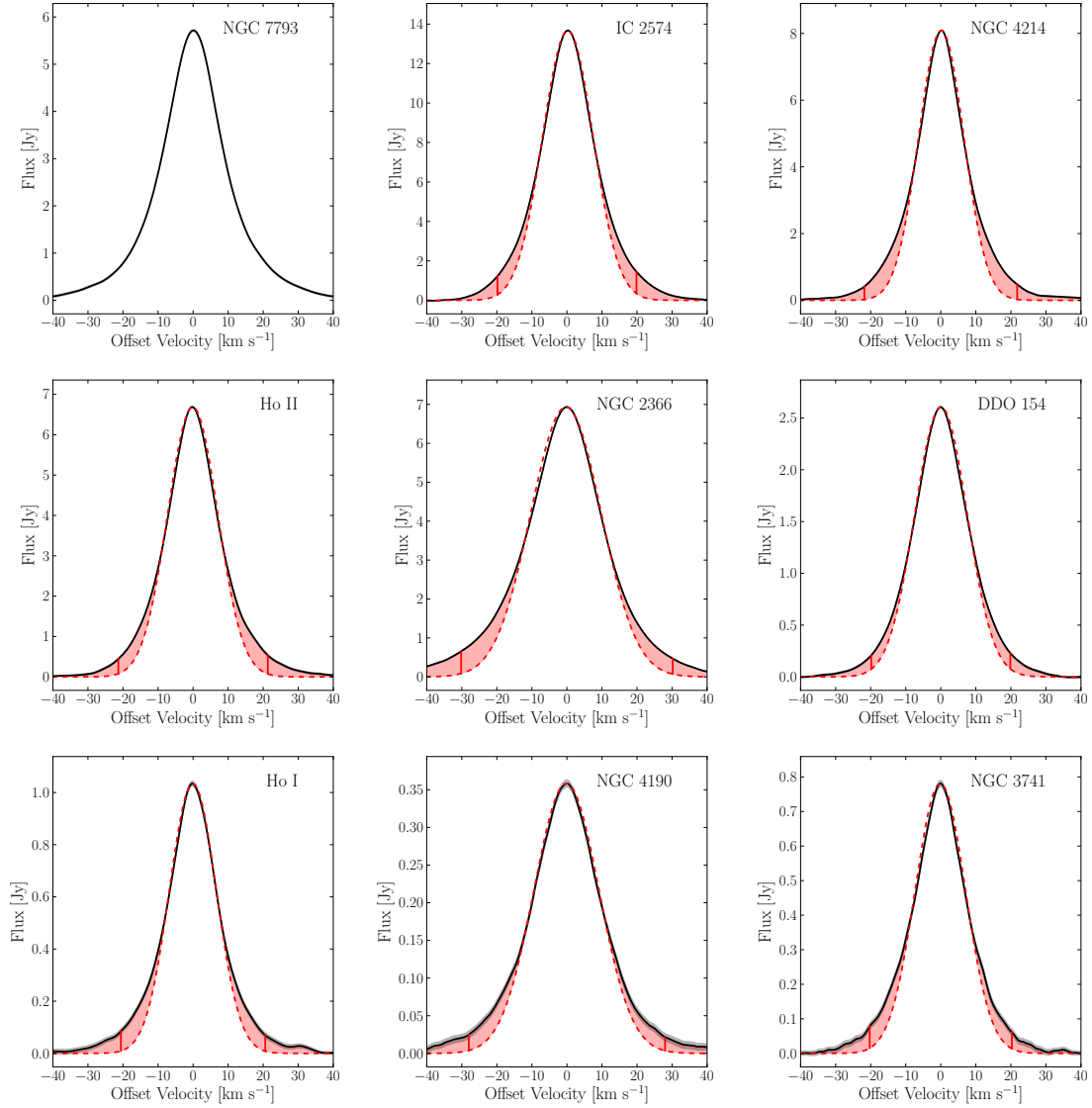


Figure 3.7a H I superprofiles. In each panel, the black line represents the measured superprofile for each galaxy. Grey regions around the superprofile are the $1\text{-}\sigma$ uncertainties on the flux. The dashed red line shows a Gaussian scaled to the amplitude and the half-width at half-maximum of the superprofile. Shaded red regions between this line and the superprofile are the “wing” regions and represent f_{wings} . The vertical red line is the characteristic velocity of the wings, σ_{wings} . As the superprofiles are the analogue of integrated H I spectra, but with the rotational velocity removed, we plot flux in Jy versus offset velocity. However, the Jy value is not indicative of our signal in a single channel. Galaxies are ordered by decreasing $M_{\text{baryon,tot}}$.

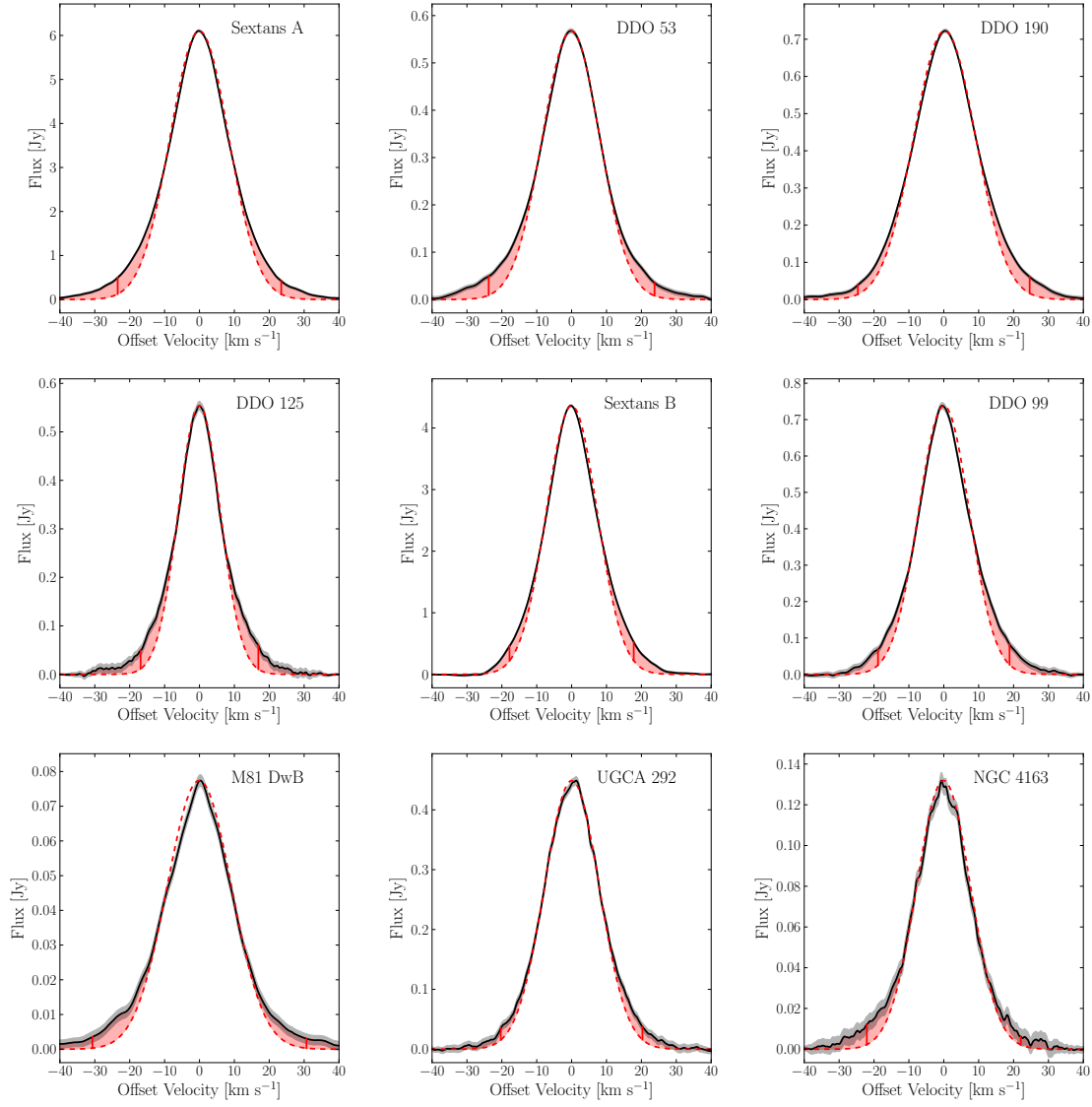


Figure 3.7b H I superprofiles (continued). Galaxies are ordered by decreasing $M_{\text{baryon,tot}}$.

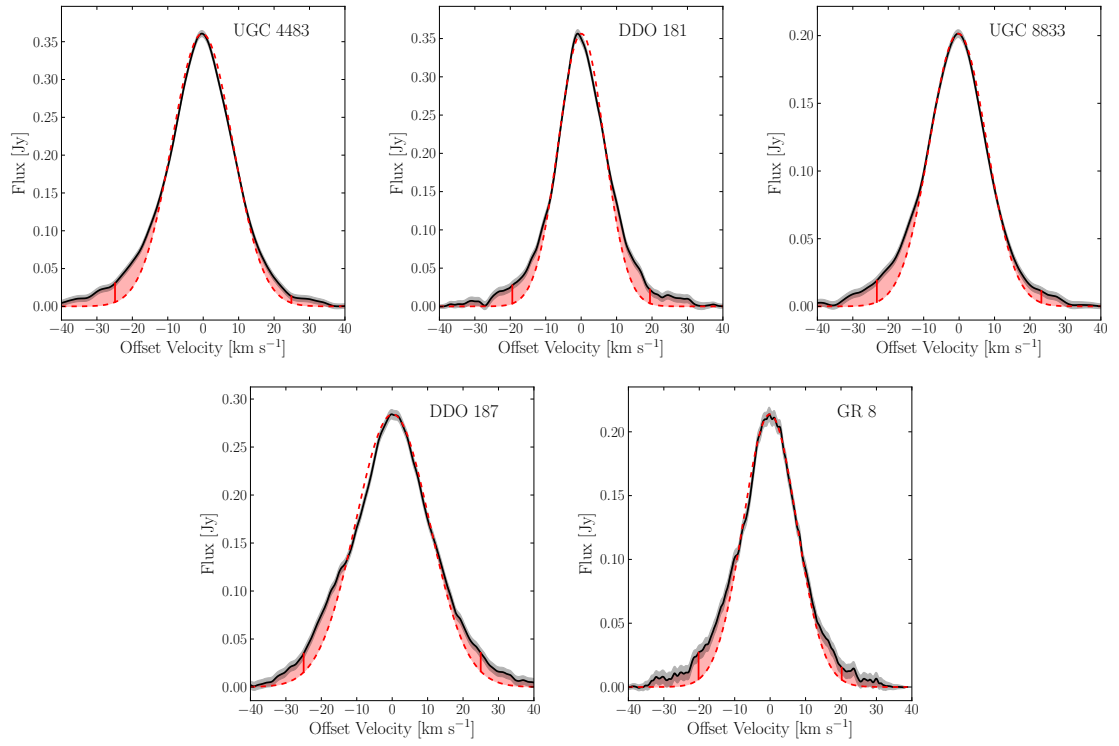


Figure 3.7c H I superprofiles (continued). Galaxies are ordered by decreasing $M_{\text{baryon,tot}}$.

where σ_{chan} is the *rms* noise level in a single channel of the data cube, N_{pix} is the number of pixels contributing to each superprofile point, and $N_{\text{pix}/\text{beam}}$ is the number of pixels per beam (I2012).

In the left panel of Figure 3.8, we apply this formula to the superprofile generated from the standard cube and to that from the rescaled cube. The upper panel shows the absolute flux measured in each superprofile. In the lower panel we have normalized the superprofiles so that the maxima are the same. It is clear that the fractional noise is much larger in the rescaled cube.

In the right panel, we have rescaled the noise for the superprofile generated from the rescaled cube by the ratio of total fluxes, $F_{\text{rescaled}}/F_{\text{standard}}$ such that the noise is given by Equation 3.8. This rescaling produces a noise estimate with a similar fractional uncertainty compared to the standard cube. This estimate is not exact, because the highest noise spikes are contained in the clean components. However, the majority of the noise is in the residuals, which are rescaled. This method also provides a noise estimate that matches the fractional uncertainty on each point compared to superprofiles generated from the standard cubes. Since it is a better representation of the fractional uncertainty on each superprofile point, we adopt Equation 3.8 when calculating the effects of noise on the superprofiles.

3.3.5 Effects of Observational Settings on Superprofile Shapes and Measured Parameters

We have performed a number of tests to ensure the validity of our results and to estimate uncertainties on the measured parameters, σ_{central} , σ_{wings} , f_{wings} , and a_{wings} . In particular, we have examined the effects of v_{peak} uncertainties (3.3.5.1); finite spatial resolution (3.3.5.2); finite velocity resolution (3.3.5.3); and noise on each superprofile point (3.3.5.4). Finally, we review the final uncertainties on the measured parameters (3.3.5.5).

3.3.5.1 Uncertainties in v_{peak}

We explore how our superprofile parameters are affected by the uncertainties in determining v_{peak} , which could possibly generate broader superprofiles or more flux in the wings.

For each of our four test galaxies (GR 8, Sextans A, UGC 4483, and NGC 2366), we

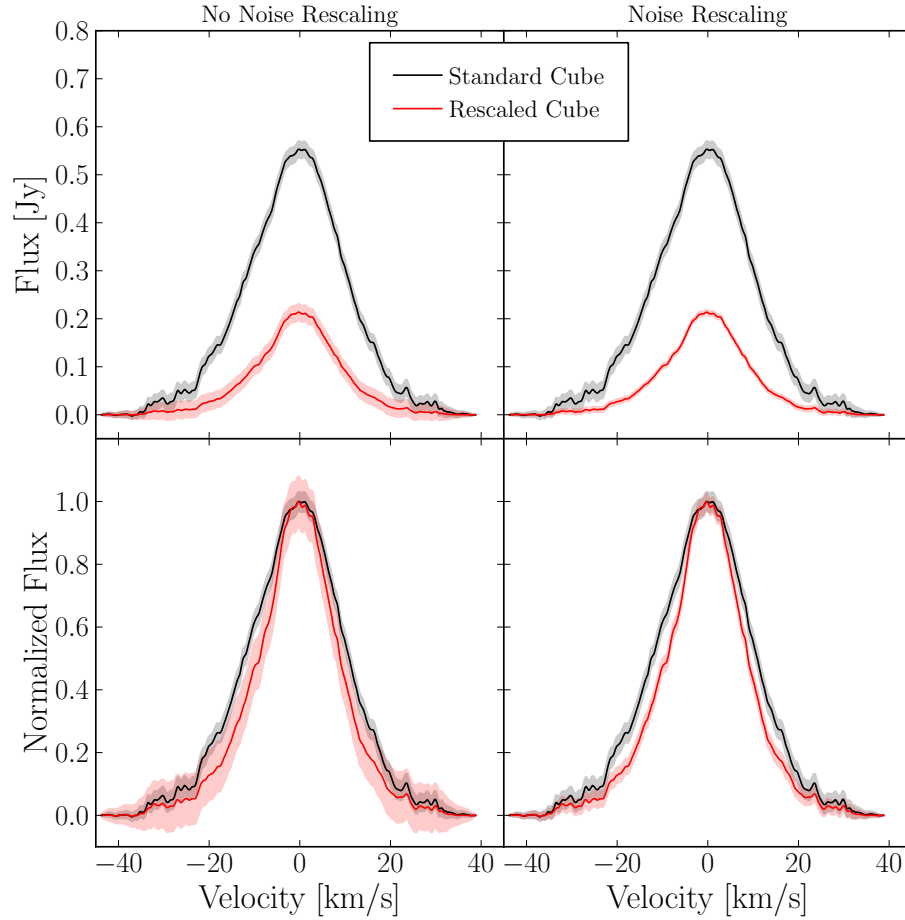


Figure 3.8 A comparison of noise estimates for the superprofiles generated from the standard cube (black) and from the rescaled cube (red) for the galaxy GR 8. The solid lines represent the superprofiles, while the shaded regions show the $1\text{-}\sigma$ noise estimate. The upper panels show the absolute flux measured in each superprofile, while the lower panels show the superprofiles after normalizing to the same maximum amplitude. The left panels show the noise estimate given by Equation 3.9 for both the standard and rescaled superprofiles. The right panels show the noise estimate given by Equation 3.9 for the standard superprofile and that given by Equation 3.8 for the rescaled superprofile, where the noise is scaled by the ratio of fluxes between the rescaled and standard superprofile. The rescaled noise approximately matches the fractional uncertainty of noise in the standard superprofile.

start with the pixel-by-pixel uncertainty in determining v_{peak} as a function of S/N ratio, determined from our Monte Carlo tests for the four test galaxies (§ 3.3.2; Figure 3.6). We first assume that all pixels would contribute a Gaussian with a width of σ_{central} in the absence of any uncertainties on v_{peak} . For each pixel above our $S/N > 5$ threshold, we generate a random offset drawn from a Gaussian with that pixel’s standard deviation of determining v_{peak} and with the S/N as the amplitude. We generate a fake superprofile by summing all of the σ_{central} Gaussians with their respective velocity offsets.

The results of this test are shown in Figure 3.9 for our four test galaxies. For each of the four galaxies, the upper panel shows the “observed” fake superprofile as the black solid line; the input superprofile we would have expected in the absence of any uncertainties on v_{peak} as the blue dash-dot line; and the HWHM-scaled Gaussian fit as the dashed red line. In all cases, the differences are smaller than the line widths. The lower panel shows the residuals (i.e., “observed” - fit and “observed” - input).

The differences between the input Gaussian, the “observed” fake superprofile, and the fit are < 0.005 in all cases. We also find that the width of the superprofile is increased by $< 0.5\%$. The uncertainties in v_{peak} therefore have a negligible effect on the superprofile shapes and parameters.

3.3.5.2 Finite Spatial Resolution

The combination of finite spatial resolution and rising rotation curves at the centers of galaxies can increase the width of observed H I line-of-sight spectra in the central regions, which could then either increase the width or mimic H I in the wings of the observed superprofile. Our sample of dwarf galaxies likely have either slowly-rising rotation curves (DDO 154 and NGC 2366; e.g., de Blok et al., 2008) or primarily display solid body rotation typical of dwarfs (Oh et al., 2011). Because these rotation curves have a smaller gradient with increasing radius, we expect to see less of an effect from beam smearing in the central regions compared to larger spiral galaxies, but we must still to understand its effects.

To quantify the effects of beam smearing, we have developed a Python module to generate a suite of model galaxy observations using NGC 2366 as our test galaxy. This galaxy

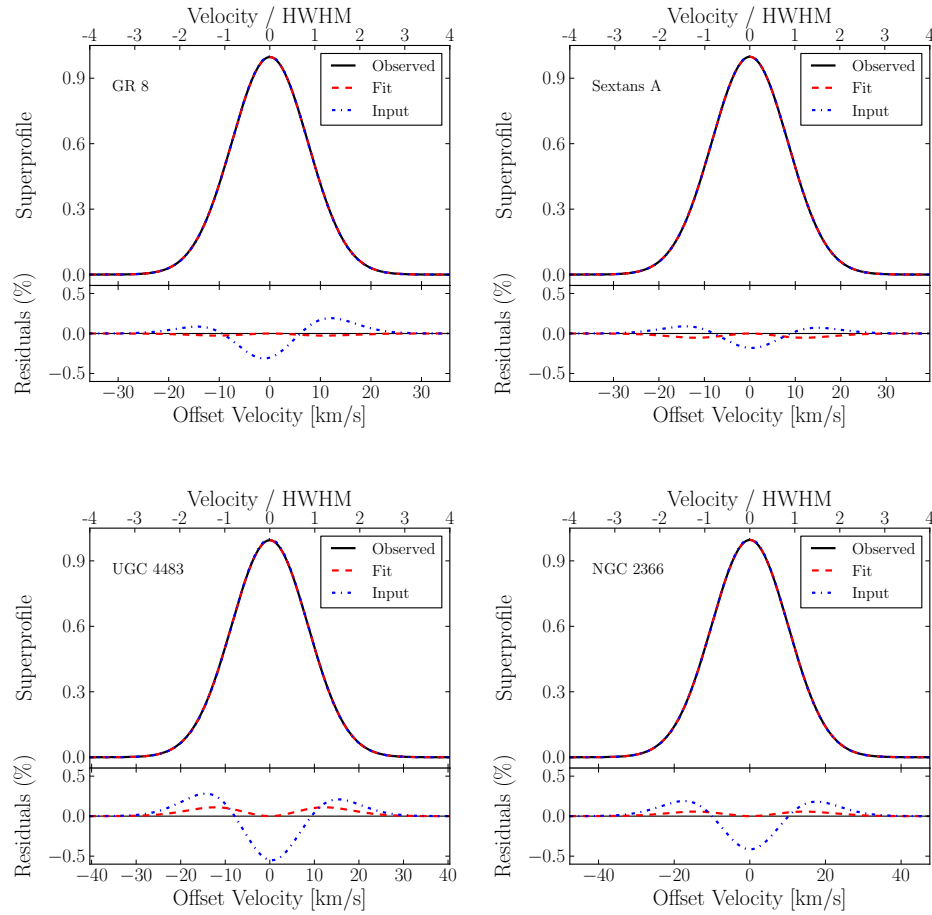


Figure 3.9 Model superprofiles with included uncertainties in our v_{peak} measurements. Each panel shows a different galaxy. The black line represents the fake superprofile. The dashed blue line is the input Gaussian and the dashed red line is the HWHM-Gaussian fit to the fake superprofile. All lines are plotted in the top panel, but the differences are smaller than the line widths. The bottom panel shows the residuals (i.e., observed - fit and observed - input). Uncertainties in v_{peak} broaden the profile slightly, but the effects are ~ 100 times smaller than the observed amplitude of the wings. The effect due to uncertainties in v_{peak} is therefore negligible. Measurement errors in v_{peak} therefore do not create the shape of the observed superprofiles.

has the steepest rotation curve of our sample, and thus would be the most affected by this particular bias. We use the observed H I surface brightness distribution plus the observed inclination and position angle from de Blok et al. (2008) to generate the model H I distribution. We also assume that the disk has an exponential distribution in the z -direction with a scale height $h_z = 500$ pc, a typical observed value for H I scale heights in dwarfs (e.g., Banerjee et al., 2011; Warren et al., 2011). Changing this assumption to either 100 pc or 1 kpc does not strongly influence our results.

We next impose a rotation curve that can be modeled as a linear rise for radii smaller than r_{flat} , with a flat regime at larger radii with circular velocity v_{flat} .

Finally, we assume that all line-of-sight H I spectra have Gaussian velocity distributions with a dispersion of 6 km s^{-1} . While this assumption is not necessarily indicative of the true dispersion as a function of radius (e.g., Tamburro et al., 2009), it does allow us to quantify the effects of beam smearing on a uniform H I profile. In order to estimate the effects of declining velocity dispersion, we also generate a model where the intrinsic velocity dispersion is chosen by an exponential fit to the radial average of the second moment map.

For this test, we use three models: one with the observed $r_{\text{flat}} = 1.9$ kpc, $v_{\text{flat}} = 60 \text{ km s}^{-1}$ (de Blok et al., 2008), and $\sigma_{\text{HI}} = 6 \text{ km s}^{-1}$; a second with an extreme $r_{\text{flat}} = 0.5$, $v_{\text{flat}} = 60$, and, $\sigma_{\text{HI}} = 6 \text{ km s}^{-1}$; and a third with $r_{\text{flat}} = 1.9$, $v_{\text{flat}} = 60$, and $\sigma_{\text{HI}}(r)$ set by the exponential fit to the second moment map.

To place H I clouds in the model cube, we draw a sample of points from the H I surface brightness distribution, assuming each cloud represents a gas cloud at the observed spatial position. We then distribute these points randomly in the z -direction using our assumed exponential z distribution. Each point is smoothed in velocity space into a Gaussian with the central velocity determined by the rotation curve at that radius and the width dependent on the model. Finally, we scale the cube so that the total H I mass is the same as measured in the galaxy. This yields a cube that has H I line-of-sight spectra unaffected by spatial resolution with a velocity resolution of 2.6 km s^{-1} .

To reproduce the effects of finite spatial resolution, we smooth the cube to our working 200 pc resolution using a circular Gaussian beam with a FWHM of 200 pc. For both the true and convolved cube, we find v_{peak} for each pixel and then generate a superprofile using

the same method as described in §3.3. We fit and parameterize the superprofile using a single Gaussian scaled by the superprofile’s HWHM (§3.4.2).

We show the resulting true and smoothed model superprofiles compared to the observed superprofile in Figure 3.10. In all cases, the superprofile from the smoothed cube shows very small differences compared to the true cube. The measured Gaussian dispersion is slightly wider by $\Delta\sigma_{\text{central,spatial}} \lesssim 0.5 \text{ km s}^{-1}$. Additionally, the convolved cubes have a negligible fraction in the wings ($\Delta f_{\text{wings,spatial}} \lesssim 0.01$), a value much lower than the typical range observed in our sample ($0.05 < f_{\text{wings}} < 0.15$). With such a small contribution to the wings, σ_{wings} should not be strongly affected by beam smearing. We note that the superprofile generated from the model with exponentially declining σ_{HI} is well-fit by a Gaussian with a width $\sim 10 \text{ km s}^{-1}$, similar to the Tamburro et al. (2009) results. None of these models is able to reproduce wings at the observed magnitude.

In summary, while finite spatial resolution does contribute a small amount of broadening, it is at a low level compared to the observed widths and is not strong enough to generate spurious flux in the wings.

3.3.5.3 Finite Velocity Resolution

We also examine the effects that finite velocity resolution has on our results. Since our sample is composed of galaxies observed with a variety of velocity resolutions (0.6, 1.3, and 2.6 km s^{-1}), we must quantify any effects that arise from these differences. For each galaxy, we bin the observed standard and flux-rescaled cubes to the coarser velocity resolutions of our sample. We then find v_{peak} , generate a superprofile, and measure parameters for each new resolution.

In Figure 3.11 we show the superprofiles generated from the binned cubes for DDO 125. The upper panels shows the superprofiles themselves, and the lower panels show the difference between superprofiles generated from the binned cube and the original cube. The superprofiles behave similarly for $\Delta v = 0.6, 1.3$ and 2.6 km s^{-1} , but the superprofile for the $\Delta v = 5.2 \text{ km s}^{-1}$ cube shows $> 5 \%$ differences compared to the original. Similar behavior is evident in all the superprofiles generated from cubes binned to $\Delta v = 5.2 \text{ km s}^{-1}$, and

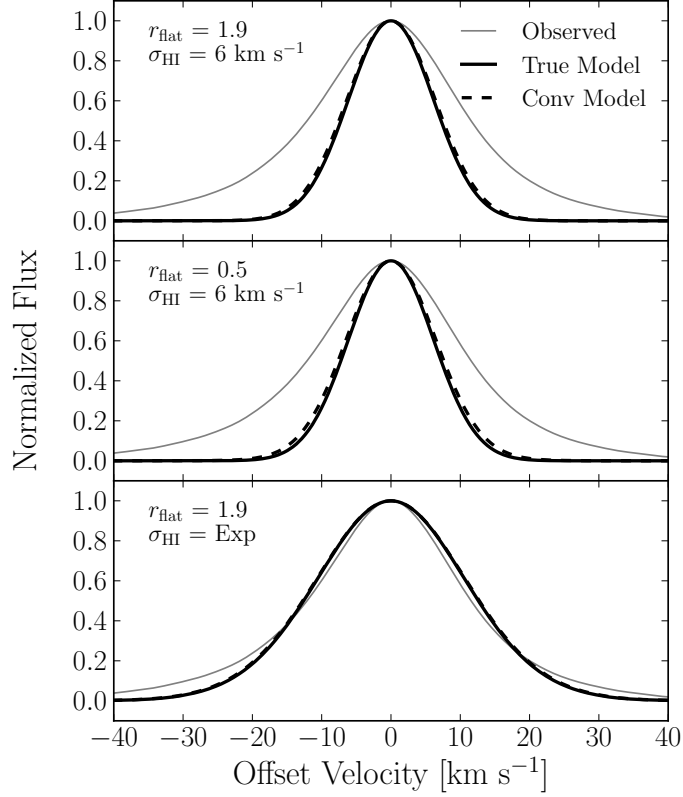


Figure 3.10 The resulting superprofiles for three NGC 2366 models without spatial smoothing applied (thick black line) and smoothed to 200 pc (thick dashed line). The observed superprofile for NGC 2366 is shown in grey. The upper panel is for the model using the observed rotation curve parameters and fixed velocity dispersion. The middle panel shows a rotation curve with a more extreme rise in the center, but the larger amount of beam smearing produces no noticeable effect on the profile. The bottom panel shows a model with velocity dispersion that declines with radius based on the second moment map. In all cases, the effects of beam smearing are not strong enough to produce the wings or to substantially widen the intrinsic superprofile.

thus galaxies whose original data cubes have $\Delta v = 5.2 \text{ km s}^{-1}$ have been excluded from our sample.

We show the resulting parameters as a function of bin size for all galaxies in Figure 3.12. The four panels in the plot are σ_{central} , σ_{wings} , f_{wings} , and a_{wings} . Each color represents a different galaxy. We find that three of our four parameters (σ_{central} , σ_{wings} and f_{wings}) are relatively well-behaved with increasing velocity resolution, showing minor variations relative to the range seen in the sample. However, the standard deviation of variations in a_{wings} is ~ 0.06 ; we account for this variation in the final uncertainties (§3.3.5.5).

In general, larger velocity resolution slightly increases the width of the central component and the velocity of the wings, which then places slightly less flux in the wings. Comparing the same galaxy at 1.3 km s^{-1} to 0.6 km s^{-1} , we find median differences of $\Delta\sigma_{\text{central,vel}} = 0.08$, $\Delta\sigma_{\text{wings,vel}} = 0.13$, and $\Delta f_{\text{wings,vel}} = -0.005$. Comparing between 2.6 and 1.3 km s^{-1} , we find median differences of $\Delta\sigma_{\text{central,vel}} = 0.17$, $\Delta\sigma_{\text{wings,vel}} = 0.32$, and $\Delta f_{\text{wings,vel}} = -0.006$.

3.3.5.4 Noise

The final influence on the measured parameters is the noise of the superprofiles and is especially important for the lowest-mass dwarfs. To quantify the effects of noise on the measured parameters, we start with the noise estimate for each point (Equation 3.8; § 3.3.4). For each sample galaxy, we assume that the measured superprofile is true. We then add noise to each point drawn from a Gaussian distribution with a width σ_{SP} calculated using Equation 3.8. Finally, we measure the parameters from this “noisy” superprofile.

After repeating the above process 10,000 times, we have obtained an estimate of the typical range of parameters allowed by the noise on the superprofiles. For each parameter, we fit a Gaussian to the histogram of “noisy” parameter values and adopt its width as the uncertainty due to superprofile noise on each parameter.

The median uncertainties and interquartile ranges on the parameters due to noise are: $\Delta\sigma_{\text{central,noise}} = 0.05^{0.13}_{0.03} \text{ km s}^{-1}$; $\Delta\sigma_{\text{wings,noise}} = 1.9^{2.5}_{0.8} \text{ km s}^{-1}$; $\Delta f_{\text{wings,noise}} = 0.014^{0.021}_{0.006}$; and $\Delta a_{\text{wings,noise}} = 0.030^{0.051}_{0.009}$.

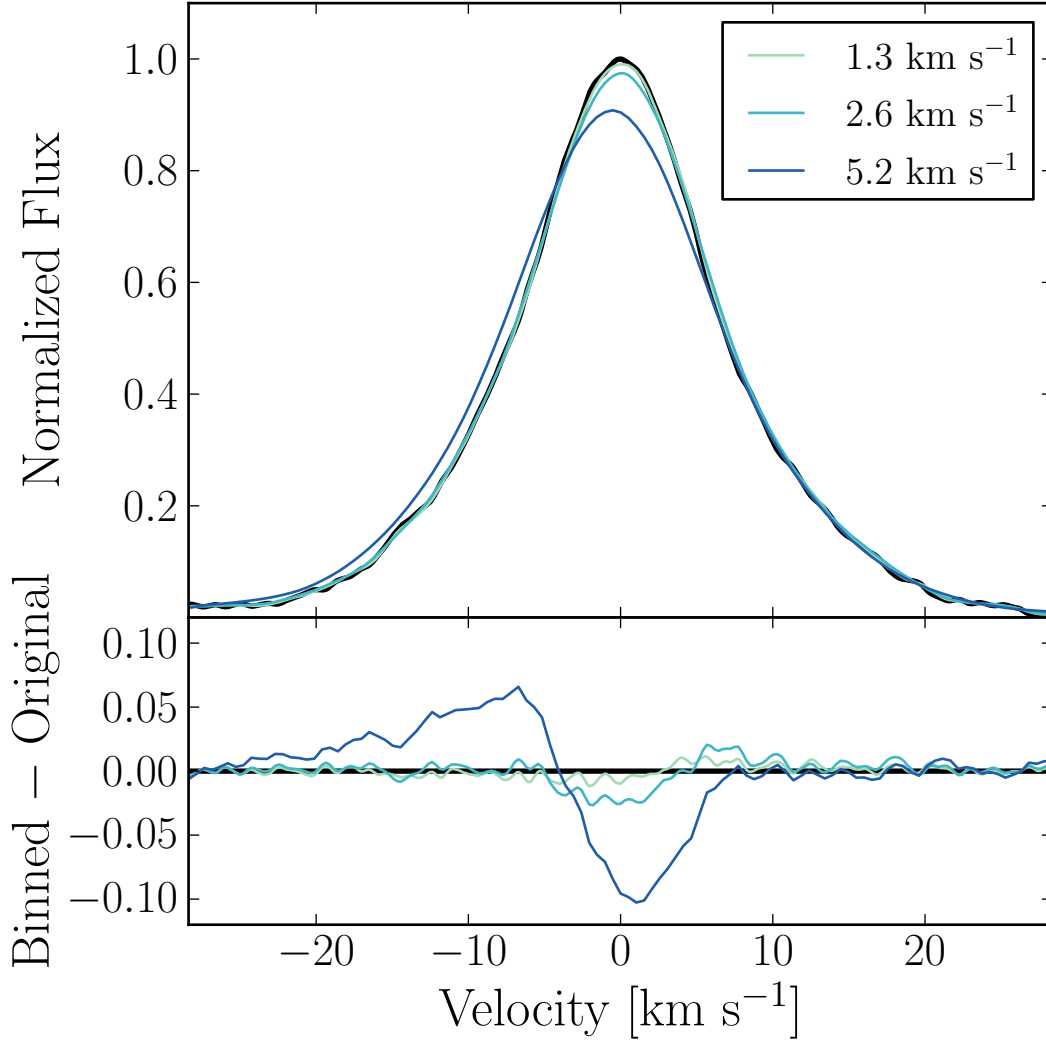


Figure 3.11 Superprofiles generated from binned cubes for DDO 125. The thick black line represents the original superprofile. Colored lines represent superprofiles generated from cubes binned to $\Delta v = 1.3, 2.6$, and 5.2 km s^{-1} . While the differences from the original superprofile are small for the $\Delta v = 1.3$ and 2.6 km s^{-1} observations, the superprofile generated from the $\Delta v = 5.2 \text{ km s}^{-1}$ cube is often different by more than 5% compared to the original. In the $\Delta v = 5.2 \text{ km s}^{-1}$ cubes, the superprofiles are noticeably wider and shorter, thus leading to artificially inflated σ_{central} values and decreased f_{wings} values.

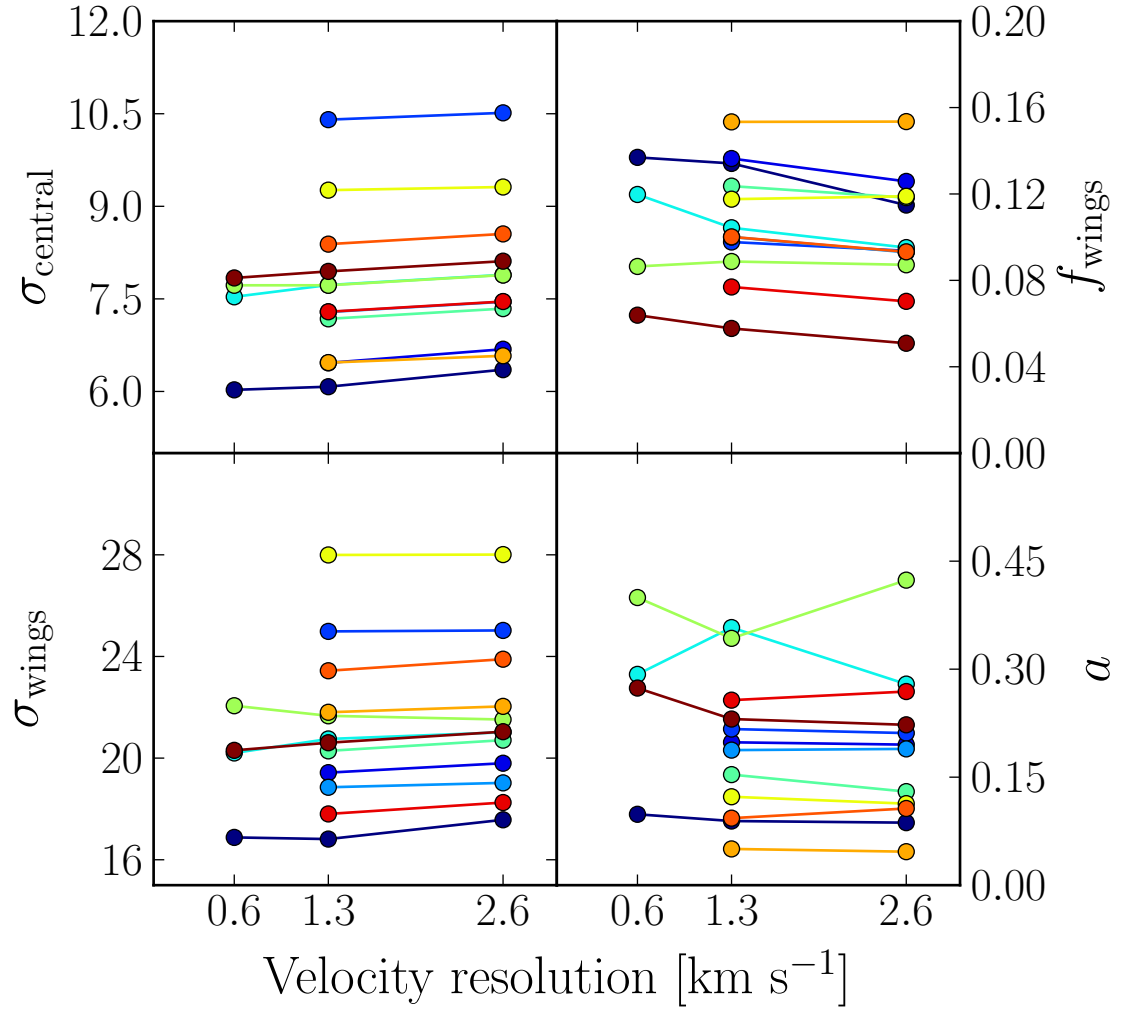


Figure 3.12 The change in each parameter (σ_{central} , σ_{wings} , f_{wings} , and a_{wings}) with increasing velocity resolution. Each colored line represents a single galaxy. The parameters generally show only modest changes with velocity resolution. The most variable is a_{wings} , whose variation has been accounted for in the uncertainties.

3.3.5.5 Overview of Parameter Uncertainties

We use the above tests to estimate the total uncertainty of the measured superprofile parameters. We include only uncertainties that have a non-negligible effect on each parameter in its total uncertainty estimate by adding the uncertainties due to various observational effects in quadrature.

For each galaxy, the final uncertainty for σ_{central} is:

$$\Delta\sigma_{\text{central}} = \sqrt{(0.5 \text{ km s}^{-1})^2 + (0.17 \text{ km s}^{-1})^2 + (\Delta\sigma_{\text{central,noise}})^2}. \quad (3.10)$$

The 0.5 km s^{-1} and 0.17 km s^{-1} errors are due to the effects of finite spatial resolution and finite velocity resolution. The value for $\Delta\sigma_{\text{central,noise}}$ is different for each galaxy. We do not include errors from v_{peak} uncertainties, as they are an order of magnitude lower than the other uncertainties. The $\Delta\sigma_{\text{central}}$ values are dominated by errors due to finite spatial resolution.

The final uncertainty of σ_{wings} is:

$$\Delta\sigma_{\text{wings}} = \sqrt{(0.13 \text{ km s}^{-1})^2 + (\Delta\sigma_{\text{wings,noise}})^2}. \quad (3.11)$$

The 0.13 km s^{-1} error is due to the effects of finite velocity resolution, and $\Delta\sigma_{\text{wings,noise}}$ is different for every galaxy. We do not include errors from v_{peak} uncertainties or finite spatial resolution, as the small amounts of flux they contribute to the wings do not strongly change σ_{wings} values. The $\Delta\sigma_{\text{wings}}$ values are dominated by uncertainties due to noise on the superprofiles.

The final uncertainties for f_{wings} is:

$$\Delta f_{\text{wings}} = \sqrt{(0.01)^2 + (\Delta f_{\text{wings,noise}})^2}. \quad (3.12)$$

The 0.01 uncertainty is due to finite spatial resolution. As before, $\Delta f_{\text{wings,noise}}$ is different for each galaxy. We neglect uncertainties due to finite velocity resolution and v_{peak} uncertainties, as they are over an order of magnitude smaller than the included uncertainties. Both values contribute approximately equally to the final uncertainty Δf_{wings} .

The final uncertainty for a_{wings} is:

$$\Delta a_{\text{wings}} = \sqrt{(0.06)^2 + (\Delta a_{\text{wings,noise}})^2}. \quad (3.13)$$

The 0.06 uncertainty is due to finite velocity resolution, as the peak determination is less precise in cubes that have larger velocity resolutions. We do not include uncertainties from finite spatial resolution in this estimate. The included uncertainties contribute fractionally different amounts in different galaxies, so Δa_{wings} is not typically dominated by either uncertainty.

3.4 Characterizing the Superprofiles

In this section we discuss our analysis of the superprofiles. We first give an overview of their general properties (§ 3.4.1). We then discuss the parameterization chosen to characterize the superprofiles and to quantify the observed asymmetry (§ 3.4.2). We then discuss the physical interpretation of the parameterization (§ 3.4.3) and provide a comparison with other studies of H I kinematics (§ 3.4.4).

3.4.1 Overview of the Final Global Line Profiles

In Figure 3.7a we show the superprofile for each galaxy, overlaid with a Gaussian scaled to the amplitude and to the half-width half-maximum (HWHM) of the superprofiles. We also shade in transparent red the regions in the wings where there is more H I than expected compared to the Gaussian. The superprofiles show similar structures from galaxy to galaxy — namely, a central narrow peak with additional wings to either side.

To compare the overall shape of the superprofiles from galaxy to galaxy, we plot all the superprofiles together in Figure 3.13. We normalize each superprofile so that its maximum flux is 1, and we scale the velocity axis by the HWHM of the superprofile. Regions where the scaled superprofiles overlap are darker. We also overplot a Gaussian with the same scaling, shown as the dashed line. Residuals from the scaled Gaussian are shown in the bottom panel. Because we have plotted each individual line with some transparency, regions where the superprofiles overlap are darker.

The superprofiles in Figure 3.13 exhibit remarkably similar shapes, especially in the central regions. Typically, the profiles are peakier than a Gaussian in the central regions, and show wider wings whose residual amplitude peaks at approximately $2 \times \text{HWHM}$. The

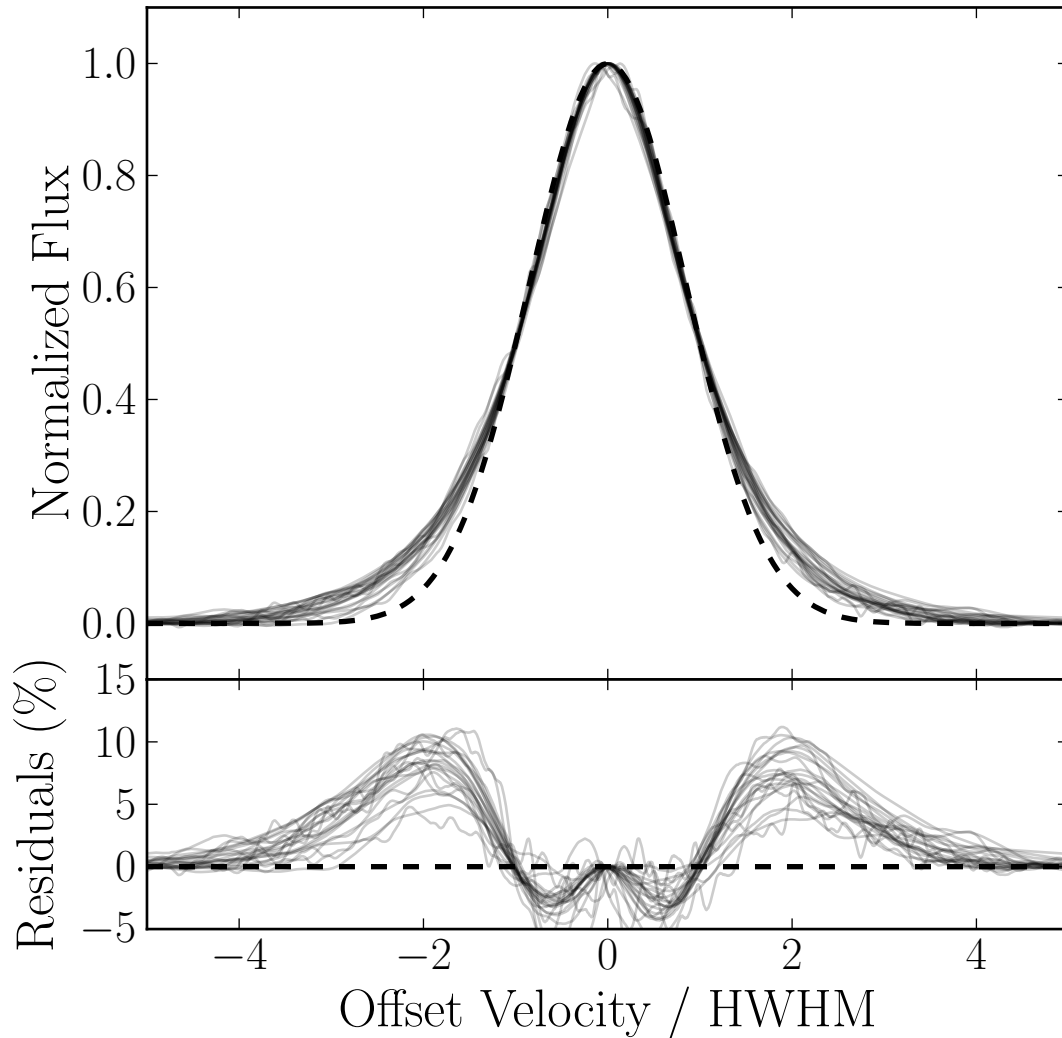


Figure 3.13 Each solid black line is the superprofile for a single galaxy. They have been normalized to their maximum height on the y-axis. The velocity axis has been scaled by the superprofile HWHM value. The superprofile lines have been plotted with transparency; overlap regions are darker. The thick dashed line is a Gaussian with amplitude = 1 and HWHM = 1. The lower panel shows the residuals from the Gaussian overlay. Compared to the Gaussian, the superprofiles are slightly more narrowly-peaked and have more flux in the wings. The superprofiles show a remarkably uniform shape, with the primary variations in the amount of gas moving faster than expected from the Gaussian overlay.

amplitude of the non-Gaussian wings varies from galaxy to galaxy, but the general shape does not change.

3.4.2 Superprofile Decomposition

We first parameterize the superprofiles with a single Gaussian. Although a Gaussian is not the optimal match to the detailed shape of the profile, it is a widely used parameterization and provides an estimate of the average profile width. Because the Gaussian shape is a poor match to the overall profile, especially in the wing regions, we do not perform a traditional χ^2 minimization of the fit, but instead scale the width of the Gaussian to match the HWHM of the superprofile and the amplitude to match the peak of the superprofile. If we had instead fit the superprofile with uniform or noise-based weighting, the width of the Gaussian would increase to compensate for the wings. In contrast, the HWHM scaling provides a simple estimate of the average H I kinematics without relying on fitting details.

The HWHM-scaled Gaussian is shown in Figure 3.7a as a dashed red line overlaid on the superprofile for each galaxy. We measure four parameters using this HWHM-scaled fit.

First, we measure σ_{central} , the width of the central peak scaled to match the HWHM of the superprofile. This parameter characterizes the average H I line width in each galaxy. The use of σ_{central} instead of the HWHM value is chosen to facilitate comparison with other studies, which often describe line widths in terms of a Gaussian σ . We find that the median $\sigma_{\text{central}} = 7.7 \text{ km s}^{-1}$ with interquartile range $7.2 - 8.5 \text{ km s}^{-1}$. These widths typically are $\gtrsim 3$ times larger than the coarsest velocity resolution of the observations.

Next, we measure the fraction of H I in the wings:

$$f_{\text{wings}} = \frac{\sum_{|v| > \text{HWHM}} [S(v) - G(v)]}{\sum_{|v| > 0} S(v)}, \quad (3.14)$$

where v is the offset velocity, $S(v)$ is the superprofile, and $G(v)$ is the single Gaussian scaled to the superprofile HWHM. The f_{wings} parameter measures the fraction of gas moving at velocities faster than expected compared to the bulk of H I. We find median values of $f_{\text{wings}} = 0.11$ with an interquartile range $0.1 - 0.13$. The measured f_{wings} values are quite small, which

indicates that the majority of the H I is contained in the central peak. In Figure 3.7a, the regions of the superprofiles that contribute to f_{wings} are shown as transparent red regions.

Third, we measure the root mean squared velocity of excess flux in the wings, weighted by the fraction of gas moving faster expected based on the HWHM-scaled Gaussian:

$$\sigma_{\text{wings}}^2 = \frac{\sum_{|v| > \text{HWHM}} [S(v) - G(v)] v^2}{\sum_{|v| > \text{HWHM}} S(v) - G(v)}. \quad (3.15)$$

The σ_{wings} parameter measures the excess energy in the wings of the profile per unit H I mass. It is also equal to the characteristic velocity of excess gas. We find median values of $\sigma_{\text{wings}} = 21.8 \text{ km s}^{-1}$ with an interquartile range $20.2 - 25.0 \text{ km s}^{-1}$. These values are typically ~ 8 times the coarsest velocity resolution of our data, and a factor of ~ 2 smaller than the median characteristic inclination-corrected rotational velocity $w_{20}/2$. In Figure 3.7a, σ_{wings} is shown as a solid vertical red line on other side of the superprofile.

Finally, we quantify the asymmetry of the residuals in the wing regions:

$$a_{\text{wings}} = \frac{\sum_{|v| > \text{HWHM}} \sqrt{(S(v) - S(-v))^2}}{\sum_{|v| > \text{HWHM}} S(v) - G(v)}, \quad (3.16)$$

where $S(-v)$ is simply the mirror image of $S(v)$ around the peak. This parameter ranges between 0 in the case of complete symmetry to 1 if all the excess flux was concentrated on one side of the superprofile. We find a median value of $a_{\text{wings}} = 0.22$ with an interquartile range $0.17 - 0.30$.

We have also evaluated the asymmetry of the superprofiles around the peak:

$$a_{\text{global}} = \frac{\sum_v \sqrt{(S(v) - S(-v))^2}}{\sum_v S(v)}. \quad (3.17)$$

To first order, the superprofiles are very symmetric. We find a median global asymmetry of only 0.05 with an interquartile range between $0.03 - 0.08$ for the superprofiles. In all cases, approximately 80% of the asymmetry is from the wings of the profile, while regions

with velocities less than the HWHM are considerably more symmetric. We therefore do not include a_{global} in our parameters as it is less sensitive to asymmetries compared to a_{wings} .

In Table 3.4 we report the measured quantities from our single Gaussian fits. We list (1) the galaxy name; (2) σ_{central} and associated uncertainty of the HWHM Gaussian; (3) σ_{wings} and associated uncertainty; (4) f_{wings} and associated uncertainty; (5) the asymmetry parameter a_{wings} and associated uncertainty; (6) the global asymmetry a_{global} ; and (7) the number of independent resolution elements comprising each superprofile, $N_{\text{beams}} = N_{\text{pix}, S/N>5} / N_{\text{pix/beam}}$. We show the distribution of σ_{central} , σ_{wings} , f_{wings} , and a_{wings} in Figure 3.14.

We discuss the determination of uncertainties on these parameters in § 3.3.5.

3.4.3 Physical Interpretation of the Superprofiles

The parameterization described in § 3.4.2 implicitly assumes that the majority of the H I has a velocity dispersion that is reasonably well-described by σ_{central} . The central peak can then be taken to represent the average kinematics of widespread well-thermalized H I gas across the galaxy. Thermal temperatures implied by the measured σ_{central} values are $\sim 4,000\text{--}12,000$ K, a range that brackets the predicted stable ISM temperature of $T \sim 7000$ K (Wolfire et al., 1995), but with a larger range. Gas in this temperature range can radiate its energy away in $\sim 10^3$ years, a timescale too short to replenish the lost energy from external sources. Therefore, the value of σ_{central} may be better interpreted as random turbulent velocities, which decay more slowly but still require an energy source to maintain over the galaxy lifetime. The deviations from a Gaussian profile can then potentially be explained by the fact that the central peak is likely to be the sum of Gaussians with a range of velocity widths due to the decline of velocity dispersion of warm H I with radius (Tamburro et al., 2009; Warren et al., 2012). Additionally, cold H I with velocity dispersions $< 6 \text{ km s}^{-1}$ has been identified in some of the sample galaxies along individual lines of sight, but it makes up a small fraction of the H I, with typical fractions of only $\lesssim 20\%$ (e.g., Young et al., 2003; Warren et al., 2012). Because cold H I is present along some lines of sight that contribute to the superprofiles, its small velocity dispersion could explain why the observed

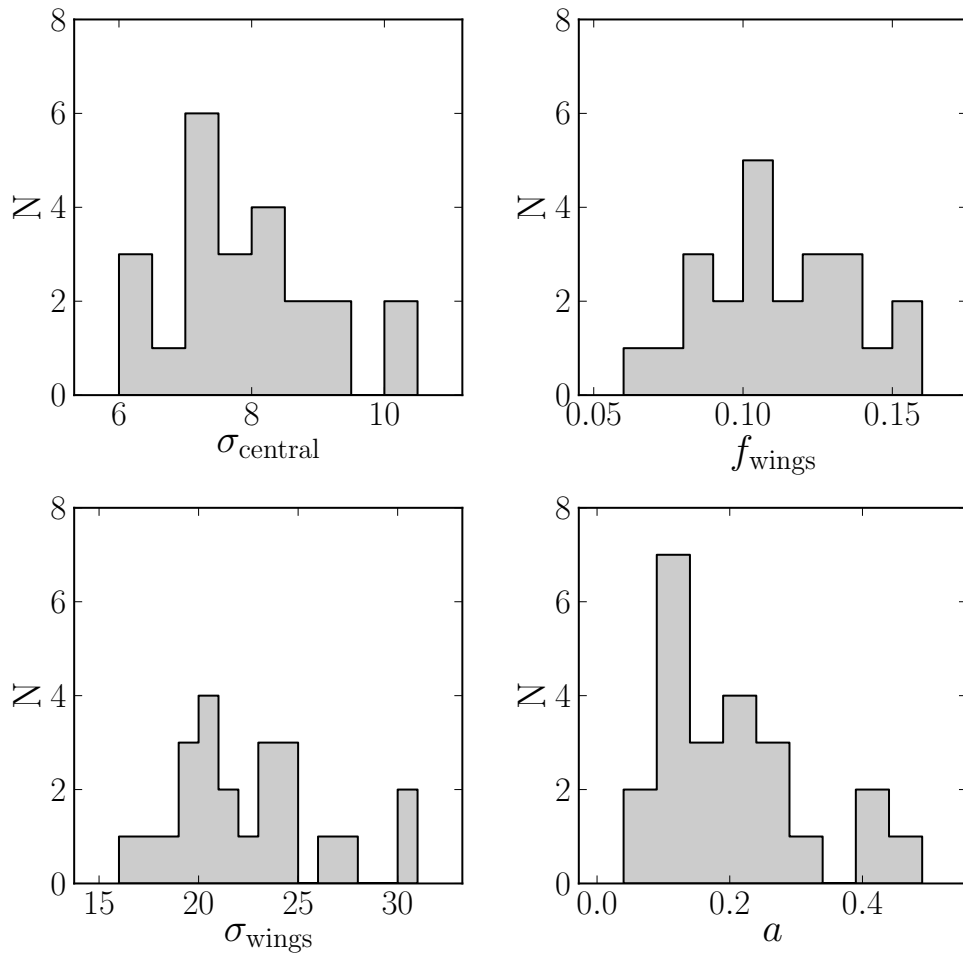


Figure 3.14 The distribution of measured parameters σ_{central} , σ_{wings} , f_{wings} , and a_{wings} in our sample galaxies.

Table 3.4: HWHM-scaled Gaussian parameters for the superprofiles. (1) Galaxy name. (2) Average intensity-weighted global second moment value. (3) Width of central superprofile peak. (4) Characteristic velocity of the wings. (5) Fraction of H I in the wings. (6) Wing asymmetry parameter. (7) Number of independent beams contributing to superprofile.

1	2	3	4	5	6	7
Galaxy	σ_{m2}	σ_{central}	σ_{wings}	f_{wings}	a_{wings}	N_{beams}
	(km s ⁻¹)	(km s ⁻¹)	(km s ⁻¹)			
NGC 7793	11.3	8.1 ± 0.5	26.0 ± 1.4	0.15 ± 0.02	0.04 ± 0.06	909
IC 2574	9.3	7.2 ± 0.5	19.8 ± 1.0	0.12 ± 0.02	0.11 ± 0.06	2443
NGC 4214	9.3	6.5 ± 0.5	21.8 ± 1.2	0.15 ± 0.02	0.05 ± 0.06	1558
Ho II	9.0	7.1 ± 0.5	21.3 ± 1.0	0.12 ± 0.02	0.14 ± 0.06	925
NGC 2366	13.2	10.1 ± 0.5	30.2 ± 0.9	0.13 ± 0.02	0.22 ± 0.06	892
DDO 154	8.6	7.5 ± 0.5	19.8 ± 0.4	0.09 ± 0.02	0.09 ± 0.06	682
Ho I	9.0	6.7 ± 0.5	20.6 ± 2.1	0.15 ± 0.03	0.11 ± 0.06	162
NGC 4190	11.6	9.3 ± 0.6	28.0 ± 7.2	0.12 ± 0.03	0.12 ± 0.07	45
NGC 3741	8.5	7.2 ± 0.5	20.3 ± 3.0	0.12 ± 0.03	0.15 ± 0.07	112
Sextans A	9.5	8.4 ± 0.5	23.4 ± 1.0	0.10 ± 0.02	0.09 ± 0.06	215
DDO 53	10.3	8.2 ± 0.5	23.8 ± 1.6	0.11 ± 0.03	0.18 ± 0.07	93
DDO 190	10.4	8.9 ± 0.5	24.6 ± 3.1	0.09 ± 0.02	0.25 ± 0.08	76
DDO 125	7.0	6.0 ± 0.5	16.9 ± 2.3	0.14 ± 0.03	0.10 ± 0.07	53
Sextans B	7.9	7.3 ± 0.5	17.8 ± 0.7	0.08 ± 0.02	0.26 ± 0.07	259
DDO 99	8.0	7.3 ± 0.5	18.9 ± 1.6	0.10 ± 0.03	0.19 ± 0.08	92
M81 DwB	12.5	9.2 ± 0.6	30.7 ± 5.0	0.11 ± 0.05	0.23 ± 0.08	20
UGCA 292	8.4	7.8 ± 0.5	20.3 ± 4.8	0.06 ± 0.03	0.27 ± 0.10	45
NGC 4163	8.5	7.7 ± 0.6	22.1 ± 3.1	0.09 ± 0.04	0.40 ± 0.12	14
UGC 4483	9.9	8.5 ± 0.6	24.9 ± 2.6	0.10 ± 0.03	0.41 ± 0.11	55
DDO 181	7.8	6.5 ± 0.5	19.4 ± 2.8	0.14 ± 0.04	0.20 ± 0.08	54
UGC 8833	9.6	8.0 ± 0.6	23.2 ± 3.2	0.11 ± 0.03	0.46 ± 0.13	30
DDO 187	11.3	10.4 ± 0.6	25.0 ± 3.3	0.10 ± 0.03	0.22 ± 0.08	23
GR 8	8.0	7.5 ± 0.5	20.2 ± 2.4	0.12 ± 0.04	0.29 ± 0.10	17

superprofiles are peakier than a Gaussian profile.

Gas in the wings of the superprofiles can then be interpreted as localized regions where HI is moving faster than expected compared to the average velocity dispersion. These anomalous motions likely require additional energy input to drive gas from its undisturbed state into the wings of the profile. The superposition of this energetic gas atop the turbulent component of the central peak produces superprofile wings with amplitudes higher than expected from the turbulent component alone.

An alternative physically-motivated decomposition of the superprofiles is to consider them to be the sum of the CNM and WNM, characterized by narrow and broad velocity components. This approach has been recently pursued in a similar study of THINGS galaxies (I2012), motivated by the fact that HI can exist at two stable temperatures and that some individual line-of-sight spectra show evidence of these two phases. In this scenario, the ratio of HI flux in the narrow component to that in the broad component provides a measurement of the relative amounts of cold and warm HI. However, this interpretation also implies that the two Gaussian components are well-thermalized but independent, and that only two distinct warm and cold gas populations exist in a single galaxy. It also presumes that the line widths are directly connected to the thermal temperatures of the gas, which is difficult to reconcile with both the short thermal timescales and the mismatch between the inferred kinetic temperatures and the predicted thermal temperatures of the CNM and WNM. We have found that double Gaussian fits to the superprofiles are indeed a good representation of the overall shape, but we believe that interpreting the Gaussian components as representative of the CNM and WNM is not necessarily convincing for the global profiles, although it can be valid along individual lines of sight. We discuss the reasons we have chosen not to use this method in more detail in § 3.4.3.1.

To facilitate comparison with I2012, however, we have also fit the superprofiles with a double Gaussian using the I2012 methodology. As in I2012, the double Gaussian fits are weighted by the inverse of the approximate uncertainty due to noise on each point. The results of these fits are given in Table 3.5. We list (1) the galaxy name; (2) the width of the narrow component, σ_n ; (3) the width of the broad component, σ_b ; (4) the area of the

narrow component relative to that of the broad component, A_n/A_b ; and (5) the width of the narrow component relative to that of the broad component, σ_n/σ_b .

For the reasons given in § 3.4.2, 3.4.3, 3.4.3.1, we have chosen to parameterize the superprofiles based on the simple HWHM scaling discussed above. We interpret the superprofiles physically as exhibiting a central turbulent peak with more energetic gas in the high-velocity wings to either side.

3.4.3.1 *The Interpretation of Double Gaussian Fits*

In a recent study, I2012 parameterized superprofiles for THINGS galaxies using double Gaussian fits and then argued that the two components were representative of cold and warm HI in the galaxies. We had independently pursued this approach for our study based on the low reduced χ^2 value of double Gaussian fits compared to single Gaussian fits. Unlike I2012, we chose to abandon this parameterization in favor of the simpler HWHM parameterization for reasons described in this section.

We have previously given results for our double Gaussian fits in § 3.4.3 and Table 3.5. However, a number of potential concerns about the physical meaning of the double Gaussian fits arose as we explored them in more detail.

We first refer to the strong similarity in shape seen in Figure 3.13, when all superprofiles are scaled by their HWHM value. We now question whether the same similarity is seen when scaling by width of the narrow or broad Gaussian components, which might be expected if σ_n or σ_b were physically relevant quantities. In Figure 3.15 we again show the scaled superprofiles for all the galaxies, but we now scale the velocity axis by a different measured parameter in each panel: HWHM (upper panel); the width of the narrow component of the double Gaussian fit, σ_n (middle panel); and the width of the broad component of the double Gaussian fit, σ_b (lower panel). The left column shows the superprofiles after normalizing the scaled velocity axes so that the median width of the superprofiles is aligned, to better show the variation in shape. We then plot the median superprofile in red. The right column of Figure 3.15 shows each superprofile minus the median superprofile for that scaling over the same velocity range.

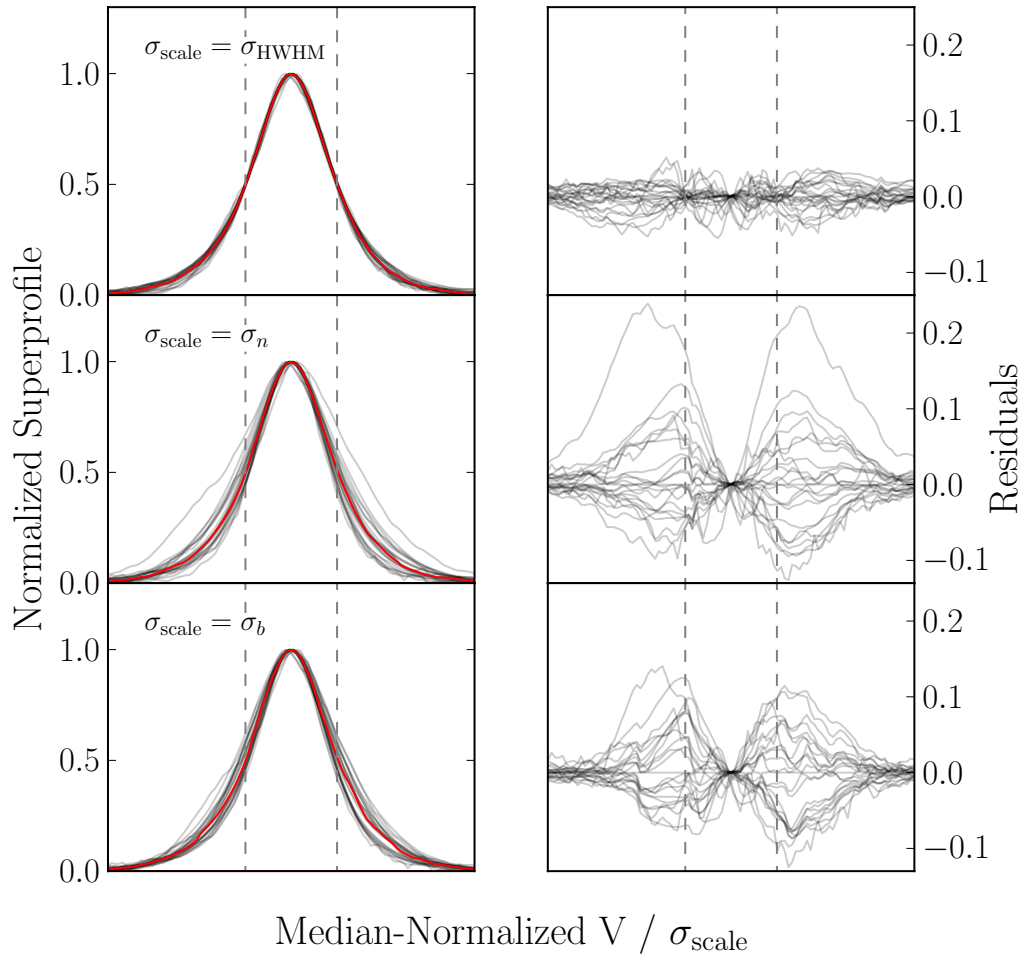


Figure 3.15 Scaled superprofiles for all the galaxies. The top panels scale the velocity axis by σ_{central} , the middle panels by σ_n , and the bottom panel by σ_b . The scaled velocity axes are then normalized such that the median scaled superprofile has the same width in all panels to better show the variation in shape. The median superprofile is shown in red. On the left we show the normalized superprofiles, and on the right we show the differences from the median superprofile. The HWHM scaling provides the best overall description of the shape of the superprofiles.

Table 3.5: Double Gaussian fit parameters for the superprofiles. All uncertainties are calculated from noise uncertainties only. (1) Galaxy name. (2) Width of narrow Gaussian component. (3) Width of wide Gaussian component. (4) Ratio of area of narrow Gaussian component to broad Gaussian component. (5) Ratio of narrow width to broad width.

1	2	3	4	5
Galaxy	σ_n	σ_b	A_n/A_b	σ_n/σ_b
	(km s ⁻¹)	(km s ⁻¹)		
NGC 7793	6.3 ± 0.1	14.7 ± 0.4	0.75 ± 0.02	0.43 ± 0.01
IC 2574	5.3 ± 0.1	11.0 ± 0.2	0.48 ± 0.02	0.48 ± 0.01
NGC 4214	4.5 ± 0.0	10.3 ± 0.2	0.43 ± 0.01	0.43 ± 0.01
Ho II	5.3 ± 0.1	11.4 ± 0.3	0.59 ± 0.04	0.47 ± 0.01
NGC 2366	7.9 ± 0.1	17.1 ± 0.3	0.73 ± 0.02	0.46 ± 0.01
DDO 154	5.4 ± 0.2	10.4 ± 0.4	0.45 ± 0.07	0.52 ± 0.01
Ho I	5.3 ± 0.2	11.6 ± 0.9	0.71 ± 0.10	0.45 ± 0.02
NGC 4190	7.6 ± 0.3	15.8 ± 2.2	0.93 ± 0.17	0.48 ± 0.04
NGC 3741	4.7 ± 0.4	10.5 ± 0.8	0.34 ± 0.09	0.45 ± 0.01
Sextans A	6.2 ± 0.2	12.3 ± 0.4	0.54 ± 0.07	0.51 ± 0.01
DDO 53	6.8 ± 0.1	13.9 ± 1.1	1.01 ± 0.10	0.49 ± 0.03
DDO 190	6.8 ± 0.4	12.4 ± 0.9	0.53 ± 0.19	0.55 ± 0.01
DDO 125	4.2 ± 0.3	9.3 ± 0.9	0.41 ± 0.11	0.45 ± 0.01
Sextans B	4.5 ± 0.1	9.3 ± 0.2	0.22 ± 0.03	0.48 ± 0.01
DDO 99	4.7 ± 0.4	10.1 ± 0.7	0.31 ± 0.08	0.47 ± 0.01
M81 DwB	7.7 ± 0.3	15.3 ± 3.1	1.05 ± 0.06	0.51 ± 0.06
UGCA 292	6.6 ± 0.5	10.8 ± 1.6	0.84 ± 0.69	0.61 ± 0.03
NGC 4163	6.6 ± 0.2	13.3 ± 3.7	1.32 ± 0.01	0.50 ± 0.10
UGC 4483	7.0 ± 0.2	14.0 ± 1.4	0.98 ± 0.12	0.50 ± 0.03
DDO 181	5.0 ± 0.7	10.3 ± 2.0	0.60 ± 0.42	0.48 ± 0.01
UGC 8833	6.7 ± 0.2	13.2 ± 1.5	1.01 ± 0.11	0.50 ± 0.05
DDO 187	5.3 ± 0.3	13.4 ± 0.7	0.15 ± 0.03	0.40 ± 0.01
GR 8	5.3 ± 0.6	11.1 ± 1.6	0.44 ± 0.19	0.48 ± 0.02

The HWHM scaling removes most of the variations in shape among the profiles. In contrast, the specific values of σ_n and σ_b have little direct bearing on the overall profile shape. Quantitatively, the *rms* residuals around the median scaled superprofile are 5 times larger for the superprofiles scaled by either σ_n or σ_b compared to those for the HWHM-scaled superprofile. The HWHM-scaling appears to provide the best characterization of the superprofile shape.

We next ask if the Gaussian components behave similarly when scaled to the superprofile HWHM. Since the HWHM-scaled superprofile shapes are very similar, we would expect the narrow and the broad components of the double Gaussian fits to have similar properties when scaled in the same way. We plot the results of this test in Figure 3.16. The left panel shows the superprofile for each galaxy scaled to its HWHM. We then overplot the two Gaussian components, which have also been scaled to the same HWHM as the corresponding superprofile. The upper panel shows the narrow component, while the lower panel shows the broad component. At first glance, the shapes of the scaled Gaussian components are strikingly different compared to the similarity in the global superprofiles' shapes. In other words, the properties of the two Gaussian components vary wildly, while somehow conspiring to preserve the same overall shape.

The right panel of Figure 3.16 is the same as the left panel, but for clarity only Sextans B and NGC 7793 are shown. Although the upper $\sim 50\%$ of the superprofiles are nearly identical, the best-fit double Gaussians are very different. Since the superprofile for NGC 7793 has broader wings relative to the superprofile HWHM, the broad Gaussian is forced to a larger σ_b value and a smaller amplitude to fit the wings. The narrow component is then left to make up the remainder of the central peak. Because the wings are broad, which leads to a low-amplitude broad Gaussian, the narrower component is forced to a high amplitude to match the center of the profile. In contrast, the superprofile for Sextans B has lower level wings. The broad Gaussian component therefore has a higher amplitude, leaving less of the central peak for the narrow component. This behavior indicates that the relative amplitude and fractional area of the broad component are strongly driven by the shape of the wings. Even though the wings of NGC 7793 have only $\sim 9\%$ more flux than those of Sextans B, the relative amplitudes of the broad components differ by nearly a factor of two, and the

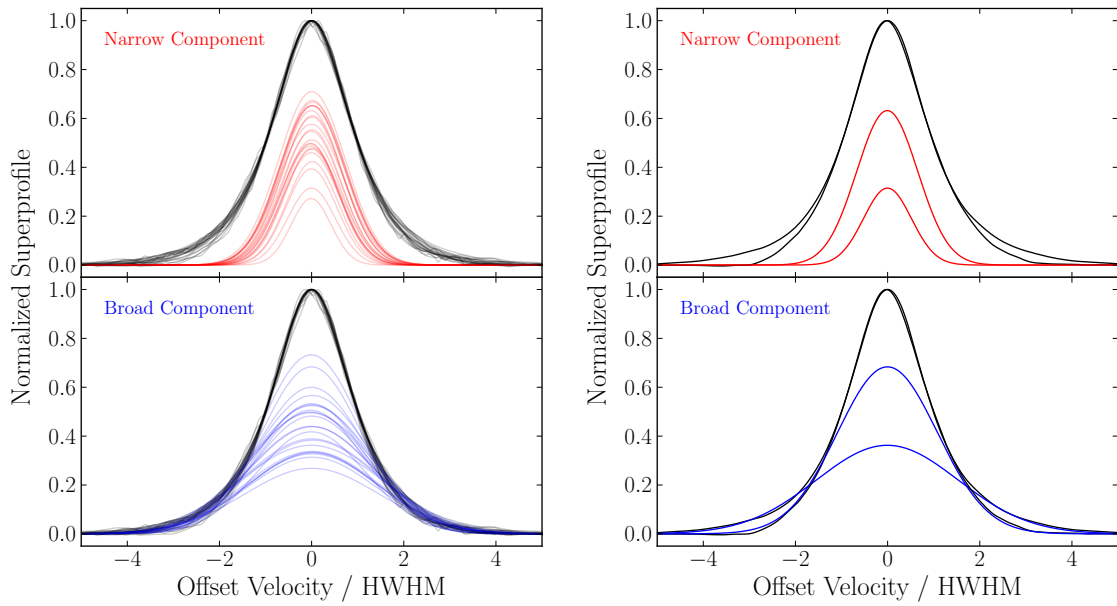


Figure 3.16 Double Gaussian fit shapes compared to the overall superprofile shapes. The black lines are the full superprofile, while the red and blue lines represent that narrow and broad Gaussian components of a double Gaussian fit. Both the superprofiles and Gaussian components have been scaled to the HWHM of that specific superprofile. The left panel shows the full sample, while the right panel highlights NGC 7793 and Sextans B to show the drastic difference in Gaussian components for superprofiles whose wing fluxes differ by only 9% when scaled to the same HWHM. This small change drives large differences in the best-fit double Gaussian components.

fractional areas of the broad components differ by more than a factor of three. The large differences in double Gaussian parameters for superprofiles with remarkably similar shapes is the first indication that the double Gaussian fits may not be tracing physically-meaningful properties.

We see further evidence for this behavior when we quantitatively explore the correlations among the double Gaussian parameters. To provide a relative comparison, we have generated superprofiles for galaxies in I2012 following their methodology for their well-behaved “clean” subsample. In particular, we have used the natural weighted cubes at their instrumental resolution and included all pixels with $S/N > 3$. We do not apply any masking. We can then calculate the HWHM of each superprofile.

Based on Figure 3.16, we have speculated that the relative strength of the narrow and broad components are being set primarily by the relative velocity of the wings compared to the central profile (i.e., σ_b/HWHM). We explore this idea in Figure 3.17, where we plot the amplitude ratio between the narrow and broad Gaussian components versus σ_b/HWHM . The left panel of the plot shows the galaxies in our sample, using the double Gaussian fits to the superprofiles discussed in this paper (Table 3.5). The right panel shows the equivalent data for the clean subsample of I2012. For this comparison, we calculate the Narrow / Broad amplitude ratio, based on the formula for the area under a Gaussian, as follows:

$$\text{Narrow / Broad Amplitude} = \frac{A_n \sigma_b}{A_b \sigma_n}, \quad (3.18)$$

where A_n/A_b is the ratio of the areas under the narrow and broad components, and σ_n and σ_b are the widths of the narrow and broad Gaussian components. All numbers are taken directly from I2012. In this case, we have taken σ_b directly from I2012 and calculated the HWHM from our I2012-like superprofiles.

It is immediately clear that profiles with broader wings relative to their characteristic HWHM width have narrow components with much higher amplitude ratios compared to the broad component. This correlation is a quantitative representation of the behavior shown in Figure 3.16; the broad Gaussian component primarily fits the wings, leaving the narrow Gaussian to fit the remainder of the superprofile as best it can. This behavior is exacerbated by the $1/\sqrt{N}$ weighting scheme. Because this scheme gives pixels with fewer contributing

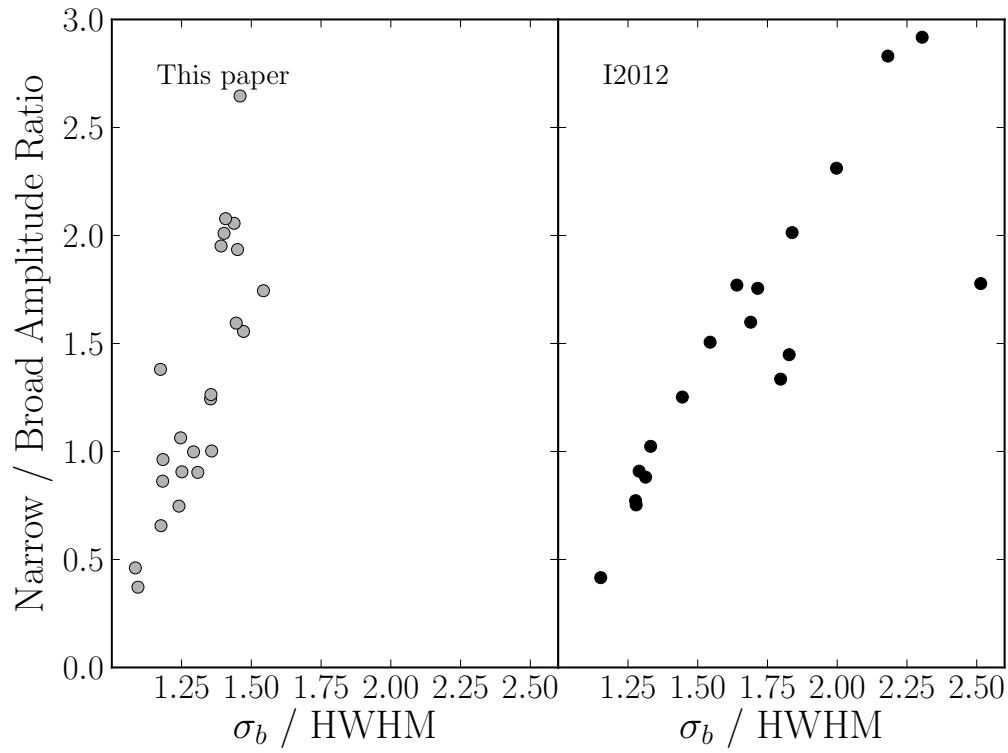


Figure 3.17 The relationship between Narrow / Broad Amplitude of double Gaussian fits compared to the width of the wings relative to the characteristic superprofile width measured by the HWHM. The grey points in the left panel are galaxies from our sample, while those in right panel (black) are taken from I2012. In both cases, there is a clear trend that galaxies with broader wings have relatively lower broad amplitudes.

points more weight, the superprofile wings, which are produced by only a small fraction of the H I, are weighted most strongly. Since the relative broadness of the wings strongly affects the relative amplitudes of the two Gaussians, it is unclear if the two components are tracing the same type of gas in superprofiles with varying levels of wing importance.

We can also look at the ratio of narrow to broad component areas compared to the fraction of gas in the wings of the profile (f_{wings}) as measured in § 3.4.2. In Figure 3.18 we plot A_n/A_b versus f_{wings} . Again, the left panel shows data from our sample, while the right panel shows that from I2012. For the latter, we have taken A_n/A_b directly from I2012, and we have used our I2012-like superprofiles to measure f_{wings} with the caveat that we have not brought the I2012 sample to a common physical resolution. If the broad Gaussian fit were indeed tracing a warm component, then on average we would expect galaxies with more flux in the wings to have a higher fraction of gas in the broad component, leading to lower A_n/A_b values. For the I2012 numbers, we find an unexpected positive correlation, where galaxies with *more* flux in the wings, as measured with f_{wings} , have a higher A_n/A_b values and therefore a *higher* fraction of gas in the narrow component. We do not see a similar trend in our data, but it is possibly due to the fact that we are measuring smaller galaxies with lower overall S/N ratios, higher asymmetries, and a smaller range in f_{wings} .

These two figures call the physical interpretation of the double Gaussian fits into question. It is unclear if the parameters are measuring physical quantities in the galaxies, or if they simply reflect the strength of the wings. The correlations between physical properties and both σ_n/σ_b and A_n/A_b found by I2012 were attributed to star formation, which could be responsible for driving gas into the wings of the profile. We have discussed a similar idea in this paper using a different superprofile parameterization. Surprisingly, though, A_n/A_b and σ_n/σ_b show, if anything, only weak trends with the direct measure of star formation represented by H α luminosities. Additionally, since the wings of the profile appear to set the relationship between a number of the other measured parameters, it not clear if the narrow component is truly tracing cold H I or if it is just another reflection of the superprofile wings.

We can also turn to constraints provided by previous studies of individual H I line-of-sight spectra. Many previous studies of spatially-resolved H I line profiles in external galaxies have found that the line-of-sight profiles are often well-fit by single Gaussians, with only

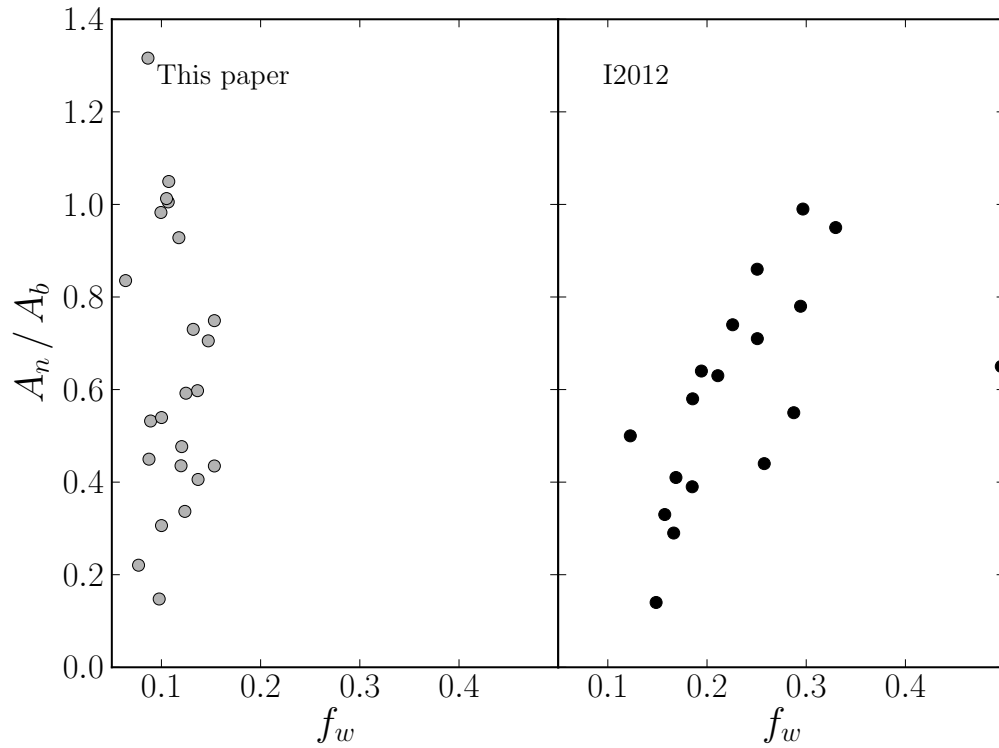


Figure 3.18 The relationship between A_n/A_b compared to the fraction of gas in the wings, f_{wings} . For galaxies in the I2012 sample, we find that galaxies with more gas in the wings have higher fraction of gas in the narrow component. If the A_n/A_b parameter were tracing the ratio between the mass of CNM to WNM, we would on average expect galaxies with more flux in the wings of the profile to have a more HI in the WNM, and therefore smaller A_n/A_b ratios. This expectation is the opposite of how the A_n/A_b parameter behaves. It is instead likely that A_n/A_b , like the amplitudes of the double Gaussian components, is driven by the relative broadness of the wings.

$\lesssim 20\%$ of profiles exhibiting non-Gaussian structures such as broad wings or asymmetries (e.g., Young et al., 2003; Warren et al., 2012). The narrow and broad Gaussians fit to these small number of line profiles are often interpreted as the emission from CNM and WNM. However, it is unclear if this interpretation extends to the statistical measurement of H I line shapes measured by the superprofiles, since information from each individual line profile is no longer distinct. For example, the asymmetric line profiles, when added together into a superprofile, can combine to form broader wings than what would be measured on a spatially-resolved basis. The spatially-resolved studies of H I line profiles have estimated the fraction of H I mass in the cold component to be only $\sim 20\%$ of the total H I mass, which implies A_n/A_b values of $\sim 25\%$ – much less than those measured by double Gaussian fits.

As an additional test of the interpretation of the Gaussian fit parameters, we can compare their values to limits placed on cold H I fractions based on double Gaussian fitting to individual line-of-sight profiles. Warren et al. (2012) estimated the *spatially-resolved* minimum and maximum fraction of cold H I, $\mathcal{F}_{cold}$, characterized by individual line of sight profiles that are best fit by a double Gaussian whose narrow component width is $\sigma < 6$ km s $^{-1}$, in a number of our sample galaxies. In Figure 3.19 we plot the limits on A_n/A_b from Warren et al. (2012) versus A_n/A_b values measured from double Gaussian fits to the global superprofile. Each box represents a single galaxy. The position and width of the box on the x -axis is determined by the A_n/A_b value and associated error from double Gaussian fits. The size of the box on the y -axis is determined by the allowed range of $A_n/A_b = \mathcal{F}_{cold}/(1 - \mathcal{F}_{cold})$ values for that galaxy as given by Warren et al. (2012). Grey boxes represent measurements from galaxies presented in this paper, while red boxes are those from I2012. For simplicity, we have assumed that our A_n/A_b uncertainty is 0.05.

The dashed line in Figure 3.19 is a line of equality, where the independent limits on A_n/A_b match double Gaussian A_n/A_b values. That is, the boxes would roughly lie along the dashed line if double Gaussian A_n/A_b values matched the independent limits. However, this behavior is not seen. Instead, the independent limits on A_n/A_b tend to be smaller than those measured by double Gaussian fits. While we might expect the independent limits on A_n/A_b to be smaller than the double Gaussian A_n/A_b values because the superprofiles are a higher S/N representation of H I spectra, we would at least expect to see the a positive

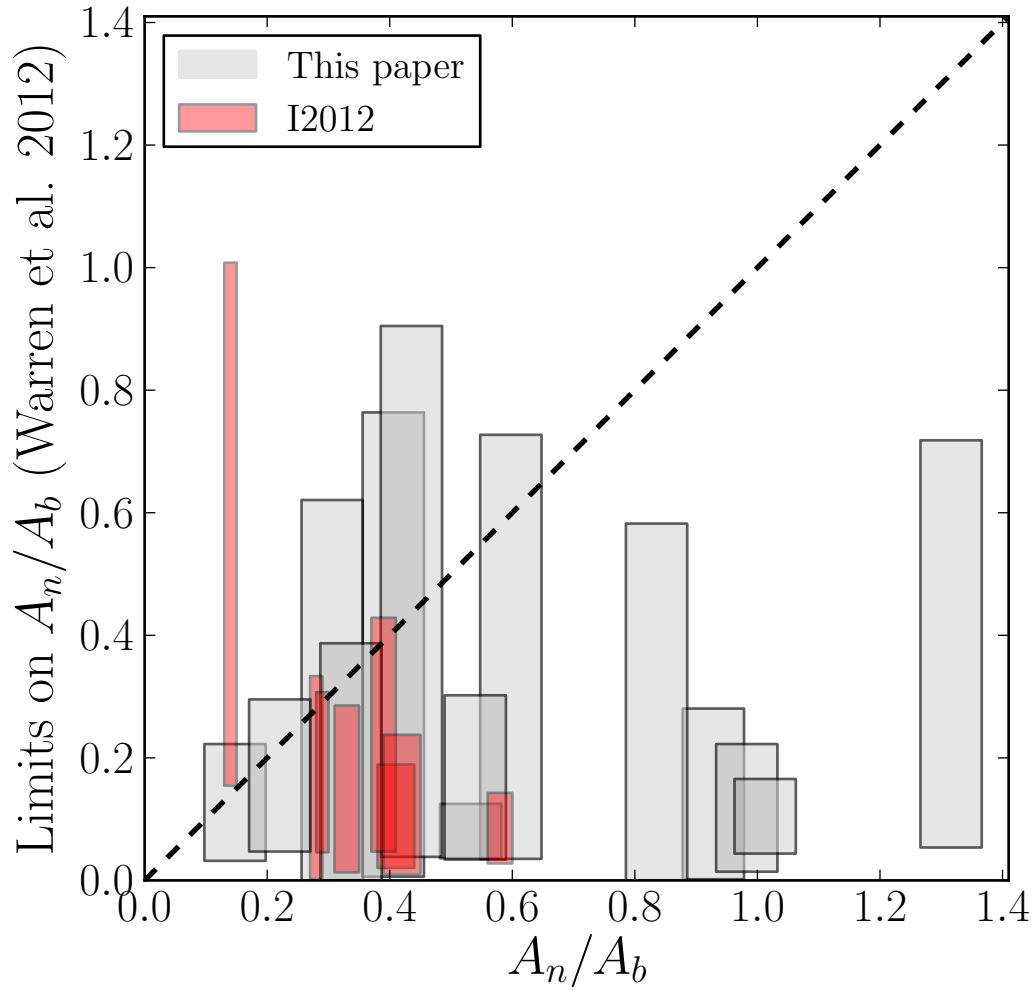


Figure 3.19 A comparison between A_n/A_b values from double Gaussian fits and independent limits on A_n/A_b from Warren et al. (2012). Each box represents an individual galaxy. The x -position and width are determined by double Gaussian A_n/A_b values and associated errors. The top and bottom of each box is the limit placed on A_n/A_b by Warren et al. (2012). The line of equality is shown as a thick dashed line. The A_n/A_b values measured by double Gaussian fits do not match the limits placed by Warren et al. (2012).

correlation between independent limits and double Gaussian A_n/A_b values. However, the data, especially the red boxes, show, if anything, a negative correlation. The fact that double Gaussian A_n/A_b values do not match independent limits indicates that the cold and warm H I interpretation may not be valid.

Finally, we can examine limits on the H I velocity dispersions from observational studies. Petric & Rupen (2007) found that double Gaussian fits to median H I profile shapes at different radii exhibited the same ratio of narrow to broad components. This finding complicates the CNM/WNM interpretation, as H I in the outskirts of disks would not be expected to have the same fraction of gas in the warm component as regions inside r_{25} . Second, the CNM/WNM interpretation of A_n/A_b values implicitly assumes that there are two well-thermalized H I components in the ISM. If this were the case, we might expect to see two characteristic velocity dispersions in the statistical ensemble of individual H I spectra widths. Braun et al. (2009) measured the non-thermal velocity dispersion of H I in M31 and found no evidence of a bimodal distribution. Instead, they find a range of non-thermal velocity dispersions between $3-25 \text{ km s}^{-1}$, with most line-of-sight profiles exhibiting widths $\sim 8 \text{ km s}^{-1}$. Based on this evidence, it therefore is more physically meaningful to interpret the central peak of the superprofiles, which show similar velocity dispersions of $\sim 8 \text{ km s}^{-1}$, as turbulence in the ISM instead of as the composite of emission from distinct cold and warm H I components. However, this last constraint may not apply if the CNM and WNM components of the ISM are well-mixed on scales smaller than the spatial resolution of the observations.

With the strength of the evidence presented above, we have chosen to parameterize the superprofiles as composed primarily of a central turbulent peak with wings to either side, instead of as two Gaussian components. The parameters of double Gaussians, when interpreted as representative of the CNM and WNM, do not behave as expected when exploring the superprofiles in more detail, as the fit is dominated by the small amount of H I in the wings. Additionally, evidence from other studies does not support the cold and warm gas interpretation of the double Gaussian fits. Previously-derived limits on A_n/A_b do not match A_n/A_b values from the CNM/WNM interpretation of double Gaussian fits, and there is no evidence for a bimodal temperature distribution in individual H I line of sight spectra

even though such an interpretation is relevant in localized regions. We therefore believe the superprofiles are better interpreted not as two Gaussian components representing the CNM and WNM, but instead as a central turbulent peak with wings generated by kinematically disturbed gas.

3.4.4 *Comparison with Other Studies*

The H I velocity dispersion and associated energy have traditionally been estimated either by fitting single Gaussian profiles to line-of-sight spectra (e.g., Petric & Rupen, 2007) or by using the second moment map (e.g., Tamburro et al., 2009). Since our method is an uncommonly-used estimate of H I turbulent velocity, we provide comparisons between our work and previous studies from Petric & Rupen (2007) and Tamburro et al. (2009).

Petric & Rupen (2007) determined σ_{HI} by fitting single Gaussians to each line-of-sight spectrum in the face-on spiral NGC 1058 at a spatial resolution of ~ 1.3 kpc, much larger than the 200 pc scales studied in this paper. The typical range of velocity dispersion in the disk was 4 - 14 km s $^{-1}$, with a majority at ~ 7 km s $^{-1}$. They also found that the median profile shape, after normalization for line-of-sight profile width, was similar to the shape observed in our superprofiles, characterized by a central narrow peak with wider wings. Many other studies have found similar shapes for the average H I line profile (e.g., Dickey et al., 1990; Boulanger & Viallefond, 1992; Kamphuis & Sancisi, 1993), but quantitative comparisons with these studies are hampered by large differences in velocity resolution or physical resolution.

Tamburro et al. (2009) used the second moment as a proxy for H I velocity dispersion. They found that galaxies have turbulent components with amplitudes of ~ 10 km s $^{-1}$. When we compare the four galaxies that overlap both samples (Ho II, NGC 4214, IC 2574, NGC 7793), we measure consistently lower σ_{central} values than the global second moment by ~ 2 km s $^{-1}$. We do not believe that the difference results from the fact that the Tamburro et al. (2009) sample focused mainly on large spirals compared to the low-mass dwarfs that dominate our sample, as all galaxies in our sample have σ_{central} values that are smaller than their global second moments. The difference is more likely due to the fact that we have

isolated the central peak in our sample, while the second moment values are affected by the presence of high velocity wings and asymmetries in the line profiles.

In Figure 3.20 we show a comparison between our measured σ_{central} value and $\langle\sigma_{\text{m}_2}\rangle$ (Equation 3.6), which provides an estimate of the turbulent width that would have been derived using the Tamburro et al. (2009) methodology. Compared to σ_{central} , in all cases the global second moment is larger by $\sim 10\text{--}50\%$, with a median of 20%. When interpreting the line widths physically, this offset suggests that the second moment leads to higher estimates of the energy necessary to drive H I turbulence.

We can also compare our results to those of I2012, who have performed the most directly analogous analysis to date. In this study, the authors generated superprofiles for a number of THINGS galaxies, eight of which overlap with our sample. However, their approach was somewhat different. The authors used the naturally-weighted standard maps and worked at the instrumental resolution. They also chose to model each superprofile as the sum of a narrow and a wide Gaussian profile representing the CNM and the WNM.

The first difference to note is that our sample is smoothed to a fixed physical resolution, as opposed to working at the instrumental resolution of $\sim 10''$ for each galaxy. While smoothing to a coarser resolution can broaden the intrinsic superprofile because the measured velocity dispersion increases at larger physical scales, matched-resolution cubes allow a more robust comparison from galaxy to galaxy by sampling the H I kinematics on the same physical scale. Since the more massive THINGS galaxies tend to be at larger distances, the varying spatial resolution could lead to spurious trends with any quantity that correlates with galaxy mass.

The superprofiles that we derive are systematically different from I2012 even if we fit them with the double Gaussian function. For the nine THINGS galaxies in common (DDO 53, DDO 154, Ho I, Ho II, IC 2574, M81 DwB, NGC 2366, NGC 4214, NGC 7793), we typically measure similar σ_n values, but find systematically smaller values of σ_b by $0.5\text{--}3\text{ km s}^{-1}$. This offset is also apparent in the σ_n/σ_b ratio; we find an average $\sigma_n/\sigma_b = 0.46$, nearly 25% higher than measured by I2012.

We believe that this difference could result from generating our superprofiles from the flux-rescaled cubes instead of the standard cubes; from using robust-weighted cubes instead

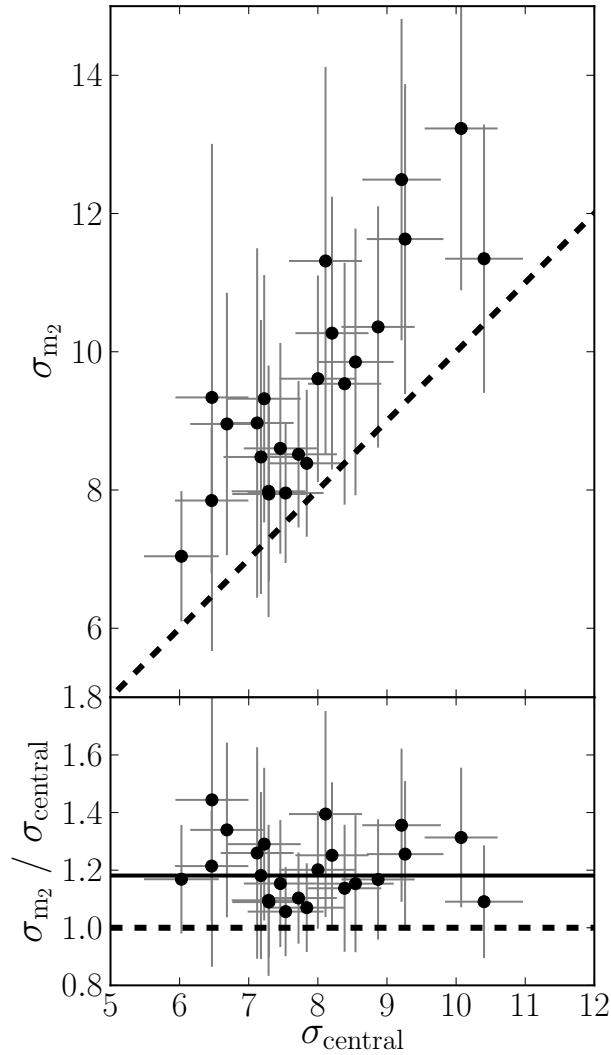


Figure 3.20 A comparison of the global second moment versus the dispersion measured by the superprofile HWHM-scaled Gaussian. The dashed line shows where the $\sigma_{m_2} = \sigma_{\text{central}}$. The error bars on the x-axis are the approximate uncertainties on σ_{central} , while those on y-axis represent the weighted standard deviation of second moment values in the pixels considered. The solid black line at $\sigma_{m_2}/\sigma_{\text{central}} \sim 1.2$ on the lower panel indicates the median ratio between σ_{m_2} and σ_{central} . The second moment overestimates the width by $\sim 10 - 50\%$.

of natural-weighted cubes; or from choosing different S/N thresholds.

First, the use of flux-rescaled cubes likely lowers the amount of flux in the wings of the profile. While the central peak of the superprofile is due to the regions of the line-of-sight spectra that are the brightest, the wings arise from low-level flux to either side of the peak. When we consider an individual line-of-sight H I spectrum, the peak of the spectrum has a higher fraction of flux in the clean components than in the residuals when compared to the lower-level emission to either side of the peak. Because the flux-rescaling correction effectively lowers the amount of flux in the residuals, the low-level emission on either side of the peak in each line-of-sight spectrum is rescaled to a relatively smaller value compared to the peak regions. The flux-rescaling correction therefore has the effect of narrowing line-of-sight profiles, which then produces a narrower central peak in the superprofiles and less flux in the wings compared to superprofiles generated from the standard (non-rescaled) data cube. With smaller wing amplitudes, the broad Gaussian component σ_b , is smaller, which could then make the σ_n/σ_b ratio larger.

Second, the synthesized beam of natural-weighted data cubes, which were used by I2012, exhibits a positive pedestal that extends to large radii which is not present in the robust-weighted data cubes that we have used to generate the superprofiles. Because of the broad pedestals in the synthesized, naturally-weighted beams, each apparently independent beam, as judged by its FWHM, actually includes flux from a much greater area. These pedestals can therefore lead to additional velocity smearing, beyond what one would expect based on the velocity field of the galaxy and the angular size of the beam. The neighboring pixels that are included at low-level, however, have offset velocities due to the overall rotation of the galaxy. Therefore, each line-of-sight spectrum also includes flux from neighboring pixels at offset velocities. This additional flux at offset velocities may translate to more flux in the wings of the superprofile, and therefore larger measured values of σ_b and smaller σ_n/σ_b ratios when compared to the robust-weighted cubes that lack these positive pedestals.

Finally, the signal-to-noise threshold was different between the two studies. At lower S/N values, determination of the peak is more difficult (see Figure 3.6). Because the determination of v_{peak} is worse for low S/N spectra, additional flux could be incorrectly added into the wings of the superprofile due to these offset v_{peak} values. This addition of

flux into the wings would likely widen the σ_b measurement and lower the σ_n / σ_b value.

3.5 Comparison with Physical Properties

In this section we examine how global physical properties of the galaxies correlate with the properties of the global H I superprofiles, as characterized by σ_{central} , σ_{wings} , f_{wings} , and a_{wings} (§ 3.4.2).

For all tests, we characterize the strength of the correlation compared to a random sample using the Spearman rank correlation coefficient. This method makes no assumptions about the functional relationship between the two input data sets, and instead tests only for a monotonic relationship between the two variables. The Spearman correlation coefficient r_s varies between -1 (monotonically decreasing) and 1 (monotonically increasing) with 0 implying no relationship. The significance of the observed value of r_s is given by p_s , where $p_s \leq 0.01$ means that random uncorrelated data produce a r_s value at least as extreme as measured $\leq 1\%$ of the time. We adopt this threshold to indicate a statistically significant relationship between two quantities.

For all following comparisons, we list r_s and p_s in Table 3.6. The coefficients for significant correlations ($p_s \leq 0.01$) are shown in bold.

Throughout this section we also present a number of figures showing the behavior of the superprofiles with a different physical property, starting with Figure 3.21. The four upper panels show σ_{central} , σ_{wings} , f_{wings} , and a_{wings} . Colors are determined by the physical property itself, with red indicating a low value and blue indicating a high value. In the lower panel, we show the scaled superprofile residuals from the HWHM Gaussian fit, as previously seen in the lower panel of Figure 3.13. In this case, though, we have added color to each line to highlight how the superprofile shape changes with that physical property. The colors of each line are the same as the corresponding point in the upper panels, though the lines have a transparency value so that overlapping regions are clearer. To better highlight any asymmetry of the superprofiles, we have reversed the velocity axis if necessary such that the wing peak with the higher area is on the left. We now discuss these figures for correlations with the physical properties calculated in § 3.2.3. We also remind the reader that many of these properties are physically connected with each other, as shown in Figure 3.1, so a

Table 3.6: Spearman correlation coefficient r_s and probability p_s between superprofile parameters and physical properties. Significant correlations (i.e., $p_s \leq 0.01$) are shown in bold.

Property	σ_{central}		σ_{wings}		f_{wings}		a_{wings}	
	r_s	p_s	r_s	p_s	r_s	p_s	r_s	p_s
w_{20}	0.079	0.720	0.261	0.229	0.262	0.227	-0.459	0.027
$M_{\text{baryon,tot}}$	-0.189	0.388	0.083	0.707	0.491	0.017	-0.769	<0.001
$M_{\star}$	-0.150	0.494	0.085	0.700	0.414	0.050	-0.655	<0.001
M_{HI}	-0.152	0.488	0.047	0.830	0.377	0.076	-0.643	<0.001
SFR	-0.071	0.747	0.221	0.310	0.486	0.019	-0.721	<0.001
SFR / M_{HI}	0.066	0.764	0.390	0.066	0.529	0.010	-0.179	0.414
$\langle \Sigma_{\text{SFR}} \rangle$	0.297	0.168	0.626	0.001	0.314	0.144	0.000	1.000
$\langle \Sigma_{\text{HI}} \rangle$	0.536	0.008	0.707	<0.001	-0.053	0.809	0.200	0.361
$\langle \Sigma_{\text{baryon}} \rangle$	0.336	0.117	0.623	0.002	0.123	0.578	0.115	0.603
i	-0.218	0.318	-0.311	0.149	0.122	0.579	-0.278	0.199

correlation with one property could be causally due to another.

3.5.1 Correlations with Galaxy Mass and Related Quantities

We start by examining trends in the superprofile parameters versus quantities that correlate with galaxy mass. While we would not expect the local HI conditions to know much about the overall galaxy potential, galaxy mass is correlated with a host of other properties that are more likely to have direct effects on the HI, such as SFR or M_{HI} .

3.5.1.1 Halo Mass

As a proxy for galaxy halo mass, we use $M_{\text{baryon,tot}}$ (§ 3.2.3.2). In Figure 3.21 we plot the correlations between galaxy mass and the parameters σ_{central} , σ_{wings} , f_{wings} , and a_{wings} derived from the superprofiles. Neither σ_{central} nor σ_{wings} shows any significant trend with

galaxy mass. This lack of correlation confirms our expectation that the driver of H I kinematics is not strongly mass-dependent; that is, it is more likely to be dependent on specific phenomena in the ISM.

However, Figure 3.21 does show a strong correlation between galaxy mass and the asymmetry a_{wings} , with more massive galaxies exhibiting less asymmetry. The asymmetry can be seen in the residuals; the red lines of low-mass galaxies show a large variation between one side of the residuals and the other, while the blue lines of higher-mass galaxies have more symmetric structure in the residuals. However, it is likely that this trend reflects of galaxy properties such as SFR that correlate with mass, instead of mass itself. Asymmetries in the line-of-sight spectra induced by star formation may propagate to asymmetries in the superprofiles, as discussed further in § 3.6.2.3, but are averaged out when more star forming regions are present.

We also find a trend between galaxy mass and f_{wings} . The p_s value is 0.017, only slightly above our cutoff for a significant correlation. There is a tentative indication that lower mass galaxies with $M_{\text{baryon,tot}} \lesssim 5 \times 10^8 M_{\odot}$ tend to have a larger scatter in f_{wings} . Galaxies with larger $M_{\text{baryon,tot}}$ exhibit higher f_{wings} values with less scatter, showing half the standard deviation relative to the median compared with their lower mass counterparts. If this trend holds true with a larger sample, it would be consistent with higher mass galaxies being able to more consistently drive H I into the wings of the superprofile. The presence of high velocity gas in lower mass galaxies could be due to more stochastic processes, with not every galaxy being able to launch high velocity gas at all times, thus leading to more scatter in f_{wings} .

We have also looked for correlations with other mass tracers, such as M_{HI} , M_{star} , and w_{20} . While the exact values of r_s and p_s change, we find similar trends between superprofile properties and other mass tracers. Such behavior is expected based on the strong correlations between $M_{\text{baryon,tot}}$ and other mass tracers shown in Figure 3.1.

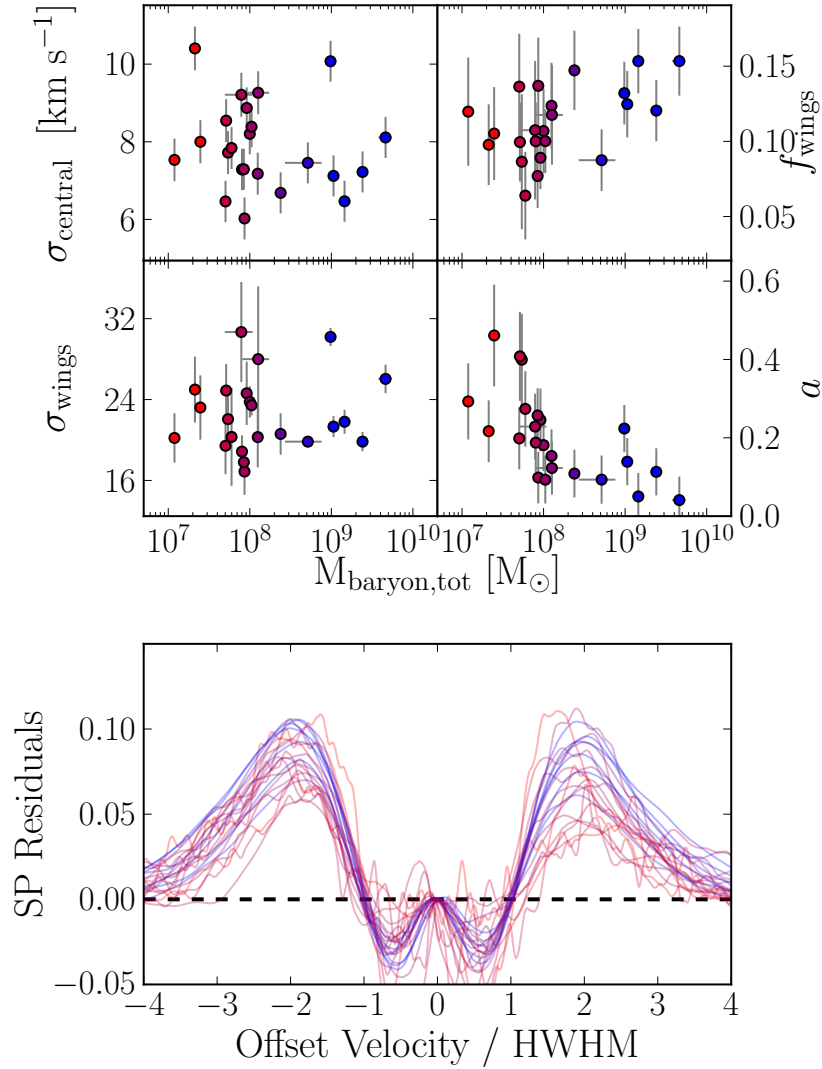


Figure 3.21 The upper panel shows the measured parameters versus galaxy $M_{\text{baryon,tot}}$. Each point is colored from blue to red based on increasing $M_{\text{baryon,tot}}$. The bottom panel shows the residuals of the normalized superprofiles. The color of the line corresponds to that on the upper panel. The lines are plotted with a transparency value, so overlap regions are more saturated. Both f_{wings} and a_{wings} show trends with increasing star formation.

3.5.1.2 *Star Formation Rate*

We plot the behavior of the superprofile parameters with SFR in Figure 3.22. As shown in Figure 3.1, SFR is strongly correlated with galaxy mass. We are therefore not surprised to see nearly-identical correlations as those in Figure 3.21. We do find statistically significant correlations between SFR and both f_{wings} and a_{wings} . The trends can be seen in the upper panels of Figure 3.22, where galaxies with higher SFRs (blue) tend to have higher f_{wings} values and lower a_{wings} values compared to the galaxies with lower SFRs (red). This behavior can also be seen in the superprofile residuals plotted in the lower panel of Figure 3.22; the blue residuals, with the highest SFR, are also among the largest and most symmetric. The red lines are typically lower and exhibit varying levels of asymmetry.

Given that the correlations between f_{wings} and a_{wings} are the same as the correlations with mass, it is possible that the f_{wings} and a_{wings} correlations are causally connected to any of the other galaxy properties that scale with mass. However, of all these properties, SFR is the only one that provides a physical mechanism for driving H I gas in the wings. It may therefore be the actual driver of the correlations with mass. We explore this connection further in § 3.5.2 below.

3.5.2 *Star Formation*

Star formation is typically proposed as the primary driver of H I turbulence in spiral galaxies within $\sim r_{25}$ (e.g., Tamburro et al., 2009). If so, then we may expect to find correlations between measures of star formation and the superprofile parameters. While the total SFR provides a measure of the overall energy input from star formation, it is strongly dependent on galaxy mass. In addition, galaxies with higher SFRs, and thus higher masses, also have larger H I masses to affect with the energy provided by star formation.

We consider two possible measures of star formation other than SFR, which was considered previously in § 3.5.1.2. These include the SFR intensity (i.e., $\langle \Sigma_{\text{SFR}} \rangle$; § 3.2.3.5), which measures the SFR concentration and thus may correlate with the efficiency of locally accelerating H I; and $\text{SFR} / M_{\text{HI}}$ (§ 3.2.3.6), which measures the ratio between the available energy of star formation and the mass of gas that the energy must couple to.

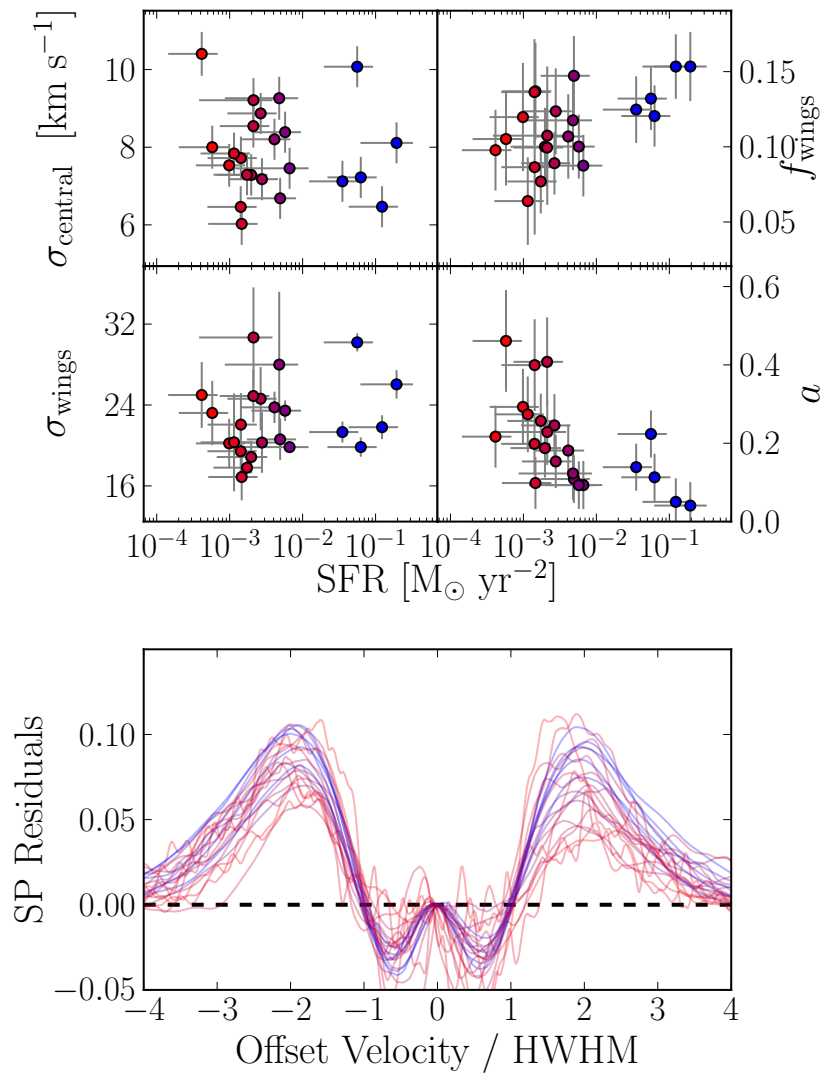


Figure 3.22 Same as Figure 3.21, but for SFR. We find that a_{wings} decreases with increasing SFR.

3.5.2.1 Σ_{SFR}

In Figure 3.23 we show the relationship between $\langle \Sigma_{\text{SFR}} \rangle$ and the superprofile parameters. We find no significant correlations with σ_{central} , f_{wings} , or a_{wings} . However, σ_{wings} shows a trend with $\langle \Sigma_{\text{SFR}} \rangle$, such that galaxies with higher $\langle \Sigma_{\text{SFR}} \rangle$ values are able to drive H I into the wings with faster average velocities.

The existence of the correlation between σ_{wings} and $\langle \Sigma_{\text{SFR}} \rangle$ is not surprising. Since energy input from star formation is a local process, more concentrated star formation should be more effective at inducing anomalous motions in the surrounding H I. At the same efficiency of converting the star formation energy into kinetic H I energy, a higher concentration of star formation energy imparts a given amount of energy into a smaller mass of H I, thus driving H I in the wings to higher velocities. We further explore the connection between star formation energy and kinetic energy in the wings of the superprofile in § 3.6.3.4.

3.5.2.2 $\text{SFR} / M_{\text{HI}}$

We might also expect SFR per unit M_{HI} to affect H I kinematics. As discussed in § 3.2.3.6, this quantity is best interpreted as the ratio between the rate of energy input from star formation and the mass of gas that can be accelerated by that energy instead of the average SFE.

We show the superprofile parameters as a function of $\text{SFR} / M_{\text{HI}}$ in Figure 3.24. We find a correlation between f_{wings} and $\text{SFR} / M_{\text{HI}}$. As a potential explanation for this trend, we invoke the argument that galaxies with higher SFR and lower M_{HI} are better able to accelerate the surrounding H I into the wings of the superprofile compared with their counterparts. However, for the most common values of $\text{SFR} / M_{\text{HI}} \sim 10^{-10} \text{ yr}^{-1}$, f_{wings} values vary by $\sim 40\%$, suggesting a large degree of stochasticity in this correlation. It is also unclear why $\text{SFR} / M_{\text{HI}}$ affects f_{wings} but not σ_{wings} .

3.5.3 *Surface Mass Density*

Disks with higher surface mass density are able to permit more turbulent motions in gas that is still bound to the disk (e.g., van der Kruit, 1981). In addition, a number of gravitational

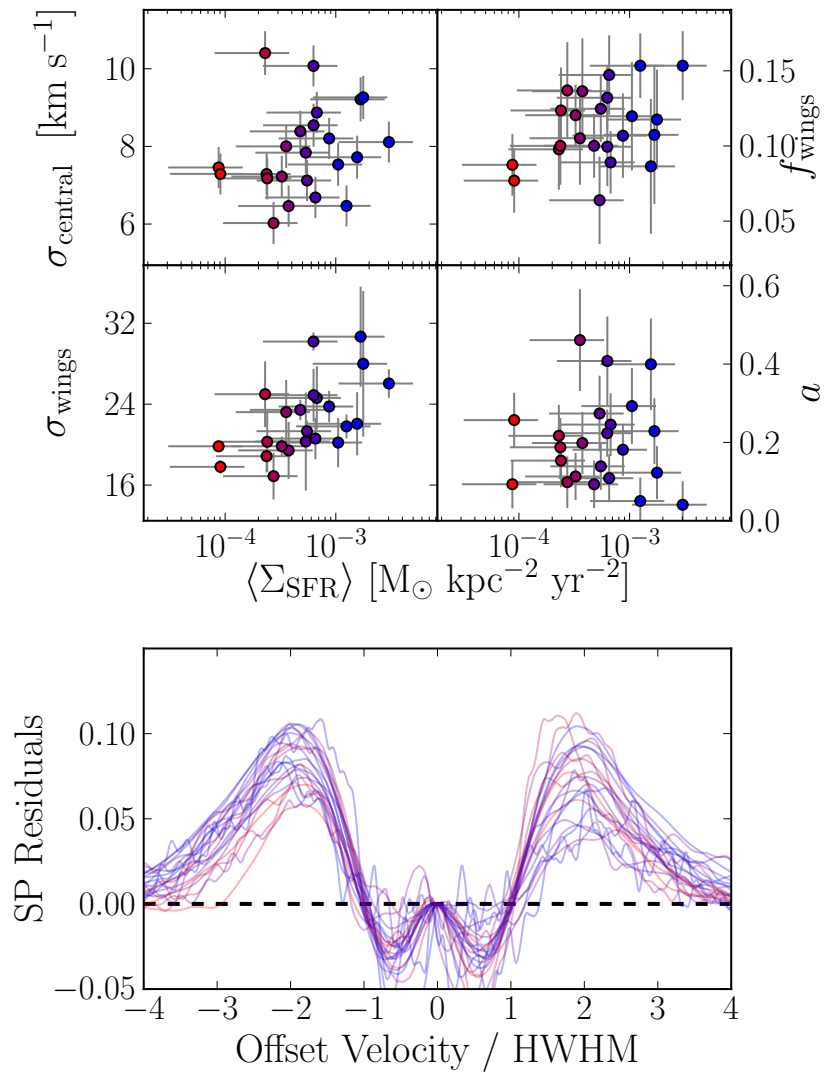


Figure 3.23 Same as Figure 3.21, but for $\langle \Sigma_{\text{SFR}} \rangle$. We find that galaxies with higher $\langle \Sigma_{\text{SFR}} \rangle$ have higher characteristic wing velocities.

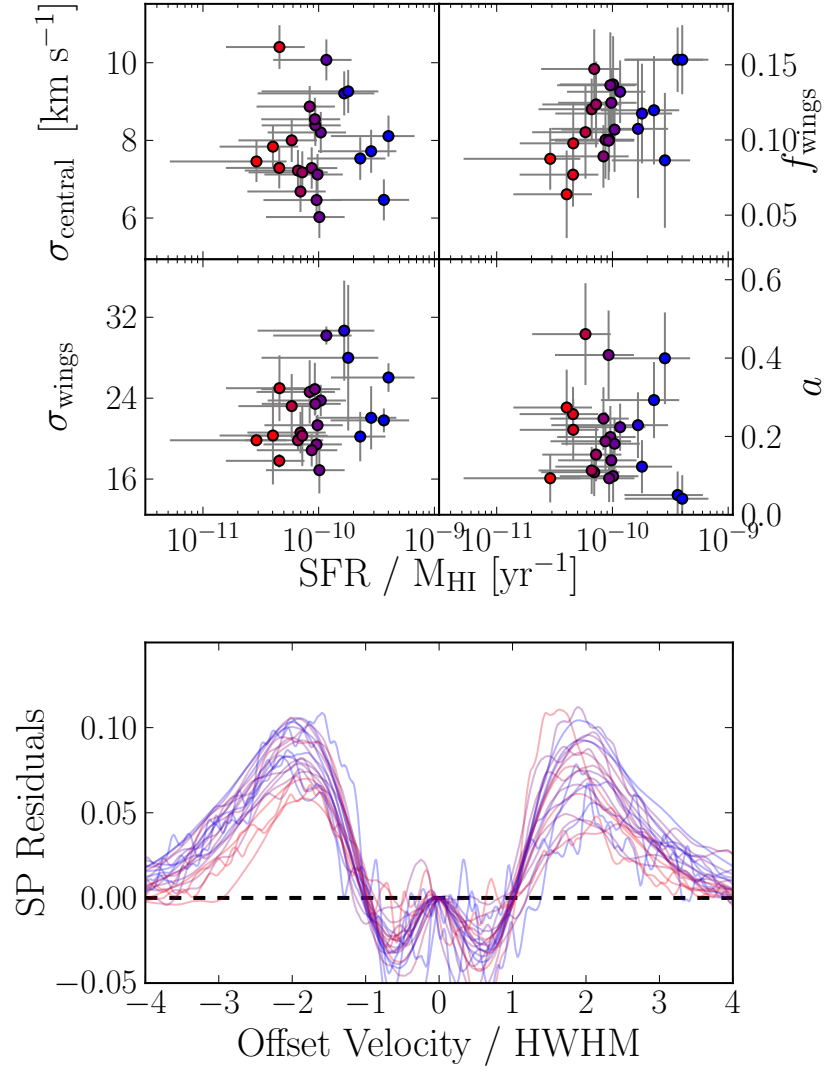


Figure 3.24 Same as Figure 3.21, but for $\text{SFR} / M_{\text{HI}}$. Galaxies with higher $\text{SFR} / M_{\text{HI}}$ also have a higher fraction of gas in the wings of their superprofiles.

instabilities have been proposed to drive turbulence in galaxy disks (e.g., Huber & Pfenninger, 2001; Wada et al., 2002), so the amplitude of turbulent motions might be expected to scale with surface mass density.

We find correlations between $\langle \Sigma_{\text{HI}} \rangle$ and both σ_{central} and σ_{wings} , as shown in Figure 3.25. This correlation may be indicative of turbulence as driven by gravitational instabilities, as explored further in § 3.6.3.1, or of a coupling with $\langle \Sigma_{\text{SFR}} \rangle$, which tends to scale with Σ_{HI} . We note, however, that no correlation was observed between σ_{central} and Σ_{SFR} . A similar correlation with $\langle \Sigma_{\text{baryon}} \rangle$ exists with σ_{wings} , but not with σ_{central} .

3.5.4 Inclination

We end by confirming that the superprofile parameters are not strongly influenced by galaxy inclination, as can be seen in Figure 3.26. There are no significant trends in any of the parameters. However, we note that uncertainties in the inclination of the dwarfs could potentially mask any underlying systematic effects.

3.5.5 Extending the Correlations to Higher Mass Galaxies

A number of massive spirals were eliminated from our sample based on the selection criteria to ensure high-quality data (§ 3.2.1.3). In this section we now include eight of these galaxies to see if the correlations we identify among the dwarfs could hold when extended to higher mass galaxies. Since this is a simple check, we do not perform the same rigorous tests as we have for the primary dwarf sample. Instead, we merely present our results and assess how the correlation coefficients change with the inclusion of more massive galaxies.

For the higher mass galaxies, we relax selection criteria (1) and (2) as given in § 3.2.1.3 by working at a spatial resolution of 400 pc and by including observations with $\Delta v = 5.2 \text{ km s}^{-1}$, with the caveat that we have not characterized the effect of observational properties on these superprofiles. We also include galaxies with de Vaucouleurs T-type ≥ 2 . Finally, we only use galaxies that are in the clean sample of I2012 to avoid contamination from bulk inflows, outflows, or H I in the Milky Way. These relaxed criteria give us eight additional, higher-mass galaxies (NGC 628, NGC 2403, NGC 2903, NGC 2976, NGC 3351, NGC 4736,

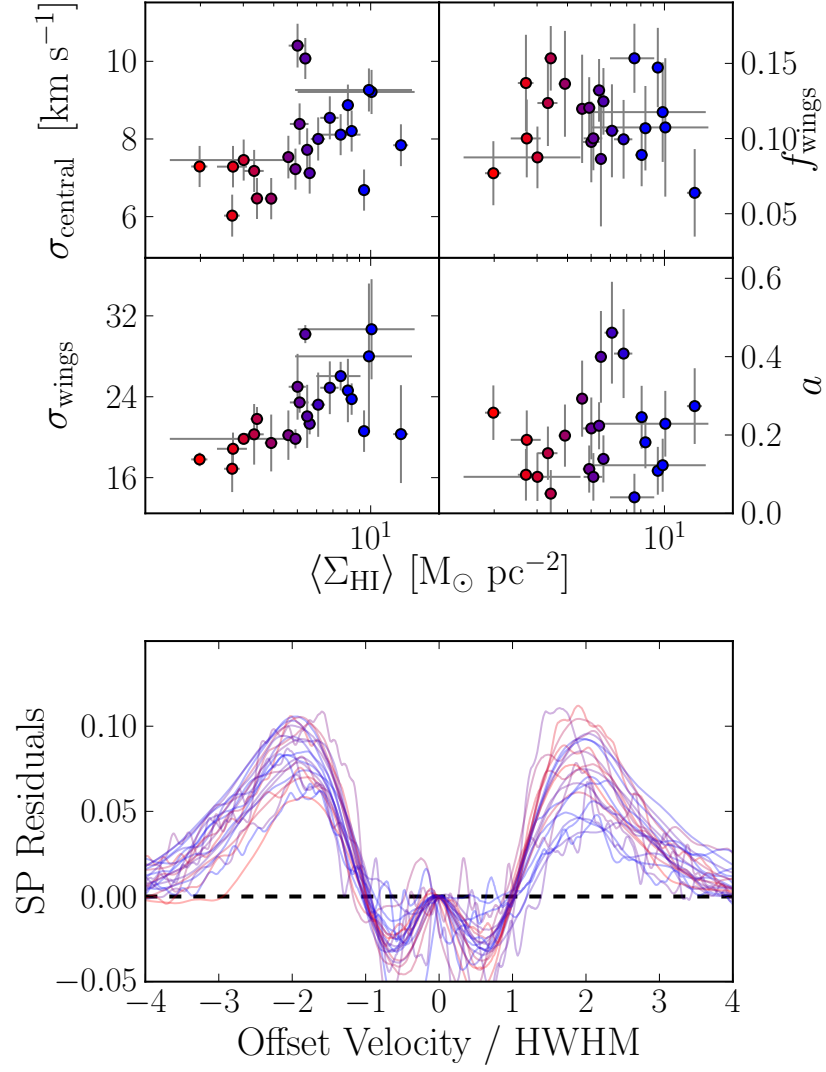


Figure 3.25 The superprofile parameters as a function of $\langle \Sigma_{\text{HI}} \rangle$. We find that both σ_{central} and σ_{wings} increase with increasing $\langle \Sigma_{\text{HI}} \rangle$.

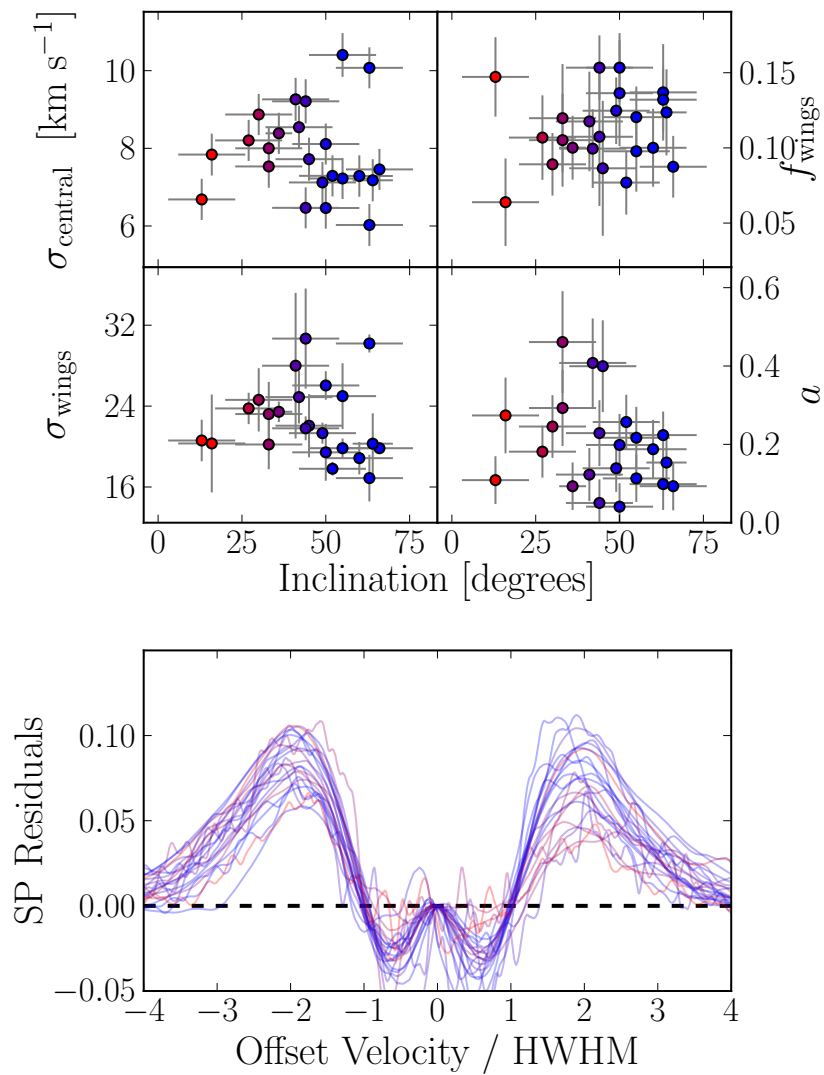


Figure 3.26 The superprofile parameters as a function of galaxy inclination. The measured parameters do not change systematically as a function of inclination, but we note that the inclinations for many of the dwarfs in our sample are very uncertain.

NGC 5055, and NGC 5236).

For each galaxy, we produce superprofiles in the same manner as we have for the dwarfs in our sample. We first smooth the data to a common physical resolution of 400 pc (following § 3.2.2). We then generate a superprofile for that galaxy after applying the same $S/N > 5$ threshold as for the primary sample (§ 3.3). Finally, we parameterize each superprofile using the HWHM-scaled Gaussians (§ 3.4.2). We list the derived superprofile parameters for these galaxies in Table 3.7.

We assess the strength of the correlations with physical properties after including the higher-mass galaxies. In Figure 3.27 we show relevant correlations between the superprofile parameters and the physical properties with which they are correlated after the inclusion of high-mass galaxies. The displayed panels are: (1) σ_{central} versus $\langle \Sigma_{\text{HI}} \rangle$; (2) σ_{central} versus $\langle \Sigma_{\text{SFR}} \rangle$; (3) σ_{wings} versus $\langle \Sigma_{\text{HI}} \rangle$; (4) σ_{wings} versus $\langle \Sigma_{\text{SFR}} \rangle$; (5) $\text{SFR} / M_{\text{HI}}$ versus f_{wings} ; and (6) SFR versus a_{wings} . The dwarf galaxies from our sample are shown with filled circles, while the higher mass galaxies are shown with open circles.

We find that σ_{central} is no longer correlated with $\langle \Sigma_{\text{HI}} \rangle$, but a trend with $\langle \Sigma_{\text{SFR}} \rangle$ is present with $r_s = 0.404$ and $p_s = 0.024$. Although this p_s value is marginally higher than our cutoff, the trend lends credence to the idea that the observed correlation between σ_{central} and $\langle \Sigma_{\text{HI}} \rangle$ for the dwarf sample may be tracing a correlation with Σ_{SFR} .

Similarly, σ_{wings} no longer shows correlations with $\langle \Sigma_{\text{HI}} \rangle$ but does with $\langle \Sigma_{\text{SFR}} \rangle$, implying that Σ_{SFR} does indeed affect the gas in the wings. The idea that H I gas in the wings of the superprofile is influenced by star formation is also supported because correlations between f_{wings} and $\text{SFR} / M_{\text{HI}}$ and between a_{wings} and SFR both remain with the inclusion of higher mass spirals.

3.6 Discussion

In this section we discuss the implications for the width of the central peak of the superprofile (§ 3.6.1) as well as the correlations we see with the wings of the superprofile (§ 3.6.2). We then compare the energy available from star formation to the kinetic energy in the H I gas (§ 3.6.3). Finally, we approximate implied H I scale heights for the sample (§ 3.6.4) and discuss the similarity of the superprofiles' shapes (§ 3.6.5).

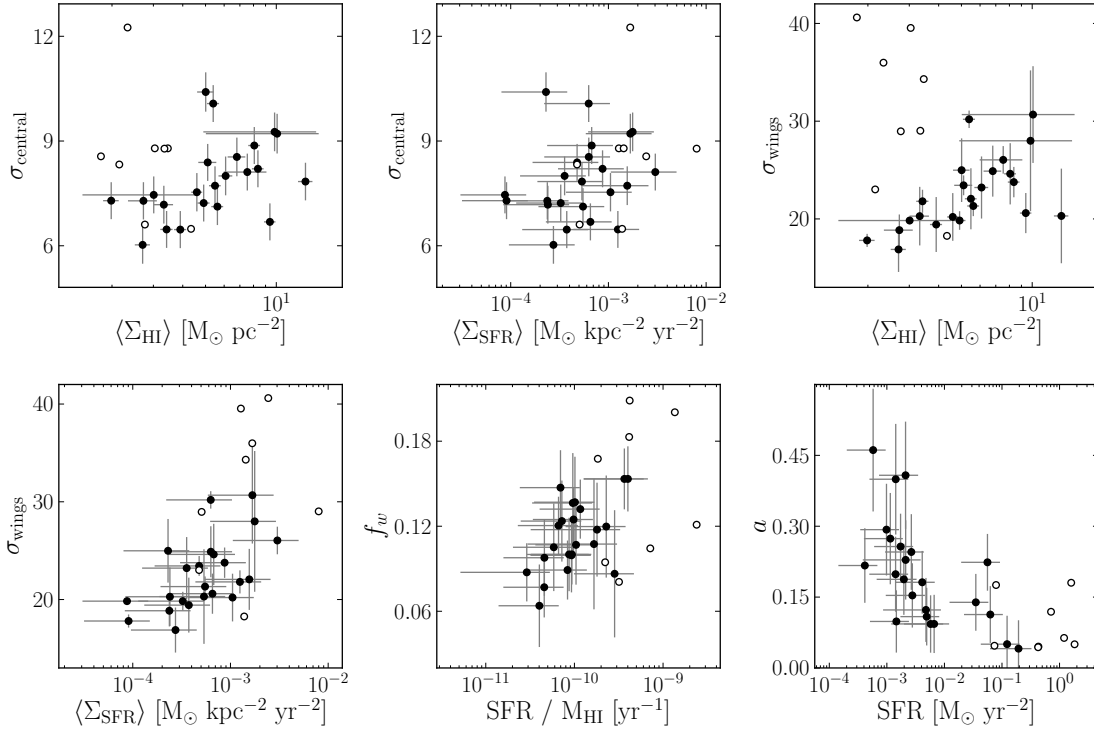


Figure 3.27 Observed superprofile properties versus physical properties when higher mass galaxies are included. The main dwarf sample is shown with filled black circles, while the higher mass galaxies are shown with open black circles. In most cases, the higher mass galaxies fit the correlations, but in a few, they do not (i.e., σ_{central} versus $\langle \Sigma_{\text{HI}} \rangle$ and σ_{wings} versus $\langle \Sigma_{\text{HI}} \rangle$).

Table 3.7: Measured superprofile parameters for higher-mass THINGS galaxies. Columns are the same as Table 3.4

1	2	3	4	5	6	7
Galaxy	$\langle\sigma_{\text{m2}}\rangle$	σ_{central}	σ_{wings}	f_w	a	N_{beams}
	(km s ⁻¹)	(km s ⁻¹)	(km s ⁻¹)			
NGC 5055	13.6	8.8	34.3	0.18	0.05	3616
NGC 2903	16.6	8.8	39.5	0.21	0.06	2186
NGC 5236	10.1	8.8	29.0	0.12	0.18	447
NGC 3351	13.5	6.6	29.0	0.17	0.05	607
NGC 4736	14.8	8.6	40.6	0.20	0.04	725
NGC 628	7.5	6.5	18.3	0.08	0.12	2819
NGC 2403	10.0	8.3	23.0	0.09	0.05	2253
NGC 2976	14.5	12.3	36.0	0.10	0.18	110

3.6.1 H I in the Central Peak

The width of the central peak, σ_{central} , has a very small range in our sample, with a median of 7.7 km s⁻¹ and interquartile range of only ± 1 km s⁻¹. The small range of observed σ_{central} values may suggest that average turbulence in the ISM is regulated in some way, such as by energy input from physical processes or external heating from the UV background (e.g., Schaye, 2004; Tamburro et al., 2009).

The only correlation we have found between σ_{central} and globally-averaged physical properties is with $\langle\Sigma_{\text{HI}}\rangle$, but this correlation disappears with the inclusion of higher mass spirals. Interestingly, we find no trend between σ_{central} and our measurements of star formation. In standard lore, star formation is the primary driver of turbulence in the warm ISM. If star formation were the sole driver of H I line widths in galaxies, we would initially have expected to have seen a connection between some measure of SFR, $\langle\Sigma_{\text{SFR}}\rangle$, or SFR / M_{HI} . We now give some potential explanations for this mismatch.

Because regions with higher $\langle\Sigma_{\text{HI}}\rangle$ also tend to have higher $\langle\Sigma_{\text{SFR}}\rangle$, the correlation be-

tween σ_{central} and $\langle \Sigma_{\text{HI}} \rangle$ could in actuality a correlation between σ_{central} and $\langle \Sigma_{\text{SFR}} \rangle$. However, this interpretation is called into question by the lack of correlation between σ_{central} and $\langle \Sigma_{\text{SFR}} \rangle$ as traced by FUV+24 μm emission. The FUV+24 μm tracer probes SFR averaged over the past 10 – 100 Myr, with the implicit assumption that the SFR has been constant over that timescale. It is unlikely that this is the case in our sample galaxies. Because the timescales over which turbulent gas in the central peak can dissipate energy are ~ 10 Myr, the FUV+24 μm timescale may be a poor match to the timescales relevant for the H I component. If we interpret the central peak as turbulent, the H I in the sample galaxies is able to dissipate its energy in $\sim 10^7$ yr. Therefore, the star formation that has occurred in the last $\sim 10^7$ yr is the primary influence on the gas. Because our SFR measurement has been averaged over a longer time, galaxies with similar average SFRs on $\sim 10^8$ yr timescales may in fact may have different SFRs in the past $\sim 10^7$ yr.

We caution that the superprofiles for the galaxies are a global average of individual H I line-of-sight spectra, so they often include regions in a single galaxy with very different star formation properties. The loss of spatial information in the superprofiles could account for the lack of correlation between star formation and σ_{central} , especially when regions with prominent star formation are mixed with those that lack strong star formation. We explore the spatial dependence of velocity dispersion in a subsequent paper.

It is certainly possible that the correlation with $\langle \Sigma_{\text{HI}} \rangle$, and not with $\langle \Sigma_{\text{SFR}} \rangle$, indicates that there is indeed no physical connection between the central peak and star formation. There are hints of this possibility in the Tamburro et al. (2009) results. In the inner regions of their more massive galaxies, they found a correlation between σ_{m2} and Σ_{SFR} . However, this correlation broke down at large radii, where σ_{m2} approaches a nearly constant value but star formation falls off dramatically. Given the similarity between dwarf galaxies and the outer disks of spirals (in terms of Σ_{SFR} , Σ_{HI} , $\Sigma_{\star}$, etc.), it is possible that our sample lies primarily in this regime.

If star formation is not setting the velocity dispersion, what else is? One commonly-adopted mechanism in spirals is the MRI, which works well in the outskirts of massive spiral galaxies where angular velocity declines with radius. In dwarfs, however, the rotation curves across much of the observable disk are closer to solid body rotation, and therefore

lack the strong differential rotation necessary for the MRI. Most dwarfs in the Local Group also show magnetic field strengths approximately three times smaller than that of spirals (Chyży et al., 2011). The combination of these two factors means that the MRI should be less effective in the dwarf galaxies that comprise our sample. Since more massive galaxies host conditions that are more conducive to MRI-driven turbulence, we might expect to see a correlation between galaxy mass and σ_{central} . However, no such trend is present. While it is possible that the range in σ_{central} values is too small to measure such a trend, it would also be surprising if the MRI conspired to produce such similar σ_{central} values across the sample without any external regulation.

Other energy sources for turbulence in galaxies include gravitational instabilities. Many of these, however, require shear in the rotating gas to function and thus fall prey to the same problems as the MRI. The most promising of these instabilities is that presented in Wada et al. (2002), which does not explicitly require shear to drive turbulent velocity dispersions and harkens back to the observed correlation between σ_{central} and $\langle \Sigma_{\text{HI}} \rangle$. While the authors have shown that this method can drive turbulence at levels observed in NGC 2915, others have noted that this instability provides energy at levels that are two orders of magnitude smaller than that required to drive the observed turbulence in the ISM (Mac Low & Klessen, 2004). We assess the ability of this gravitational instability to provide enough energy to drive turbulence in our sample galaxies in § 3.6.3.2.

Another proposed method is UV heating, which can drive thermally-broadened line widths to $\sim 6 \text{ km s}^{-1}$ (Tamburro et al., 2009). In this case, the widths are due to thermal effects, not turbulence. However, the measured σ_{central} values of the superprofiles show a much wider temperature range than can be explained by UV heating. Perhaps, however, UV heating can set the base velocity dispersion of H I profiles, and any additional dispersion is driven by other physical processes, such as star formation or instabilities.

The mechanism that drives H I velocity dispersions remains an open question and will likely become clearer in future spatially-resolved studies.

3.6.2 The Energetic H I in the Wings

Compared with σ_{central} , the properties of the superprofile wings are more correlated with galaxy physical properties. We found that: (1) the characteristic velocity of the wings, σ_{wings} , increases with both Σ_{SFR} and Σ_{HI} ; (2) the fraction of the gas in the wings, f_{wings} , increases most strongly with $\text{SFR} / M_{\text{HI}}$; and (3) the asymmetry, a_{wings} , is primarily in the wings and decreases with increasing SFR. In this section we discuss potential physical explanations for these trends.

3.6.2.1 Σ_{SFR} , Σ_{HI} , and σ_{wings}

We find correlations between σ_{wings} and both $\langle \Sigma_{\text{SFR}} \rangle$ and $\langle \Sigma_{\text{HI}} \rangle$. The fact that both correlations exist may be due to the $\langle \Sigma_{\text{SFR}} \rangle$ - $\langle \Sigma_{\text{HI}} \rangle$ connection. The correlation between σ_{wings} and Σ_{HI} may also partially be due to the correlation between σ_{central} and Σ_{HI} ; galaxies with wider central peaks, and therefore higher values of Σ_{HI} , will by definition also have higher σ_{wings} values, as we consider only gas moving faster than expected compared to the central Gaussian when calculating σ_{wings} . We therefore discuss σ_{wings} properties in relation to star formation, a potential driver for high-velocity gas in galaxies.

The behavior of σ_{wings} and Σ_{SFR} can be explained if the energy from star formation pushes H I to higher velocities than expected from the σ_{central} Gaussian. Expanding H I structures have been observed in numerous studies down to the instrumental resolution (e.g., Brinks & Bajaja, 1986; Bagetakos et al., 2011), including many smaller structures in the Milky Way (e.g., Ehlerová & Palouš, 2005). Presumably smaller expanding H I structures exist below the current limits of spatial resolution. Both Type 2 and Type 3 holes, as defined by Brinks & Bajaja (1986), show H I offsets in velocity space along a single line-of-sight spectrum, which would contribute H I emission to the wings of a global superprofile.

H I holes are often thought to be due to star formation (e.g., McCray & Kafatos, 1987), although direct spatial correlation with young, massive stars is not always seen (e.g., Rhode et al., 1999). Recent studies have found that multiple star formation events over the age of the hole do provide enough energy to drive H I hole formation, though other regions

show similar star formation histories without the presence of H I holes (e.g., Weisz et al., 2009a; Warren et al., 2011; Cannon et al., 2011). H I gas with anomalous velocities has also been linked to the presence of H I holes and star forming regions in the spiral NGC 6946 (Boomsma et al., 2008). However, projection effects make these measurements difficult, so such studies are only appropriate in a small number of face-on spirals.

If similar expanding H I structures exist at smaller spatial scales, we can explore their connection with superprofile parameters in more detail using the canonical Chevalier equation (Chevalier, 1974), which relates star formation energy and H I hole properties:

$$E \text{ (erg)} = 5.3 \times 10^{43} \left(\frac{n_0}{\text{cm}^{-3}} \right)^{1.12} \left(\frac{r_{\text{hole}}}{\text{pc}} \right)^{3.12} \left(\frac{v_{\text{exp}}}{1 \text{ km s}^{-1}} \right)^{1.4}. \quad (3.19)$$

Here, E is the enclosed, single-burst energy required to drive the expansion, n_0 is the density of the surrounding ambient medium, r_{hole} is the radius of the hole, and v_{exp} is the expansion velocity. This equation provides a description of the energy of an expanding shell in an idealized ISM, with the assumption of uniform density which does not hold true on global scales. This equation is also complicated by the fact that multiple bursts can provide energy to drive H I hole expansion. However, it still allows us to explore the relation between the physical quantities involved in the expansion. The energy density of the hole, $\sim E_{\text{hole}}/r^3$, scales most strongly with v_{exp} , with weaker dependencies on n_0 and r_{hole} . If we assume that the energy source for the hole is due to star formation, a higher concentration of star formation energy within the hole should lead to faster expansion velocities. Because there is no reason not to expect smaller expanding structures below the 200 pc resolution of our data, these structures may manifest as the high-velocity wings observed in the superprofiles. Thus, for a given H I mass, higher concentrations of energy due to larger Σ_{SFR} should lead to faster expansion velocities and therefore to higher measured σ_{wings} values. It is unclear, however, why Σ_{SFR} would influence σ_{wings} without also driving more gas into the wings of the profile, as measured by f_{wings} .

3.6.2.2 $\text{SFR} / M_{\text{HI}}$ and f_{wings}

The fraction of gas in the wings is correlated not with Σ_{SFR} but with $\text{SFR} / M_{\text{HI}}$ for dwarf galaxies. Such behavior can again be ascribed to expanding H I structures. At a fixed SFR,

and therefore a fixed energy input into the ISM, galaxies with smaller H I masses should show more pronounced effects on the H I kinematics. Therefore, galaxies with relatively high SFRs compared to their H I masses should be able to perturb the H I content more easily, as seen in the correlation between $\text{SFR} / M_{\text{HI}}$ and f_{wings} . More H I is pushed into the wings of the superprofile if the galaxy has a high SFR relative to its H I content, or if it has a smaller amount of H I to move around with the energy available from star formation.

The correlations between f_{wings} and σ_{wings} indicate that star formation does indeed play a role in driving H I to anomalous velocities seen in the wings of the superprofile. It is unclear why f_{wings} and not σ_{wings} would scale with $\text{SFR} / M_{\text{HI}}$. However, the correlation coefficient between $\text{SFR} / M_{\text{HI}}$ and σ_{wings} implies $p_s = 0.066$, which indicates only a 7% probability of finding a correlation this extreme from a random sample.

3.6.2.3 *Star Formation as a Driver of Asymmetry*

Since the properties of the superprofile wings appear to be connected to star formation, it is not surprising that asymmetries in the wings can also be attributed to star formation. Due to the inhomogeneity of the ISM, individual star forming regions can affect the local H I gas asymmetrically. This effect can then result in asymmetric line profiles near star forming regions, which contributes to asymmetry in the wings of the global superprofile. The average of a large number of asymmetric H I regions should average out to produce a symmetric superprofile, while the average of only a few asymmetric regions is more likely to retain net asymmetry in the superprofile. If galaxies with larger SFR have more individual star forming events compared to their counterparts with smaller SFR, we would expect an anti-correlation between SFR and a_{wings} , as is observed. We note that it may also be easier for more massive galaxies to remove the signatures of asymmetric H I motions, regardless of their origin, due to their deeper gravitational potential wells.

Asymmetric H I motions have already been observed near star forming regions. Young et al. (2003) found that H I line-of-sight spectra exhibit asymmetry near regions of star formation on 200 pc scales, though this behavior was not seen in the sample observed by Begum et al. (2008), with somewhat more coarse resolutions of 300 - 700 pc. We also find

that some galaxies show asymmetric profiles near regions of star formation. To measure this, we use the difference between v_{peak} from Gauss-Hermite fits and the intensity-weighted mean velocity from the first moment map (v_{IWM}). As previously seen in Figure 3.2, v_{IWM} and v_{peak} from Gauss-Hermite fits are offset for asymmetric profiles. In Figure 3.28, we plot Σ_{SFR} compared to the difference between v_{peak} and v_{IWM} . Red indicates regions where $v_{\text{peak}} < v_{\text{IWM}}$, while blue shows regions where $v_{\text{peak}} > v_{\text{IWM}}$ km s⁻¹. Transparency has been added to show the underlying Σ_{SFR} in grey, and regions where $v_{\text{peak}} = v_{\text{IWM}}$ are more transparent than regions where they are different. In these galaxies, some star formation regions also show asymmetric profiles. The spatial overlap between star formation and asymmetric profiles is not proof that star formation is the cause of asymmetry, as there are regions with no apparent star formation that also show asymmetric profiles, but it indicates that star formation may be one cause of asymmetry in H I line-of-sight spectra. If this is the case, the correlation between a_{wings} and SFR is not surprising.

We next estimate the number of star forming events, N_{SF} , in a galaxy based on its SFR plus a fiducial star formation timescale and mass. We first assume that star formation is linearly proportional to H₂ mass, with a timescale $\tau_{\text{dep}} \sim \Sigma_{\text{H}_2}/\Sigma_{\text{SFR}}$. This timescale estimates approximately how long it will take a galaxy to use up its entire H₂ reservoir, and has been found to remarkably independent to environment (Bigiel et al., 2011; Bolatto et al., 2011). We can then estimate N_{SF} :

$$N_{\text{SF}} = \frac{\text{SFR} \times \tau_{\text{dep}}}{M_{\text{SF}}} \quad (3.20)$$

where M_{SF} is the typical mass of a star forming region. The numerator is an estimate of H₂ mass in our galaxies, while the denominator is the average mass of a star formation clump.

It is becoming clear that τ_{dep} may be universal as it does not appear to vary much from galaxy to galaxy (e.g., Bigiel et al., 2011). Bolatto et al. (2011) measure $\tau_{\text{dep}} \sim 1.6$ Gyr in the Small Magellanic Cloud for the same spatial scales of 200 pc as our data, a value very similar to the $\tau_{\text{dep}} \sim 2.35$ Gyr measured by Bigiel et al. (2011). The SMC value is likely the best comparison, since it has an H I mass and SFR similar to our sample (Stanimirovic et al., 1999; Harris & Zaritsky, 2004). If we assume that star formation arises from Giant Molecular Clouds (GMCs) with average masses of M_{MC} , whose sizes are well-matched to our

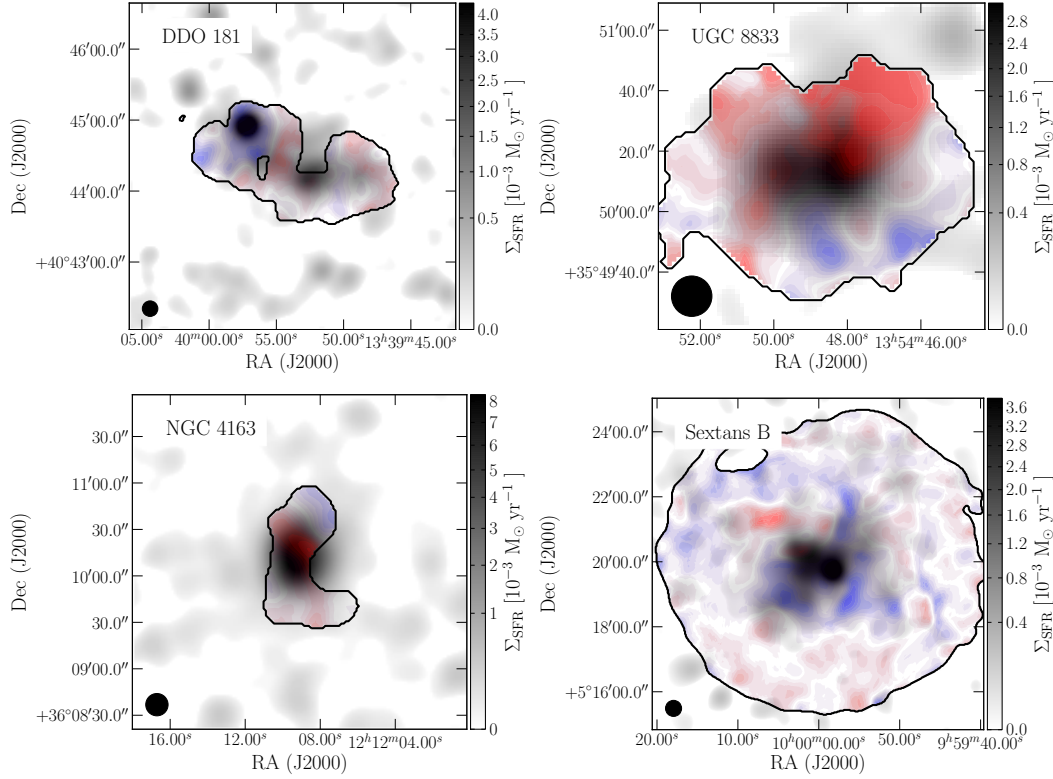


Figure 3.28 Example galaxies in our sample that show asymmetric H I line-of-sight profiles near star forming regions. The background image is Σ_{SFR} , with the black line representing the $S/N > 5$ threshold. The color overlays represent asymmetric line-of-sight profiles, with blue indicating line-of-sight spectra where the first moment is smaller than v_{peak} and red showing where the first moment is larger than v_{peak} . The color ranges from -5 to 5 km s^{-1} differences. Regions with small absolute differences between v_{peak} and the first moment are also shown with more transparency, and those with large absolute differences are less transparent. We note that not all star forming regions are associated with asymmetrical line-of-sight profiles, and not all asymmetric line-of-sight profiles are near star forming regions. However, the observed overlap between some star forming regions and the strongest H I line-of-sight asymmetries may indicate that star formation can be one driver of asymmetry in H I line profiles.

200 pc scale and therefore provide an estimate of the number of 200 pc resolution elements with star formation, we can calculate the number of spatially-resolved elements with star formation:

$$N_{\text{SF}} = 1.6 \left(\frac{\text{SFR}}{1 \times 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1}} \right) \left(\frac{\tau_{\text{dep}}}{1.6 \times 10^9 \text{ yr}} \right) \left(\frac{\text{M}_{\text{MC}}}{1 \times 10^6 \text{ M}_{\odot}} \right)^{-1}. \quad (3.21)$$

This equation provides an approximation of the number of resolution elements in our sample that have star formation.

At the low end of our sample, the observed $\text{SFR} \sim 1 \times 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ yields only a few regions of active star formation. Indeed, many of the low-mass galaxies in our sample show only a few clumps of star formation as traced by FUV + $24\mu\text{m}$ emission, while the higher mass galaxies have a more widespread, smooth star formation distribution across their disks. With our above assumption that each SF event has a chance to drive asymmetric HI outflows, we would therefore expect that these potential asymmetries do not always average out at the low star formation rates characteristic of our sample. At the higher end of our sample, where $\text{SFR} \sim 1 \times 10^{-1}$, we would expect a few hundred regions of active star formation. While each individual region may produce asymmetric HI motions, the average over the large number of SF events in the entire galaxy produces an overall symmetric distribution. However, very large HI holes or extreme star formation events could still produce observable asymmetric HI outflows even in galaxies with relatively high star formation rates. This behavior has been seen in NGC 2366 (van Eymeren et al., 2009a), which also has a high $a_{\text{wings}} = 0.22$ value compared to its relatively high SFR, though it is unclear if this asymmetry is due to star formation or the high degree of non-circular motions in the northwestern region (Oh et al., 2011).

3.6.3 Comparison of Energy in the HI gas to Energy Sources

In this section we estimate the kinetic energy of the HI gas using the superprofile and compare it to the energy available from physical processes. In § 3.6.3.1 we assess the ability of both the Wada et al. (2002) gravitational instability (§ 3.6.3.2) and star formation (§ 3.6.3.3) to provide enough energy to drive turbulence at levels indicated by the central peak. We then examine the efficiencies required for star formation to move HI into the

wings of the superprofiles (§ 3.6.3.4). Finally, we discuss whether star formation can drive the full H I kinematics measured by the superprofile (§ 3.6.3.5).

3.6.3.1 Energy in the central H I peak

We first estimate the kinetic energy contained in the central peak of the superprofile. We assume that the majority of gas in the central peak can be reasonably approximated by a Gaussian profile with a width σ_{central} and that the velocity dispersion is isotropic in three dimensions. The energy in the central peak is therefore:

$$E_{\text{HI,central}} = \frac{3}{2} (1 - f_{\text{wings}}) (1 - f_{\text{cold}}) M_{\text{HI}} \sigma_{\text{central}}^2 \quad (3.22)$$

where M_{HI} is the measured H I mass of the superprofile. The $(1 - f_{\text{wings}})$ factor accounts for the fraction of H I in the wings, so $(1 - f_{\text{wings}})M_{\text{HI}}$ represents the H I mass contained in the central peak of the superprofile. The f_{cold} variable represents the fraction of H I gas that is in the cold phase, which has a narrower velocity dispersion compared to the average turbulent component. The velocity dispersion of this gas is likely thermal, and therefore cold H I should not be included in our calculation of turbulent energy. Typical measured fractions are $f_{\text{cold}} \lesssim 10 - 20\%$ (e.g., Young et al., 2003; Warren et al., 2012). Without strong constraints on individual values for cold H I fractions, we choose $f_{\text{cold}} = 0.15$ for our analysis.

3.6.3.2 Energy from Gravitational Instabilities

The energy provided by gravitational instabilities over a timescale τ is:

$$E_{\text{grav}} = \dot{\epsilon}_{\text{grav}} (1 - f_{\text{wings}})(1 - f_{\text{cold}})M_{\text{HI}} \tau. \quad (3.23)$$

As before, the $(1 - f_{\text{wings}})(1 - f_{\text{cold}})M_{\text{HI}}$ factor represents the approximate H I mass contained in the turbulent central peak.

We now calculate the amount of energy released into the ISM based on the gravitational instability proposed by Wada et al. (2002). This instability allows the gas to extract energy from rotation instead of from shear, so it is a potential source of energy for dwarf galaxies

that lie primarily in the regime of solid body rotation. Wada et al. (2002) approximate the energy supply rate per unit mass as:

$$\frac{\dot{\epsilon}_{\text{grav}}}{\text{km}^2 \text{s}^{-3}} \sim 5 \left(\frac{\Omega}{\text{s}^{-1}} \right) \left(\frac{\Sigma_{\text{gas}}}{10 \text{ M}_{\odot} \text{ pc}^2} \right) \left(\frac{\lambda}{100 \text{ pc}} \right)^2 \left(\frac{h_z}{100 \text{ pc}} \right)^{-1}. \quad (3.24)$$

Here, Ω is the angular velocity, Σ_{gas} is the gas surface density, λ is the scale length of turbulence, and h_z is the scale height of the disk. We approximate $\Omega \sim (w_{20}/2)/(1.5r_{25})$, where w_{20} has been corrected for inclination and $1.5r_{25}$ is the approximate extent of H I in galaxies. This approximation provides an order-of-magnitude estimate for the angular velocity of gas in our sample (Giovanelli & Haynes, 1988; Swaters et al., 2009). We use the $\langle \Sigma_{\text{gas}} \rangle$ measurement for the gas surface density and choose $\lambda = 100 \text{ pc}$ following Tamburro et al. (2009). Based on studies of the scale height in dwarf galaxies by Banerjee et al. (2011), we approximate the scale height of our sample as 500 pc.

We must then find the timescale over which the H I can dissipate its energy. If the H I in the central peak is turbulent, this timescale is the turbulent timescale as given by Mac Low (1999):

$$\tau_D \simeq 9.8 \text{ Myr} \left(\frac{\lambda}{100 \text{ pc}} \right) \left(\frac{\sigma}{10 \text{ km s}^{-1}} \right)^{-1}, \quad (3.25)$$

where λ is the turbulent driving scale and σ is the H I velocity dispersion. Following Tamburro et al. (2009), we estimate $\lambda \sim 100 \text{ pc}$. We also set $\sigma = \sigma_{\text{central}}$ as measured from the superprofile for each galaxy. For our measured σ_{central} values, the turbulent timescale ranges from 9 – 16 Myr.

To convert the available energy to H I kinetic energy, the conversion efficiency, $\epsilon_{\text{grav}} \equiv E_{\text{HI}}/E_{\text{grav}}$ must be taken into account. We do not adopt a single value for ϵ_{grav} , and instead measure the range of the range of ϵ_{grav} that is compatible with our data. In general, implied efficiencies of $\epsilon_{\text{grav}} > 1$ are unphysical in that the H I component has more turbulent kinetic energy than can be provided over the timescale.

In Figure 3.29, we compare E_{grav} to the kinetic energy contained in the central peak. In the left panel, we plot E_{grav} versus the energy in the central peak. We have shown the background in grey to represent the fact that the required efficiencies are > 1 and are therefore unphysical. Dashed lines represent constant ϵ_{grav} . The left panel shows the inferred value of ϵ_{grav} necessary to drive turbulence.

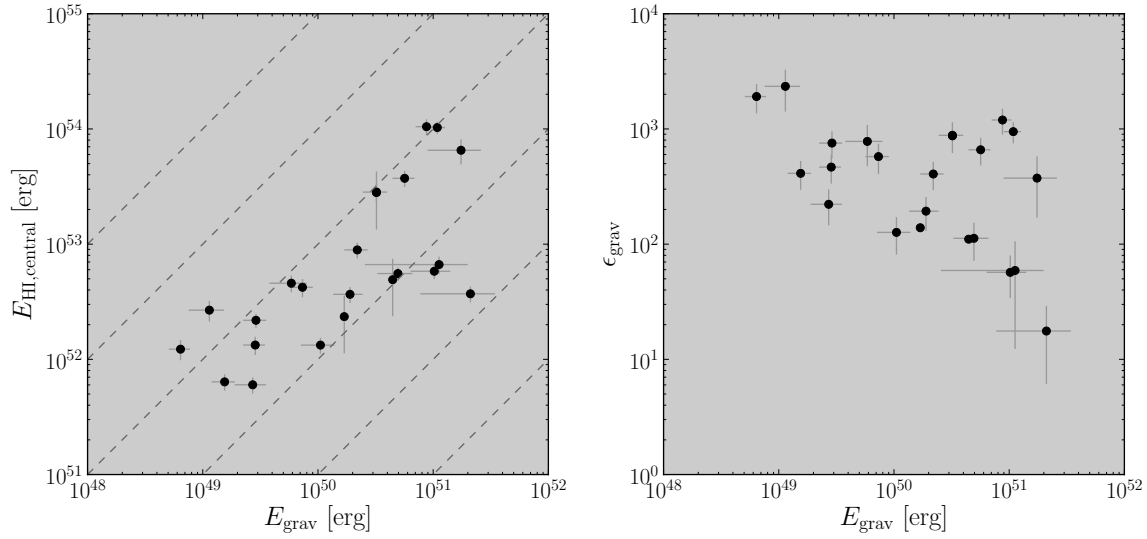


Figure 3.29 The left panel shows the energy available from the gravitational instability in Wada et al. (2002) over one turbulent timescale versus the turbulent energy in the central HI component as determined by the HWHM Gaussian fit (left). The entire background has been shaded in grey to represent the fact that all required efficiencies are unphysical, i.e., > 1 . The right panel shows the associated implied efficiencies ($\epsilon \equiv E_{\text{HI,central}}/E_{\text{grav}}$) versus input gravitational energy. It is clear that this instability cannot provide enough energy to drive the central peak in these galaxies over a single turbulent dissipation timescale.

In all cases, the gravitational instability cannot provide enough energy to drive the observed levels of H I turbulence, falling short by a factor of $10 - 10^3$ in spite of the fact that the correlation between $\langle \Sigma_{\text{HI}} \rangle$ and σ_{central} may have initially pointed at this driver. The discrepancy between $E_{\text{HI,central}}$ and E_{grav} appears to be more extreme in small galaxies with low values of E_{grav} . We note that in nearly all cases, changing any of our assumptions by a factor of two does not alter the result that the H I harbors far more energy on average across the disk than the gravitational instability can provide. The inability of this instability to drive turbulence has been noted before (e.g., Mac Low & Klessen, 2004), so our results confirm this idea. It is possible that other gravitational instabilities are operating to produce the observed σ_{central} values, but any candidate instability must be able to function efficiently in galaxies with low internal shear.

3.6.3.3 *Energy from Star Formation*

We next turn to star formation as a driver of H I velocity dispersion. Even though there is no straightforward correlation between measures of star formation and σ_{central} , this assessment provides a limit on the efficiencies necessary to couple energy from star formation to the H I gas if it is indeed, as widely regarded, the driver of H I turbulence for the bulk of the gas.

From the measured star formation rate, we can estimate the energy released into the ISM by SNe over the turbulent dissipation timescale τ_D as:

$$E_{\text{SF}} \sim \dot{E}_{\text{SF}} \tau_D \quad (3.26)$$

where $\dot{E}_{\text{SF}} \tau_D$ is the total amount of energy released from the stellar population over one turbulent timescale. This equation implicitly assumes that the rate of energy input from the stellar population has been constant over τ_D .

To estimate $\dot{E}_{\text{SF}}$, we use the formalism proposed by Tamburro et al. (2009), assuming that the majority of the star formation energy is released by SNe explosions. On average, each explosion provides 10^{51} ergs of mechanical energy. We take the number of SN per unit stellar mass formed to be $\eta_{\text{SN}} = 1.3 \times 10^{-2} \text{ SN } M_{\odot}^{-1}$, assuming a Kroupa (2001) IMF with an upper mass limit of $120 M_{\odot}$. We next assume that the SFR measured by FUV + $24\mu\text{m}$ observations has been constant over the τ_D timescale. The total energy available to the H I

due to SNe is then:

$$E_{\text{SF}} = \eta_{\text{SN}} (\text{SFR} \times \tau_D) 10^{51} \text{ergs.} \quad (3.27)$$

Since the measured SFRs of our sample are averaged over $10 - 100$ Myr, this equation assumes that this average measurement is representative of the SFR over τ_D for our galaxies, which is ~ 10 Myr (e.g., Equation 3.25). This assumption may fail in the case of galaxies with bursty star formation histories, since a large recent burst may be able to affect the H I gas while an older burst may not. However, the energy from supernovae is smoothed out over ~ 50 Myr after a burst, so minor fluctuations in the star formation history may not be too important. It also assumes that the initial mass function (IMF) is well-sampled, which may be an issue for galaxies with very low SFRs. This formalism indicates that the galaxies with the lowest SFRs ($\sim 0.5 - 1 \times 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1}$) would have approximate 1 SNe over $1 - 2 \times 10^5$ yr. We note that stellar winds can provide additional mechanical energy into the ISM.

As with E_{grav} , the conversion efficiency between energy available from star formation and H I kinetic energy, $\epsilon_{\text{SF}} \equiv E_{\text{HI}}/E_{\text{SF}}$, must be taken into account. Values of $\epsilon_{\text{SF}} > 1$ are unphysical, as in these cases star formation provides less energy than is contained in the central H I peak. Additional limits have been placed on ϵ_{SF} by simulations. Thornton et al. (1998) found that the average efficiency $\langle \epsilon_{\text{SF}} \rangle \sim 0.1$, while other simulations measure efficiencies that can be as high as 0.5 (Tenorio-Tagle et al., 1991). As with ϵ_{grav} , we measure the range of ϵ_{SF} that is compatible with our data.

In Figure 3.30, we compare the energy provided by SNe over one turbulent timescale to the energy in the H I gas. The format is the same as Figure 3.29. In the left panel, we plot the star formation energy versus the kinetic energy in the central H I peak. The dashed grey lines show constant ϵ_{SF} . The unphysical region where $\epsilon_{\text{SF}} > 1$ is shown in dark grey. The simulations by Thornton et al. (1998) suggest that ϵ_{SF} is never higher than 0.1; we shade regions above this threshold in light grey. The left panel shows the inferred values of ϵ_{SF} necessary to drive turbulence with star formation energy. Again, we have shown efficiencies above the more stringent theoretical maximum of 0.1 from Thornton et al. (1998) in light grey.

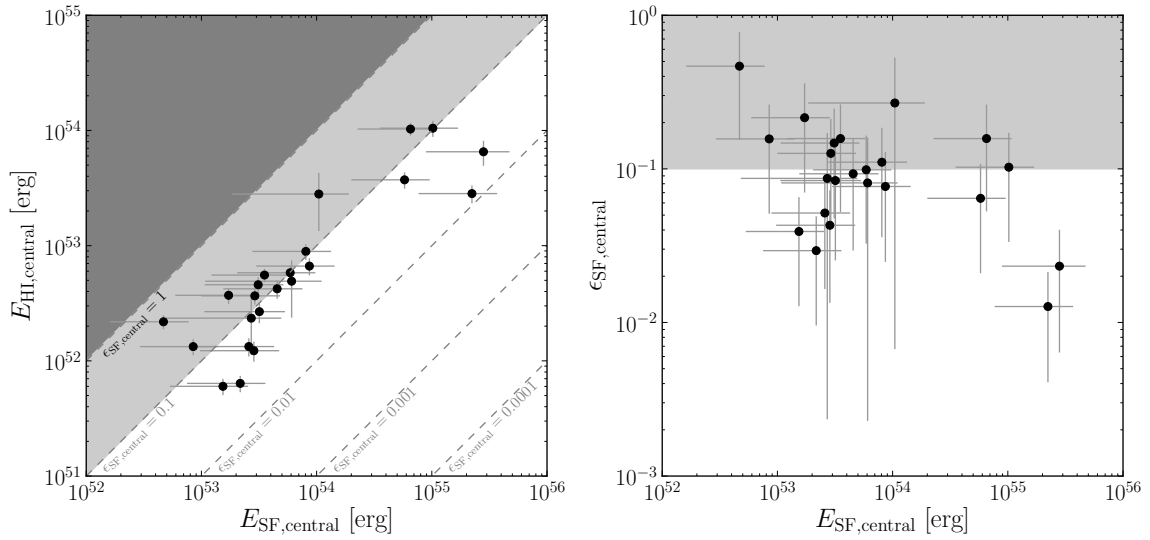


Figure 3.30 The left panel shows the energy available from star formation over one turbulent timescale versus the central H I component as determined by the HWHM Gaussian fit (left). The dashed grey lines are constant efficiency, and the shaded grey region represents unphysical efficiencies where $\epsilon_{\text{SF,turb}} > 1$. The majority of galaxies require efficiencies of only 0.01 - 0.1 to maintain the observed superprofile width. The right panel shows $\epsilon_{\text{SF,turb}}$ versus E_{SF} . We do not see any significant trends between $\epsilon_{\text{SF,turb}}$ and E_{SF} . The mean efficiency required is $\epsilon_{\text{SF,wings}} = 0.117 \pm 0.096$.

For all galaxies, we find that recent star formation provides enough energy to drive the observed turbulence over a single turbulent timescale with efficiencies $0.01 \lesssim \epsilon_{\text{SF}} \lesssim 0.1$, well in line with the limits from both Tenorio-Tagle et al. (1991) and Thornton et al. (1998). However, it is likely that some fraction of this energy ($\sim 35\%$, e.g., Joung et al., 2009) goes into accelerating H I from its undisturbed state into the wings of the superprofile, as explored in the following section. In this sense, these efficiency estimates are lower limits. On the other hand, some of the mass in the central peak is likely kinematically associated with the wings, thus lowering ϵ_{SF} values.

3.6.3.4 The Superprofile Wings

Next we compare the kinetic energy contained in the wings of the superprofiles to that provided by star formation. Although the wings contain only a small fraction of the H I mass ($\langle f_{\text{wings}} \rangle \sim 0.11$), the velocities are very high ($\langle \sigma_{\text{wings}} / \sigma_{\text{central}} \rangle \sim 3$), suggesting that they may harbor a significant fraction of the kinetic energy.

We calculate the kinetic energy in the wings as follows. If all H I in the galaxy started in the central turbulent component, some extra energy is necessary to accelerate the gas from $v \sim \sigma_{\text{central}}$ to $v \sim \sigma_{\text{wings}}$. The excess kinetic energy in the wings is then:

$$E_{\text{wings}} = \frac{3}{2} f_{\text{wings}} M_{\text{HI}} (\sigma_{\text{wings}}^2 - \sigma_{\text{central}}^2). \quad (3.28)$$

Based on our definition of σ_{wings} (Equation 3.15), this gives the total energy necessary to accelerate a mass $f_{\text{wings}} M_{\text{HI}}$ from a Gaussian velocity distribution into the observed wings of the superprofile. Because some of the H I in the central peak may be kinematically associated with the wings, this assumption provides a lower limit on the energy contained in the wings.

We next must choose a timescale over which to consider energy input from star formation for the wings. The relevant timescale to consider is not necessarily straightforward because the source of kinematics in the wings is unclear. If the wings are representative of bulk motions, such as away from star forming regions, the relevant timescale should be related to how long these bulk motions are expected to persist. On the other hand, if the wings are turbulent, the best timescale may be the turbulent timescale given in Equation 3.25.

Because the source of the wings is not necessarily clear and because neither case provides a definitive timescale, we assess the ability of star formation to provide enough energy over both timescales in turn.

First, we consider the scenario where the wings represent bulk gas motion away from star forming regions. To estimate the relevant timescale associated with this component, we capitalize on recent studies of H I holes, as these structures often exhibit velocity structures similar to what we expect to find in the wings. The kinematic age of H I holes can be estimated based on their size and expansion velocities, if observable. This calculation is very uncertain and typically provides at most an upper limit to the true age as expansion velocities are expected to slow over time. However, they provide an order-of-magnitude estimate of the timescale over which these structures are observable. Seven galaxies overlap between our sample and that of Bagetakos et al. (2011) (NGC 2366, Holmberg II, IC 2574, Holmberg I, NGC 4214, DDO 154, and NGC 7793), who find a mean kinematic age in dwarfs of ~ 32.5 Myr. We therefore adopt this value for τ_{holes} with the caveat that it is uncertain, and only consider star formation energy input over the approximate timescale on which H I signatures of expansions are expected to decay. We use the same formalism as in Equation 3.27 and § 3.6.3.3 to estimate star formation energy, substituting 32.5 Myr for τ_D .

In Figure 3.31, we compare the energy available from star formation to the energy in the superprofile wings. In the left panel, we plot the star formation energy versus the wing kinetic energy for each galaxy. Dashed grey lines indicate a constant efficiency of transferring star formation energy to kinetic H I energy, where $\epsilon_{\text{SF,wings}} \equiv E_{\text{wings}}/E_{\text{SF}}$. As in Figures 3.29 and 3.30, grey regions of the plot show unphysical or theoretically prohibited efficiencies, i.e., $\epsilon_{\text{SF,wings}} > 1$ and $\epsilon_{\text{SF,wings}} > 0.1$. The right panel shows the inferred efficiency $\epsilon_{\text{SF,wings}}$ versus the star formation energy available.

We find that all of galaxies require efficiencies of only < 0.05 to produce enough energy to drive H I gas into the wings over a timescale of 32.5 Myr. The distribution has a median $\epsilon_{\text{SF,wings}} = 0.013$ with a standard deviation of 0.007. These estimates are well below with the theoretical maximum of 0.1 – 0.5 found by Tenorio-Tagle et al. (1991) and Thornton et al. (1998), and are in line with simulations by Joung et al. (2009) that show that $\sim 35\%$

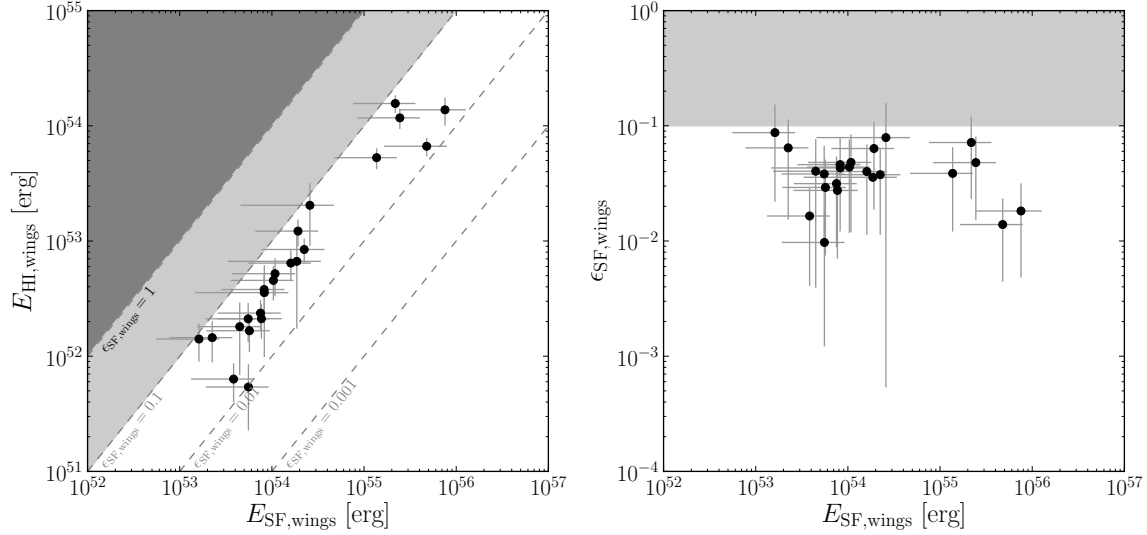


Figure 3.31 The left panel shows the energy available from star formation over 32.5 Myr versus H I energy in the wings of the superprofile. The dashed grey lines indicate constant efficiency, and the shaded grey region represents unphysical efficiencies where $\epsilon_{\text{SF,wings}} > 1$. The right panel shows $\epsilon_{\text{SF,wings}}$ versus E_{SF} . The mean required efficiency is $\epsilon_{\text{SF,wings}} = 0.042 \pm 0.020$.

of star formation energy goes into driving large-scale bulk motions. The required efficiencies are also much lower than estimates of efficiencies necessary to drive larger H I holes, which range between 1 - 40% at their kinematic ages (e.g., Weisz et al., 2009a; Warren et al., 2011; Cannon et al., 2011; Bagetakos et al., 2011). However, we have derived these estimates from global properties. A more precise determination is necessary using spatially-resolved data scales, as previous studies have shown that the value of the second moment declines with radius Tamburro et al. (2009), therefore changing the energy in the wings based on location in the galaxy.

We next consider the possibility that the gas in the wings is instead representative of a turbulent component. In this case, the relevant timescale to consider is the turbulent dissipation timescale, as given by Equation 3.25. Even though the velocity profile of H I in the wings is not Gaussian in our parameterization, it again provides an order-of-magnitude estimate of how long this component can dissipate its energy if it is indeed turbulent. In this case, it may be more relevant to use measured σ_b values for double Gaussian fits instead

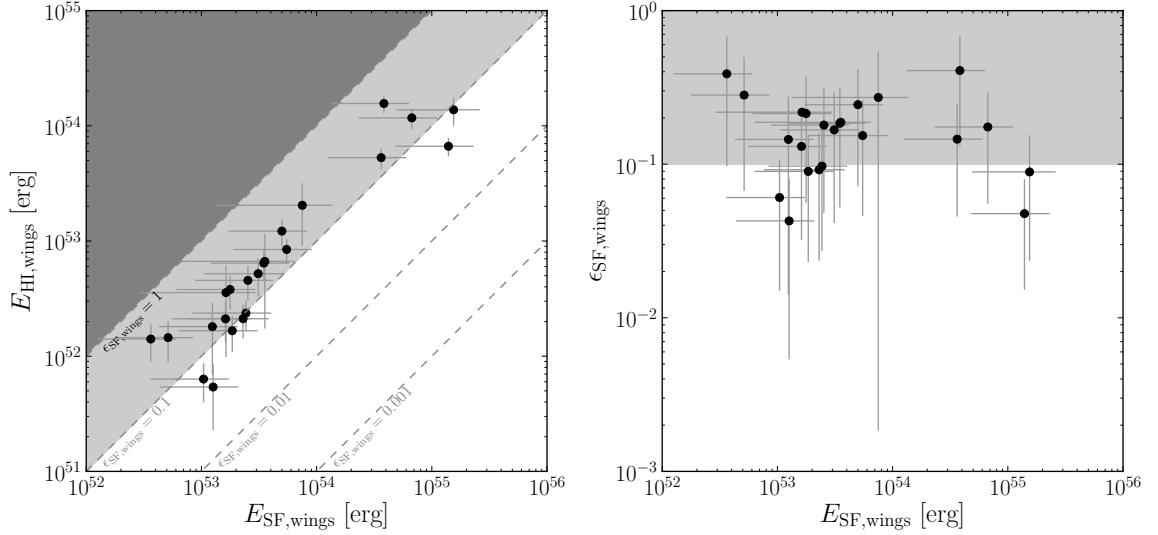


Figure 3.32 The left panel shows the energy available from star formation over one turbulent timescale versus H I energy in the wings of the superprofile. The dashed grey lines are constant efficiency, and the shaded grey region represents unphysical efficiencies where $\epsilon_{\text{SF,wings}} > 1$. The right panel shows $\epsilon_{\text{SF,wings}}$ versus E_{SF} . The mean required efficiency is $\epsilon_{\text{SF,wings}} = 0.174 \pm 0.095$.

of σ_{wings} , because our parameterization explicitly removes gas with small velocities from the σ_{wings} calculation. Because the double Gaussian fits appear to be determined primarily by the wings (see § 3.4.3.1), we choose to use σ_b to calculate τ_D as the second timescale to consider. If we substitute σ_b for σ in Equation 3.25, we obtain values for $\tau_D \sim 6 - 10$ Myr, or $\sim 70\%$ of those determined for the central component. As before, we use Equation 3.27 to calculate the input energy over this turbulent dissipation timescale determined for the wings.

Figure 3.32 shows the comparison of energy in the wings to energy provided by star formation over one turbulent timescale. The format is the same as Figure 3.30. In this case, implied efficiencies are higher by a factor of $\sim 3 - 5$ due to the difference in timescales, and are much closer to the theoretical maximum of 0.1 found by Thornton et al. (1998).

3.6.3.5 The Entire Superprofile

In this section we assess whether star formation provides enough energy to produce the H I velocity distribution seen in the superprofiles. In this case, the kinetic energy of the entire superprofile is simply:

$$E_{\text{SP}} = \frac{3}{2} \sum_v M(v) v^2 \quad (3.29)$$

where $M(v)$ is the H I mass at velocity v .

As with the central peak and the wings, we must determine the timescale over which to calculate energy input from star formation. Since the relevant timescales are unclear, we use both the turbulent timescale for the central peak and a fixed timescale of $\tau = 32.5$ Myr in Equation 3.27 to calculate energy input.

We show the comparison between energies over the turbulent timescale in Figure 3.33. Over this timescale, star formation provides enough energy to drive the full shape of the superprofile, but many galaxies lie in the $\epsilon > 0.1$ region unfavored by simulations (Thornton et al., 1998).

Figure 3.34 again shows the comparison between star formation and H I energies, but over the fixed timescale of $\tau = 32.5$ Myr. Over this timescale, star formation provides enough energy to drive kinematics in the entire H I superprofile at with $\epsilon < 0.1$. We note, however, that it is likely that the central peak and the wings of the superprofile have different associated timescales and efficiencies, so choosing single values to represent both components may not be physically appropriate.

3.6.4 Estimating the Scale Height of H I in the Sample

The scale height of the H I layer perpendicular to an isothermal, self-gravitating disk can be determined based on its velocity dispersion and disk surface mass density (van der Kruit, 1981). We use a method similar to that presented in Ott et al. (2001) and Warren et al. (2011) to approximate H I scale heights for our sample. The scale height h_z is given by van der Kruit (1981) as:

$$h_z = \frac{\sigma_{\text{gas}}}{\sqrt{4\pi G \rho_t}}, \quad (3.30)$$

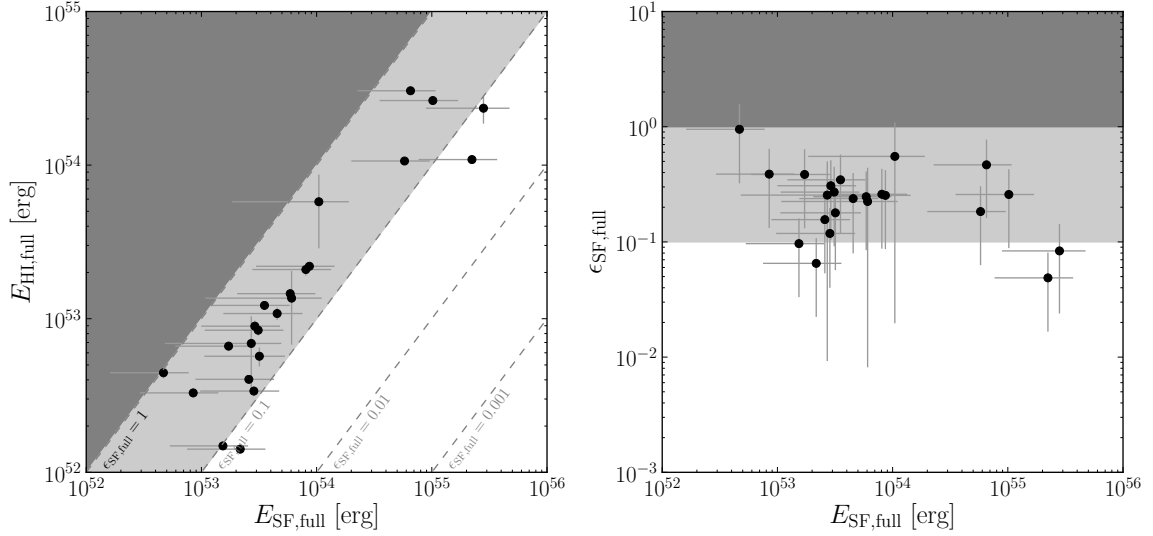


Figure 3.33 The left panel shows the energy available from star formation over a single turbulent timescale versus H I energy in the full superprofile. The dashed grey lines are constant efficiency, and the shaded dark grey region represents unphysical efficiencies where $\epsilon_{\text{SF,full}} > 1$, while light grey is where $\epsilon_{\text{SF,full}} > 0.1$. The right panel shows $\epsilon_{\text{SF,full}}$ versus E_{SF} . The mean required efficiency is $\epsilon_{\text{SF,full}} = 0.275 \pm 0.190$.

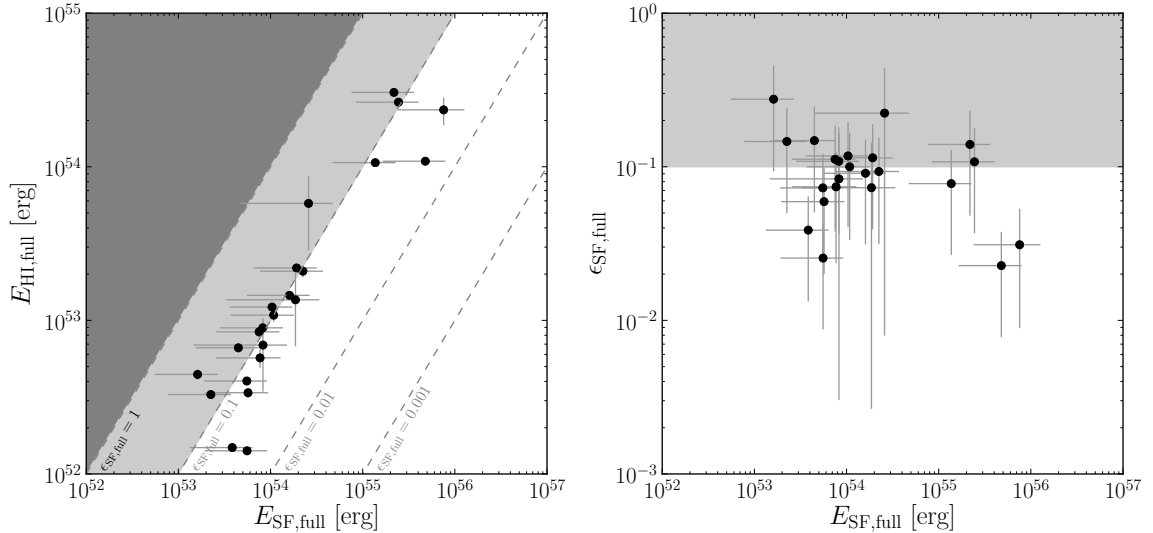


Figure 3.34 The left panel shows the energy available from star formation over 32.5 Myr versus H I energy in the full superprofile component. The dashed grey lines indicate constant efficiency, and the shaded grey region represents unphysical efficiencies where $\epsilon_{\text{SF,full}} > 0.1$ (light grey) and $\epsilon_{\text{SF,full}} > 1$ (dark grey). The mean required efficiency is $\epsilon_{\text{SF}} = 0.102 \pm 0.058$.

where σ_{gas} is the velocity dispersion perpendicular to the disk, G is the gravitational constant, and ρ_t is the stellar mass density of the disk. If we assume that H I has a Gaussian distribution in the z -direction, we find that:

$$N_{\text{HI}} = \sqrt{2\pi} h_z n_{\text{HI},0}, \quad (3.31)$$

where N_{HI} is the H I column density and $n_{\text{HI},0}$ is the number density at the midplane of the disk. These two equations were combined by Ott et al. (2001) to find an expression for H I scale height in terms of observables:

$$h_z = 579 \left(\frac{\sigma_{\text{gas}}}{10 \text{ km s}^{-1}} \right)^2 \left(\frac{N_{\text{HI}}}{10^{21} \text{ cm}^{-2}} \right)^{-1} \left(\frac{\rho_{\text{HI}}}{\rho_t} \right) \text{ pc}, \quad (3.32)$$

where ρ_{HI}/ρ_t is the ratio between H I density to total disk density, and can be approximated as $(\rho_{\text{HI}}/\rho_t) = (M_{\text{hi}}/M_t)$ where $M_t = 1.36M_{\text{HI}} + M_*$.

Using our superprofiles and measured galaxy properties, we can estimate the average H I scale height of the disk. We first assume that the velocity dispersion is isotropic, such that $\sigma_z = \sigma_{\text{central}}$. Second, we convert $\langle \Sigma_{\text{HI}} \rangle$ to N_{HI} units with the caveat that we have averaged these quantities over the disk and have not included the contribution of dark matter. We note that since these values are averaged over the disk of the galaxy, any spatial variation in these parameters is no longer distinct. H I scale heights in galaxies are expected to flare at large radii, as gas velocity dispersions remain relatively constant but disk surface density declines with radius. This method therefore gives an estimate for H I scale height that is weighted toward the regions with the highest H I surface densities. The average H I scale heights derived from these values are listed in Table 3.8. The majority of galaxies have implied scale heights between $100 < \langle h_z \rangle < 700$ pc, with a median of 320 pc and interquartile range of 210 – 480 pc.

Scale heights for some of the galaxies in our sample have been determined using other methods. Banerjee et al. (2011) modeled the dark matter and baryonic components of halos for DDO 154, Ho II, IC 2574, and NGC 2366. They obtained scale heights between ~ 130 pc at $r = 0$ kpc to ~ 1 kpc at $r = 6$ kpc for DDO 154; between ~ 180 pc at $r = 1$ kpc to ~ 1 kpc at $r = 7$ kpc for NGC 2366; between ~ 350 pc at $r = 1.5$ kpc to ~ 700 pc at $r = 9$ kpc for IC 2574; and a fixed scale height of ~ 400 pc at all radii for Ho II. Compared

Table 3.8: Implied scale heights for sample galaxies. (1) Galaxy name. (2) Average scale height implied by σ_{central} and $\langle \Sigma_{\text{HI}} \rangle$.

1	2
Galaxy	$\langle h_z \rangle$
	(pc)
NGC 7793	78 ± 43
IC 2574	336 ± 87
NGC 4214	228 ± 103
Ho II	302 ± 75
NGC 2366	479 ± 93
DDO 154	708 ± 139
Ho I	191 ± 41
NGC 4190	130 ± 65
NGC 3741	561 ± 123
Sextans A	438 ± 84
DDO 53	259 ± 51
DDO 190	214 ± 65
DDO 125	329 ± 135
Sextans B	639 ± 224
DDO 99	617 ± 161
M81 DwB	140 ± 65
UGCA 292	172 ± 29
NGC 4163	120 ± 61
UGC 4483	322 ± 67
DDO 181	346 ± 104
UGC 8833	313 ± 76
DDO 187	514 ± 108
GR 8	344 ± 100

to the Banerjee et al. (2011) scale heights, our method yields scale heights that are within the same range for DDO 154 and NGC 2366 but smaller by 35% and 25% for IC 2574 and Ho II, respectively.

3.6.5 *A Universal H I Profile Shape?*

As seen in Figure 3.13, the superprofiles show a distinct velocity distribution: a central peak with strong contributions from non-Gaussian wings. After normalization to the same HWHM, the uniformity of the profiles is striking, especially considering that the low-mass dwarf galaxies in our sample are typically characterized by irregular velocity fields and morphologies, and stochastic, varied star formation histories (Weisz et al., 2011). The residuals also show a surprisingly similar shape, with the peak often occurring at $2 \times \text{HWHM}$ across the observed range of f_{wings} . This global regularity exists in spite of the fact that the individual line-of-sight H I profiles have a much more varied shape, with some showing asymmetry (e.g., Young et al., 2003; Warren et al., 2012) or double peaks indicative of expanding structures (e.g., Bagetakos et al., 2011). Statistically, however, the sum of these profiles generates the same kinematic distribution from galaxy to galaxy.

The shape of the superprofiles on global scales is qualitatively similar to those found by other studies of average H I line profiles, which also show a mostly Gaussian central peak with broader wings (e.g., Dickey et al., 1990; Boulanger & Viallefond, 1992; Kamphuis & Sancisi, 1993; Braun, 1997; Petric & Rupen, 2007; Ianjamasimanana et al., 2012). It also matches the shape of simulated H I profiles found by Joung et al. (2009) for a supernova-driven turbulent medium, though at lower star formation intensities. However, quantitative comparisons among the surveys are hindered by the vast differences both in observational parameters such as spatial and spectral resolution as well as in techniques for removing the rotational velocity. Nonetheless, many of the studies, including our own, find that the broad central peaks can be characterized reasonably well by Gaussians with widths of 5-10 km s^{-1} , with additional wings to either side. The similarities indicate that the shape of the H I line profile, and therefore the general kinematic structure of H I line profiles, are relatively independent of galaxy properties. However, uniform studies of larger spirals with

better velocity resolution, now possible with the larger bandwidth of the newly-updated JVLA, are necessary to confirm this idea.

3.7 Conclusions

We have generated a measure of global H I kinematics in a sample of nearby dwarf galaxies from VLA-ANGST and THINGS by summing the contribution to a global line profile for each line-of-sight spectrum after removing rotation from each spectrum. The resulting superprofile for an individual galaxy provides an intensity-weighted average of its individual H I line profiles.

We interpret the superprofiles as composed of a central peak indicating average turbulence with higher-velocity wings to either side. We parameterized them with four parameters describing the width of the central peak (σ_{central}), the characteristic velocity of the wings (σ_{wings}), the fraction of gas in the wings (f_{wings}), and the asymmetry (a_{wings}). We have compared these parameters to various global galaxy properties in order to determine what, if any, physical causes are behind H I kinematics.

- The dynamic range of σ_{central} is quite small, varying only between $\sim 6 - 10 \text{ km s}^{-1}$ across our sample. We find a correlation between σ_{central} and $\langle \Sigma_{\text{HI}} \rangle$ in the dwarf sample which is not significant once higher mass galaxies are added. The measured σ_{central} values are close to but slightly higher than line widths that can be driven by background UV heating. It is possible that base H I velocity dispersions are set by this heating, with star formation imparting only additional energy.
- The characteristic velocity of gas in the wings, σ_{wings} , increases with $\langle \Sigma_{\text{SFR}} \rangle$, $\langle \Sigma_{\text{baryon}} \rangle$, and $\langle \Sigma_{\text{HI}} \rangle$, implying that star formation could be one way to accelerate H I to velocities faster than expected compared to the surrounding turbulent medium.
- The fraction of gas in the wings, f_{wings} , increases with galaxy mass and with SFR / M_{HI} , so galaxies with relatively high SFR or low M_{HI} could be better able to accelerate H I to higher velocities.

- The asymmetry, a_{wings} , decreases with both SFR and with galaxy mass, and is primarily in the wing regions. This supports the idea that star formation can accelerate H I away asymmetrically, so galaxies with smaller SFR likely have fewer star-forming regions and thus show more asymmetry.

In all cases, our trends exhibit large scatter. Since many of the physical properties we examined vary on both radial and spatial scales, future analyses must incorporate this information to disentangle any causal connection with H I gas kinematics.

We have also compared the energy contained in the H I superprofiles with the energy provided by the gravitational instability from Wada et al. (2002) and by star formation. We find that this gravitational instability cannot provide enough energy to drive turbulent line widths on timescales of ~ 10 Myr, while star formation can. Star formation also imparts enough energy to accelerate gas into the wings of the profile over timescales of ~ 32.5 Myr, with implied efficiencies below the theoretical maximum of 0.1 - 0.5.

We derived average H I scale heights for the sample, with most galaxies exhibiting scale heights of a few hundred pc.

Finally, we found that the average H I superprofile shape, when scaled to the same HWHM, has a remarkably similar shape from galaxy to galaxy, with variations primarily in the wings at low levels. The shape of the central component differs from a Gaussian by only ~ 0.05 with more varied wings showing additional emission 5-10% above the scaled Gaussian fit. This similarity implies that the physical processes setting the kinematics of H I in galaxies function similarly in all dwarf galaxies.

Chapter 4

DRIVERS OF H I TURBULENCE IN DWARF GALAXIES

Neutral hydrogen (H I) velocity dispersions are believed to be set by turbulence in the interstellar medium (ISM). Although turbulence is widely believed to be driven by star formation, recent studies have shown that this driving mechanism may not be dominant in regions of low star formation surface density (Σ_{SFR}), such as found in dwarf galaxies or the outer regions of spirals. We have generated average H I line profiles in a number of nearby dwarfs and low-mass spirals by co-adding H I spectra in subregions with either a common radius or Σ_{SFR} . We find that the individual spatially-resolved “superprofiles” are composed of a central narrow peak ($\sim 5 - 15 \text{ km s}^{-1}$) with higher velocity wings to either side, similar to their global counterparts as calculated for the galaxy as a whole. Under the assumption that the central peak reflects the H I turbulent velocity dispersion, we compare measures of H I kinematics determined from the superprofiles to local ISM properties, including surface mass densities and measures of star formation. The shape of the wings of the superprofiles do not show any correlation with local ISM properties, which indicates that they may be an intrinsic feature of H I line-of-sight spectra. On the other hand, the H I velocity dispersion is correlated most strongly with baryonic and H I surface mass density, which points at a gravitational origin for turbulence, but it is unclear which, if any, gravitational instabilities are able to operate efficiently in these systems. Star formation energy is typically produced at a level sufficient to drive H I turbulent motions at realistic coupling efficiencies in regimes where $\Sigma_{\text{SFR}} \gtrsim 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, as is typically found in inner spiral disks. At low star formation intensities, however, star formation cannot supply enough energy to drive the observed turbulence, nor does it uniquely determine the turbulent velocity dispersion. Nevertheless, even at low intensity, star formation does appear to provide a lower threshold for H I velocity dispersions. We find a pronounced decrease in coupling efficiency with increasing Σ_{SFR} , which would be consistent with a picture where star formation couples

to the ISM with constant efficiency, but that less of that energy is found in the neutral phase at higher Σ_{SFR} . We have examined a number of potential drivers of H I turbulence, including star formation, gravitational instabilities, the magneto-rotational instability, and accretion-driven turbulence, and found that, individually, *none* of these drivers is capable of driving the observed levels of turbulence in the low Σ_{SFR} regime. We discuss possible solutions to this conundrum.

4.1 Introduction

The local velocity dispersion of neutral hydrogen (H I) provides a good tracer of the small-scale kinematics of the interstellar medium (ISM) in disk galaxies. The velocity dispersions of H I clouds tend to range between $5 - 15 \text{ km s}^{-1}$ across a wide range of galaxy and ISM properties (e.g., Dickey et al., 1990; van Zee & Bryant, 1999; Tamburro et al., 2009). These velocity dispersions are thought to be turbulent in nature (e.g., Mac Low & Klessen, 2004) because they are much greater than the velocity dispersions expected for the stable thermal temperatures in the ISM (1 km s^{-1} and 7 km s^{-1} for the cold and warm neutral phases; e.g., Wolfire et al., 1995). H I velocity dispersions also tend to either remain constant or decrease with increasing galaxy radius in spirals and large dwarfs (Dickey et al., 1990; Boulanger & Viallefond, 1992; Petric & Rupen, 2007; Tamburro et al., 2009).

The origin of turbulent H I velocity dispersions remains uncertain, but many studies attribute H I turbulence to star formation and resulting supernova explosions (SNe; e.g., Mac Low & Klessen, 2004; Tamburro et al., 2009; Joung et al., 2009). This relationship seems to hold in the central regions of spiral galaxies, but breaks down at large radii where star formation intensity drops dramatically while H I velocity dispersions remain relatively constant (e.g., Boulanger & Viallefond, 1992; van Zee & Bryant, 1999; Tamburro et al., 2009). For some massive spiral disks, H I velocity dispersions at large radii have been tentatively attributed to turbulence induced by non-stellar sources, such as the magneto-rotational instability (MRI; e.g., Sellwood & Balbus, 1999; Zhang et al., 2012). However, this outer disk regime exhibits star formation rate intensities and H I velocity dispersions similar to those found in dwarf galaxies, which tend to have solid-body rotation curves (e.g., Oh et al., 2011) and therefore lack the shear required for the MRI to function efficiently. However,

H I velocity dispersions in the outskirts of some dwarfs are not necessarily correlated with optical features or star forming regions (e.g., Hunter et al., 1999, 2001). Studies of the relationship between star formation and H I velocity dispersions in dwarf galaxies may therefore help address the question of what provides the energy to drive H I turbulence, particularly in regions where other proposed turbulence drivers are inefficient.

Chapter 3 presented a method to characterize the average H I kinematics in dwarf galaxies by co-adding individual line-of-sight profiles after removal of the rotational velocity for a single galaxy, as also used by Ianjamasimanana et al. (2012). These “superprofiles” were composed of a central peak with higher-velocity wings to either side. We interpreted the central peak of the superprofile as representative of the average H I turbulent kinematics, with the higher velocity wings representing anomalous motions such as expanding H I holes or other bulk flows. However, our conclusions were limited by the fact that the superprofiles were generated on global scales, whereas H I velocity dispersions are known to vary across the disk.

In this paper, we extend the technique presented in Chapter 3 to analyze subregions of these same galaxies. By extending our analysis to carefully-chosen subregions, we can essentially increase the dynamic range of various quantities, such as Σ_{SFR} , Σ_{HI} , and $\Sigma_{\text{SFR}} / \Sigma_{\text{HI}}$, which were forced to galaxy-wide averages in our earlier analysis. In contrast, many of the proposed drivers of turbulence are local phenomena. This approach therefore provides a more direct assessment of which parameters influence H I kinematics.

We first compute superprofiles in radial annuli to facilitate comparison with Tamburro et al. (2009), who found that star formation does not provide enough energy to drive H I velocity dispersions outside the optical radius r_{25} of spiral galaxies. However, radius is not necessarily a good proxy for local ISM properties like Σ_{SFR} and Σ_{HI} in the low-mass dwarfs in our sample. We therefore also generate superprofiles in regions of constant Σ_{SFR} to maximize the sensitivity of the effects that star formation may have on H I kinematics. Our study is complementary to that of Tamburro et al. (2009), as we focus on lower-mass galaxies and isolate regions with similar star formation surface density.

The layout of this chapter is as follows. In § 4.2, we discuss the data used to generate spatially-resolved superprofiles and other galaxy properties. In § 4.3, we give a brief overview

of the method used to generate the superprofiles, present the spatially-resolved superprofiles, and address their robustness. In § 4.4, we compare the superprofile parameters to galaxy physical properties. In § 4.5, we then discuss the relevant correlations and compare star formation energy to H I energy. Finally, we summarize the conclusions in § 4.6. Figures of the spatially-resolved superprofiles for the entire sample are presented at the end of the chapter in §4.7 as a general reference.

4.2 Data

We use H I data from the Very Large Array ACS Nearby Galaxy Survey Treasury Program (“VLA-ANGST”; Ott et al., 2012) and The H I Nearby Galaxy Survey (“THINGS”; Walter et al., 2008). Following Chapter 3, we convolve these data to a common physical resolution of 200 pc to ensure that we are sampling ISM properties on the same physical scale for our entire sample. All spatially-resolved ancillary data have also been convolved to this resolution to ensure a robust comparison between H I kinematics and other ISM properties. We assume distances as listed in Table 3.1 of Chapter 3, as compiled from Ott et al. (2012), Walter et al. (2008), and Dalcanton et al. (2009).

4.2.1 Initial Sample Selection

We select our analysis sample for this paper from a subset of galaxies in Chapter 3. Briefly, the selection criteria used in Chapter 3 are:

1. Instrumental angular resolution smaller than 200 pc, to avoid artificially broadening H I line-of-sight spectra at coarser resolution.
2. Velocity resolution $\Delta v \leq 2.6 \text{ km s}^{-1}$, to resolve the width of the H I line-of-sight spectra.
3. Inclination $i < 70^\circ$, to avoid broadening H I line-of-sight spectra with rotation.
4. No noticeable contamination from the Milky Way or a companion, to ensure that detected H I belongs to each galaxy.

5. More than 10 independent beams across the galaxy above a signal to noise threshold of $S/N > 5$, to allow for accurate determination of the peak of H I line-of-sight spectra.
6. Available ancillary far ultraviolet (FUV, GALEX) data, to uniformly measure SFRs.

In this paper, we apply additional selection criteria to the spatially-resolved superprofiles to ensure that they are robust. We have empirically found that superprofiles with fewer than 5 contributing independent beams are too noisy to accurately determine superprofile parameters, which eliminates four low-mass galaxies (DDO 125, M81 DwB, NGC 4163, and GR 8) from the Chapter 3 sample. Second, the superprofiles in the other disks of some of the larger galaxies exhibit “clean bowls” that hinder accurate parameterization. These clean bowls are due to missing short-spacings at the VLA, and can present as negative flux on either side of the central peak in the superprofiles generated at large radii for some galaxies. We eliminate these superprofiles from our analysis, and note that they usually occur past $2r_{25}$.

General properties of the final sample are given in Table 4.1. Galaxies are listed in order of decreasing total baryonic mass ($M_{\text{baryon,tot}}$). We list: (1) the galaxy name; (2) the H I survey from which data were taken; (3-4) the position in J2000 coordinates; (5) distance in Mpc; (6) inclination in degrees; (7) total baryonic mass, $M_{\text{baryon,tot}}$; (8) total H I mass, $M_{\text{HI,tot}}$; (9) SFR as determined from FUV+24 μm emission; (10) the optical radius at a B -band surface brightness of 25 mag arcsec $^{-1}$ (r_{25}); and (11) de Vaucouleurs T-type. All references are given in Chapter 3, with the exception of the inclination for Sextans B. The $i = 52^\circ$ value given in Chapter 3 is a poor match to the H I morphology; we adopt $i = 30^\circ$, which is a much better match to the properties of the H I disk.

4.2.2 Converting Ancillary Data to Physical Properties

Detailed information about the data used and methodology for deriving galaxy physical properties are given in Chapter 3. For this study in particular, we focus on the SFR surface density (Σ_{SFR}); the star formation rate per available H I mass ($\Sigma_{\text{SFR}} / \Sigma_{\text{HI}}$); and the H I and baryonic surface densities (Σ_{HI} , Σ_{baryon}). Briefly, we calculate Σ_{SFR} using FUV

and $24\mu\text{m}$ data from the Local Volume Legacy Survey (“LVL”; Dale et al., 2009) and the methodology outlined in Leroy et al. (2008) and Chapter 3. We derive stellar surface mass density from LVL $3.6\mu\text{m}$ data and apply the conversion factor given in Leroy et al. (2008) and Chapter 3. Finally, we derive baryonic surface mass density by combining the H I gas mass, including a factor of 1.36 correction for helium, with the stellar mass. All surface densities are inclination-corrected.

For each superprofile subregion, we calculate Σ_{HI} , Σ_{baryon} , and Σ_{SFR} by taking the total M_{HI} , M_{baryon} , and SFR in that subregion divided by its inclination-corrected area. We also calculate $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$ by measuring the total SFR in that subregion divided by the total H I mass in that subregion. In the outer regions of Sextans B, the low levels of star formation plus noise conspire to produce negative total SFRs in three resolved superprofiles. In these cases, we artificially set $\Sigma_{\text{SFR}} = 10^{-6} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ and recalculate other SF-related quantities using that value.

We note that local ISM properties tend to be correlated; for example, regions with higher Σ_{SFR} tend to have higher Σ_{HI} . In Figure 4.1, we show the correlations between Σ_{SFR} , $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$, Σ_{HI} , and Σ_{baryon} as measured in subregions of constant radius (left) or constant star formation intensity (right). All of the physical properties under consideration are correlated with each other, so a correlation with one may be causally due to another.

4.3 Analysis

To estimate H I kinematics on spatially-resolved scales, we generate superprofiles in multiple subregions for each sample galaxy. We first give a brief overview of the methodology for generating and parameterizing the superprofiles in § 4.3.1 and § 4.3.2. We then discuss in detail how we generate superprofiles in spatially-resolved subregions for the sample in § 4.3.3.

4.3.1 Overview of the Superprofile Generation Procedure

A full discussion of the method used to derive superprofiles is given in Chapter 3, but we review the process here for clarity. We first measure the line-of-sight velocity of the peak (v_{peak}) of each line-of-sight spectrum, by fitting a Gauss-Hermite polynomials using the

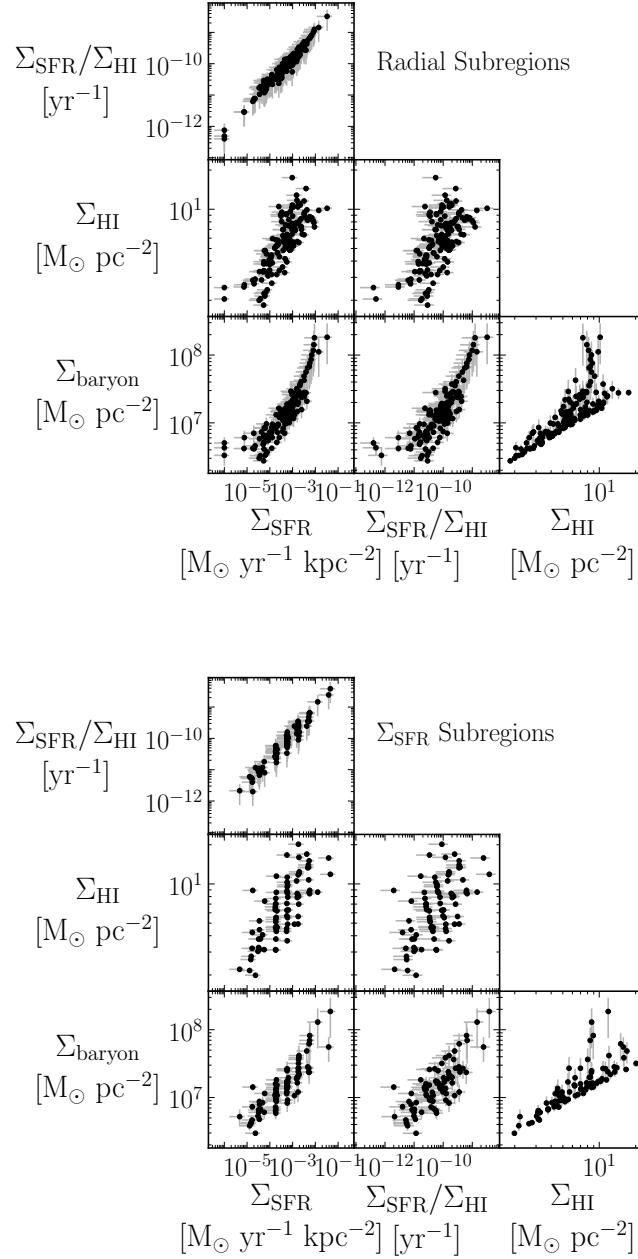


Figure 4.1 Correlations between measured ISM properties (Σ_{SFR} , $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$, Σ_{HI} , Σ_{baryon}) in subregions with constant radius (left) or constant star formation intensity (right). All axes are shown with log scaling, and the scaling of each individual panel is the same in the top and bottom panels. The resolved superprofiles are described further in § 4.3.3. The quantized lines in the left panel are an artifact of the Σ_{SFR} binning.

Table 4.1: The sample. Galaxies are listed in order of decreasing $M_{\text{baryon,tot}}$. All references are as given in Table 3.1. (1) Galaxy name. (2) H I survey. (3-4) Position in J2000 coordinates. (5) Distance in Mpc. (6) Inclination. (7) $M_{\text{baryon,tot}}$ in $\log M_{\odot}$. (8) $M_{\text{HI,tot}}$ in $\log M_{\odot}$. (9) SFR. (10) B -band r_{25} . (11) de Vaucouleurs T-type.

1	2	3	4	5	6	7	8	9	10	11
Galaxy	Survey	RA (hh:mm:ss)	Dec (dd:mm:ss)	Distance (Mpc)	i ($^{\circ}$)	$M_{\text{baryon,tot}}$ ($\log M_{\odot}$)	$M_{\text{HI,tot}}$ ($\log M_{\odot}$)	SFR ($10^{-3} M_{\odot} \text{ yr}^{-1}$)	r_{25} (kpc)	Type
NGC 7793	THINGS	23:57:49.7	-32:35:28	3.90	50	9.7	8.9	258.88	5.9	7
IC 2574	THINGS	10:28:27.7	+68:24:59	3.79	55	9.4	9.1	71.72	7.1	9
NGC 4214	THINGS	12:15:39.2	+36:19:37	3.04	44	9.2	8.6	128.09	3.0	10
Ho II	THINGS	08:19:05.0	+70:43:12	3.38	49	9.0	8.8	45.40	3.2	10
NGC 2366	THINGS	07:28:53.4	+69:12:51	3.21	63	9.0	8.8	53.98	2.0	10
DDO 154	THINGS	12:54:05.9	+27:09:10	4.30	66	8.7	8.6	5.79	1.2	10
Ho I	THINGS	09:40:32.3	+71:10:56	3.90	13	8.4	8.2	6.04	1.9	10
NGC 4190	VLA-ANGST	12:13:44.6	+36:38:00	3.50	41	8.1	7.7	5.19	0.9	10
NGC 3741	VLA-ANGST	11:36:06.4	+45:17:07	3.24	64	8.1	7.9	4.53	0.9	10
Sextans A	VLA-ANGST	10:11:00.8	-04:41:34	1.38	36	8.0	7.8	5.47	1.1	10
DDO 53	THINGS	08:34:07.2	+66:10:54	3.61	27	8.0	7.8	2.97	0.4	10
DDO 190	VLA-ANGST	14:24:43.5	+44:31:33	2.79	30	8.0	7.6	3.30	0.7	10
Sextans B	VLA-ANGST	10:00:00.1	+05:19:56	1.39	30	7.9	7.6	1.99	1.0	10
DDO 99	VLA-ANGST	11:50:53.0	+38:52:50	2.59	60	7.9	7.7	2.29	1.5	10
UGCA 292	VLA-ANGST	12:38:40.0	+32:46:00	3.62	16	7.8	7.6	1.10	0.5	10
UGC 4483	VLA-ANGST	08:37:03.0	+69:46:31	3.41	42	7.7	7.5	1.99	0.6	10
DDO 181	VLA-ANGST	13:39:53.8	+40:44:21	3.14	50	7.7	7.4	2.71	1.1	10
UGC 8833	VLA-ANGST	13:54:48.7	+35:50:15	3.08	33	7.4	7.1	0.62	0.4	10
DDO 187	VLA-ANGST	14:15:56.5	+23:03:19	2.21	55	7.3	7.1	0.44	0.5	10

standard data cube. We include only the line-of-sight spectra that have $S/N > 5$, where S/N is defined as the ratio between the maximum of the Gauss-Hermite polynomial and the noise in a single channel; simulations show that this S/N threshold results in an uncertainty of $< 2 \text{ km s}^{-1}$ in the measured v_{peak} . Finally, we shift each selected line-of-sight spectrum in the flux-rescaled data cube by its v_{peak} . During this process, we interpolate the spectra by a factor of 10, because v_{peak} can often be measured to a better accuracy than the width of a channel. These shifted spectra are then co-added to produce a flux-weighted average H I spectrum, or “superprofile.”

As discussed in Chapter 3, we estimate the noise on each pixel of the superprofiles using:

$$\sigma_{\text{SP}} = \sigma_{\text{chan}} \times \sqrt{\frac{N_{\text{pix}}}{N_{\text{pix/beam}}}} \times \frac{F_{\text{rescaled}}}{F_{\text{standard}}}, \quad (4.1)$$

where σ_{chan} is the *rms* noise in a single channel, $N_{\text{pix}}/N_{\text{pix/beam}}$ is the number of independent resolution elements contributing to each superprofile point, and $F_{\text{rescaled}}/F_{\text{standard}}$ is a factor that approximates the flux-rescaling process in the flux-rescaled data cube.

4.3.2 Overview of Superprofile Parameterization

We show an example of a global superprofile in Figure 4.2 from Chapter 3. The superprofile itself is shown as a thick black line; the uncertainties are smaller than the width of the superprofile line. The central peak is largely Gaussian, with only $\sim 5\%$ deviations, with excess flux in the wings of the superprofile. In Chapter 3, we proposed that the superprofiles could be parameterized as a turbulent peak, with wings to either side representing higher-velocity H I. We adopt the same physical interpretation in this study.

We first parameterize the central peak of the superprofile with a Gaussian profile whose amplitude and half-width half-maximum (HWHM) are matched to those of the superprofile. We adopt the standard deviation of this Gaussian profile as the width of the central peak (σ_{central}). The HWHM-scaled Gaussian profile for the global superprofile of Sextans A is shown as a dashed red line in Figure 4.2.

In addition to a Gaussian core, the superprofiles tend to have high velocity gas in excess of a single Gaussian extrapolation of the central peak. This excess high-velocity gas is shown in Figure 4.2 as the transparent red region between the HWHM-scaled Gaussian fit

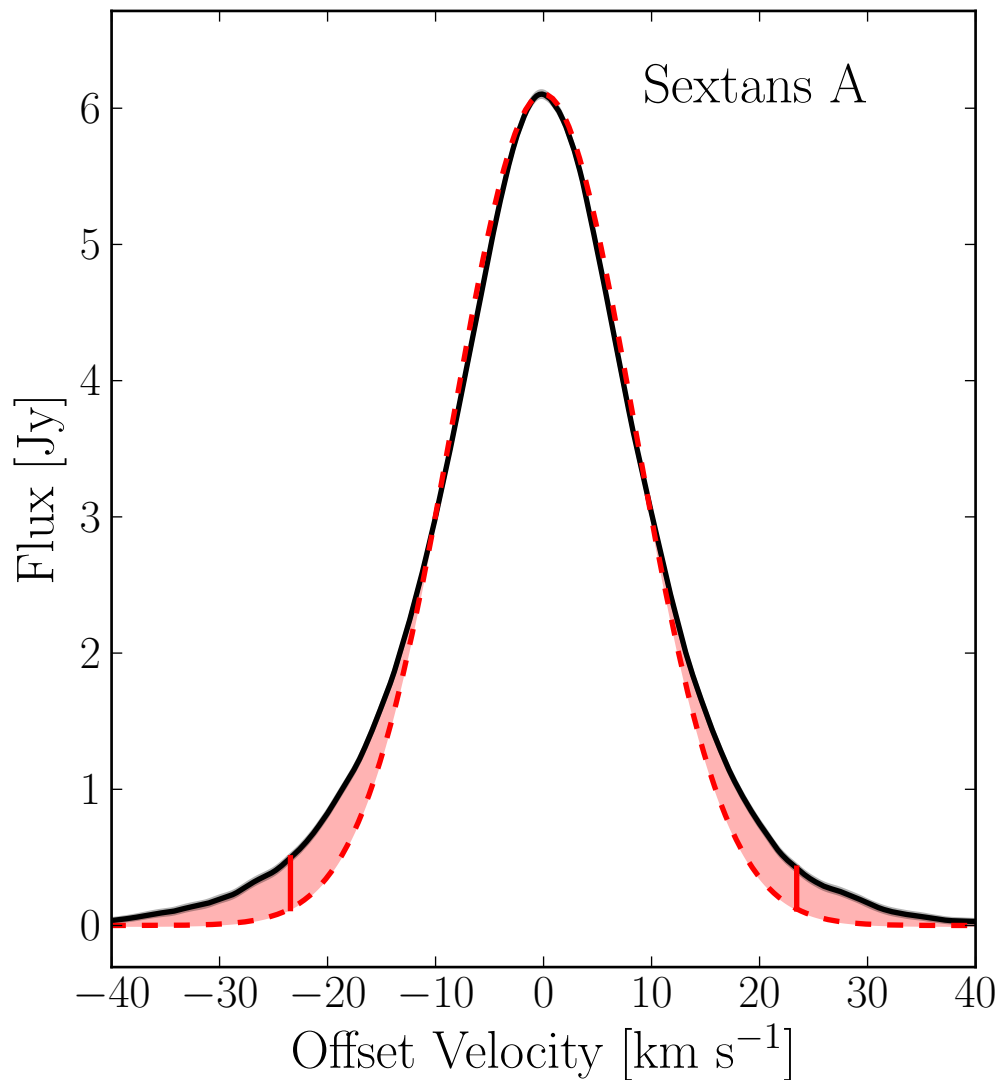


Figure 4.2 The global superprofile for Sextans A, from Chapter 3. The superprofile itself is shown as the thick black line. The uncertainties are smaller than the width of the line. The dashed red line shows the HWHM-scaled Gaussian model. The shaded red regions between the dashed red line and the superprofile represent H I in the wings of the profile, f_{wings} . The solid red lines at $\sigma_{\text{wings}} \sim \pm 23 \text{ km s}^{-1}$ represent the excess-flux-weighted root mean square velocity of the wings. Because the superprofiles are the analog of integrated line profiles but with each contributing spectra shifted by its v_{peak} , we have shown the y-axis in Jy.

and the superprofile itself. We estimate the fraction of higher-velocity gas in the wings of the superprofile using:

$$f_{\text{wings}} = \frac{\sum_{|v| > \text{HWHM}} [S(v) - G(v)]}{\sum_{|v| > 0} S(v)}, \quad (4.2)$$

where v is the velocity, $S(v)$ is the superprofile intensity at v , and $G(v)$ is the value of the HWHM-scaled Gaussian at v .

We characterize the typical velocity of the wings using the *rms* velocity of excess flux in the wings:

$$\sigma_{\text{wings}}^2 = \frac{\sum_{|v| > \text{HWHM}} [S(v) - G(v)] v^2}{\sum_{|v| > \text{HWHM}} [S(v) - G(v)]}. \quad (4.3)$$

The σ_{wings}^2 parameter provides an estimate of the energy per unit mass in the wings of the superprofile. In Figure 4.2, σ_{wings} is shown to either side of the profile as a solid vertical red line between the HWHM-scaled Gaussian profile and the superprofile.

Finally, we quantify the asymmetry of the entire superprofile around the peak using:

$$a_{\text{full}} = \frac{\sum_v \sqrt{(S(v) - S(-v))^2}}{\sum_v S(v)}. \quad (4.4)$$

This quantity differs from the asymmetry parameter a_{wings} used in Chapter 3, which was calculated only for the wings ($|v| > \text{HWHM}$). In this study, we instead use the full asymmetry (a_{full}) because the asymmetry of the wings alone is much more sensitive to noise, which has a larger effect on superprofiles calculated for galaxy subregions as they include less flux. Although the asymmetry parameter in this study may be tracing different effects than that used in Chapter 3, the change to a_{full} is not extreme because the majority of the global superprofile asymmetry was due to the wings. We have verified that the global superprofiles presented in Chapter 3 follow the same trends with a_{full} as they do with a_{wings} .

The uncertainties on the superprofile parameters are discussed in detail in §4.3.4.

4.3.3 Spatially-Resolved Superprofiles

In Chapter 3, we included all selected line-of-sight spectra in the superprofile to derive an average H I spectrum for the entire galaxy. In this study, we generate superprofiles in subregions for each galaxy, determined either by radius or by local Σ_{SFR} .

First, we derive superprofiles in subregions of constant radius for the sample galaxies. We note that it is unlikely that radius itself is the actual driver of any trends, however, because H I kinematic properties are local and have no special knowledge about their location in the galaxy. Instead, any radial correlations are more likely to reflect the fact that other galaxy properties that do affect the local ISM also correlate with radius, such as Σ_{SFR} and Σ_{HI} , in large disks. However, we include this analysis because it facilitates comparison with Tamburro et al. (2009), who worked in radial annuli for more massive galaxies from the THINGS survey, although with a different methodology than we present here. We describe the superprofile generation on radial scales in more detail in § 4.3.3.1.

Second, we generate superprofiles in regions determined by the local Σ_{SFR} . Because star formation is a commonly-cited candidate in the literature for the driver of H I turbulence, this choice allows us to directly explore how the superprofiles change as a function of local star formation properties. We discuss the Σ_{SFR} superprofiles in more detail in § 4.3.3.2.

4.3.3.1 Superprofiles in Radial Subregions

First, we explore how the superprofiles behave as a function of radius. For the nine larger galaxies in our sample, we generate superprofiles in radially-resolved bins whose widths are based on the size of the beam. For these, the width of the annulus for each radially-resolved superprofile is chosen to be approximately two times the beam area, rounded to the nearest $0.05 r_{25}$, after correcting for inclination. These bin widths correspond to physical sizes of $100 - 500$ pc. For the 10 smaller dwarf galaxies with either small sizes or poorly-defined inclinations and position angles, it is impossible to generate reliable annuli with high signal-to-noise. In these cases, we instead generate superprofiles inside and outside r_{25} (typically $0.4 - 1.5$ kpc; Table 4.1).

In Table 4.2, we list the properties of resolved superprofiles for the sample. We list (1)

the galaxy name; (2) the number of beams across the entire galaxy at $S/N > 5$; (3) the number of superprofiles in radial subregions that meet the selection criteria for the galaxy; (4) the maximum radius at which we were able to generate a superprofile; (5) the step size for radial annuli; and (6) the number of superprofiles in Σ_{SFR} subregions that meet the selection criteria for the galaxy. For those galaxies where we have generated radial superprofiles only inside and outside r_{25} , we do not have values for r_{max} or Δr .

As an example, we show the behavior of the H I superprofiles as a function of radius for NGC 7793 in Figures 4.3a - 4.3c. In Figure 4.3a, we show the annuli in which we have generated superprofiles superimposed on the H I column density (N_{HI}) map. The solid black outline indicates the region within which all 200 pc-smoothed pixels in the H I data cube have $S/N > 5$. The solid colored lines mark the midpoint of each annulus, and the corresponding shaded color regions show the pixels that contribute to that annulus. The beam is shown in the lower left corner, and the physical resolution is indicated by a scale bar in the lower right corner.

In Figure 4.3b, we show the superprofiles that correspond to the annuli in Figure 4.3a. In the upper left panel, we plot the observed superprofiles. To highlight the cumulative contribution from each radial annulus to the total superprofile, each resolved superprofile plotted also includes the superprofiles at all smaller radii. In the lower left panel, we have normalized each radial superprofile to the same peak amplitude. The superprofiles are clearly wider in the central regions of NGC 7793 than in the outskirts. This behavior has previously been observed in other galaxies but using the H I second moment (Boulanger & Viallefond, 1992; Petric & Rupen, 2007; Tamburro et al., 2009). In the upper right panel, we have normalized the superprofiles by their amplitude and HWHM, as determined from the HWHM-scaled Gaussian model (thick black line). As seen in Chapter 3, the shape of these normalized superprofiles is typically very similar. In the lower right panel, we show the residuals of the superprofiles minus the HWHM-scaled Gaussian model. When compared to a Gaussian profile, the superprofiles typically have more flux in the wings and are peakier in the center. This behavior was clearly seen in the global superprofiles from Chapter 3, but clearly persists when analyzed on smaller spatial scales.

In Figure 4.3c, we show the behavior of the superprofile parameters for NGC 7793 as

a function of radius, normalized to r_{25} . Again, the color of each point corresponds to the same colored annulus in Figure 4.3a. The left-hand panels show σ_{central} (upper) and σ_{wings} (lower), and the right-hand panels show f_{wings} (upper) and a_{full} (lower).

In Figure 4.4, we show the behavior of σ_{central} with radius for the sample. Inspection of these figures shows that the more massive galaxies, such as NGC 4214 and NGC 7793, tend to show declining σ_{central} and σ_{wings} with increasing radius. These trends are similar to those discussed by Tamburro et al. (2009), who found that H I second moment declined with radius in the more massive galaxies of their sample. In contrast, the parameters for the lower mass galaxies (e.g., Sextans A) do not vary as smoothly with radius as those in larger galaxies. Other galaxy properties, such as SFR or Σ_{HI} , do not exhibit smooth radial trends in these dwarfs, so we would not necessarily expect smooth radial trends in the superprofile parameters of lower mass galaxies. This behavior reaffirms our expectation that H I kinematics are not determined by radius itself, but by other parameters that tend to correlate with radius in higher-mass galaxies.

We show the radially-resolved superprofiles for all sample galaxies at the end of the chapter in §4.7, in order of decreasing $M_{\text{baryon,tot}}$. For those 10 dwarf galaxies where radial analysis is impossible, we plot the superprofiles inside and outside r_{25} , colored respectively by blue and red.

4.3.3.2 Σ_{SFR} -determined Superprofiles

Because star formation is often connected to H I kinematics in the literature, we also generate superprofiles based on local values of the inclination-corrected star formation rate intensity Σ_{SFR} . This choice allows us to characterize how H I kinematics change as the star formation rate varies across the galaxy in a more direct way than the radial method.

Table 4.2: Superprofiles in spatially-resolved subregions. (1) Galaxy name. (2) Velocity resolution. (3) Total number of beams above $S/N > 5$ for the entire galaxy. (4) Number of radially-resolved superprofiles for this galaxy. (5) Maximum radius for superprofile generation (radial annuli only). (6) Radial step size (radial annuli only). (7) Number of constant- Σ_{SFR} superprofiles for this galaxy.

1	2	3	4	5	6	7
Galaxy	Δv	N_{beams}	N_{radial}	r_{max}	Δr	N_{SF}
	(km s ⁻¹)			(r_{25})	(r_{25})	
NGC 7793	2.6	909	21	1.25	0.05	6
IC 2574	2.6	2442	25	1.25	0.05	5
NGC 4214	1.3	1557	20	2.10	0.10	6
Ho II	2.6	924	17	1.80	0.10	5
NGC 2366	2.6	892	12	2.40	0.20	6
DDO 154	2.6	681	8	3.20	0.40	4
Ho I	2.6	161	9	1.30	0.10	4
NGC 4190	1.3	44	2	...	...	4
NGC 3741	1.3	111	2	...	...	3
Sextans A	1.3	214	7	1.60	0.20	5
DDO 53	2.6	92	2	...	...	5
DDO 190	2.6	76	2	...	...	5
Sextans B	1.3	259	9	2.00	0.20	4
DDO 99	1.3	91	2	...	...	4
UGCA 292	0.6	45	2	...	...	4
UGC 4483	2.6	54	2	...	...	3
DDO 181	1.3	53	2	...	...	3
UGC 8833	2.6	30	2	...	...	2
DDO 187	1.3	22	2	...	...	3

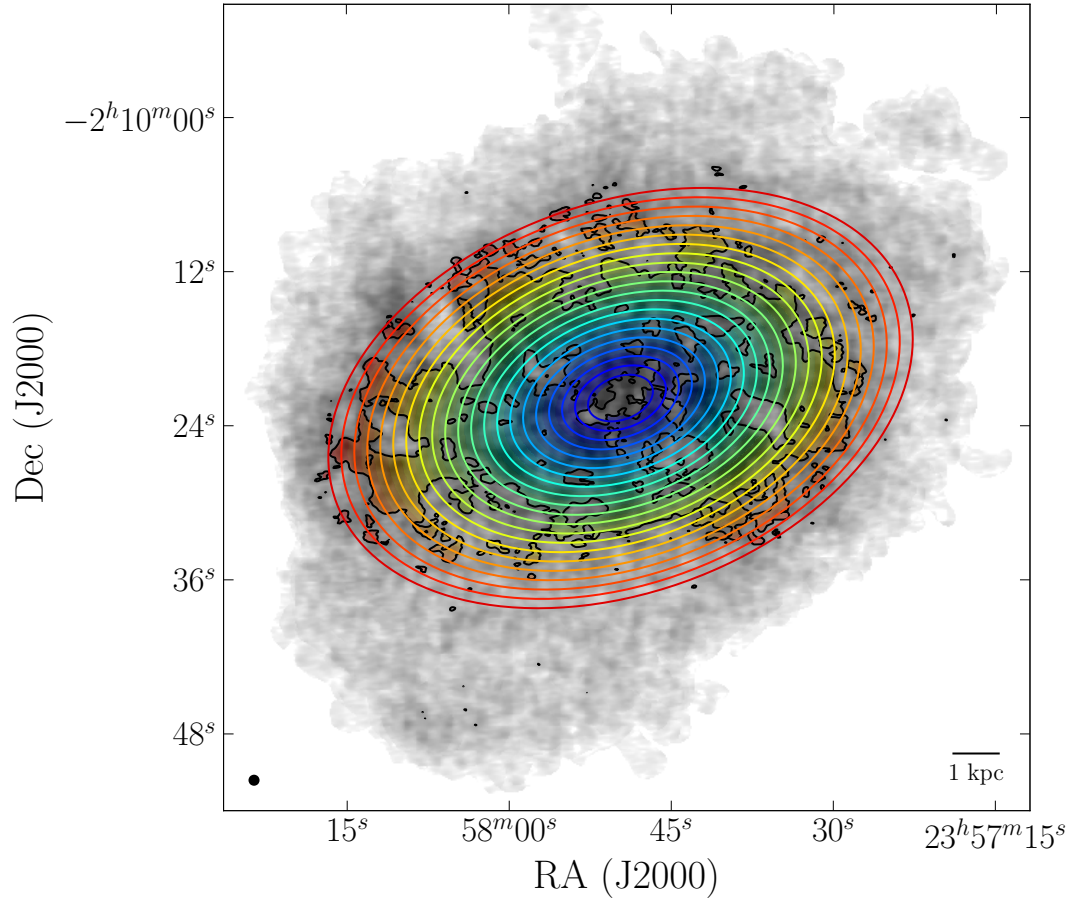


Figure 4.3a Radial annuli in which radial superprofiles are generated for NGC 7793. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

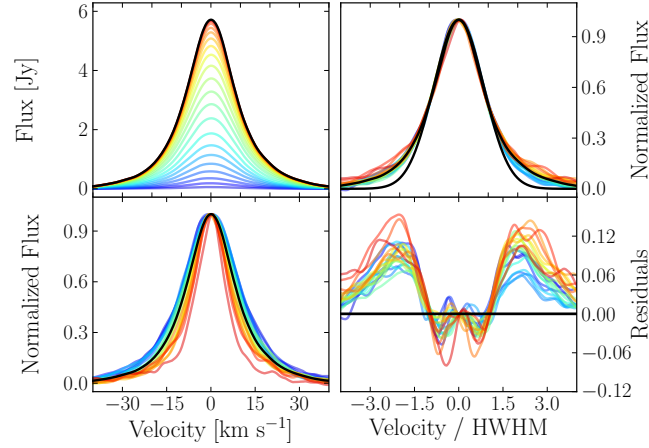


Figure 4.3b The radial superprofiles in NGC 7793, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

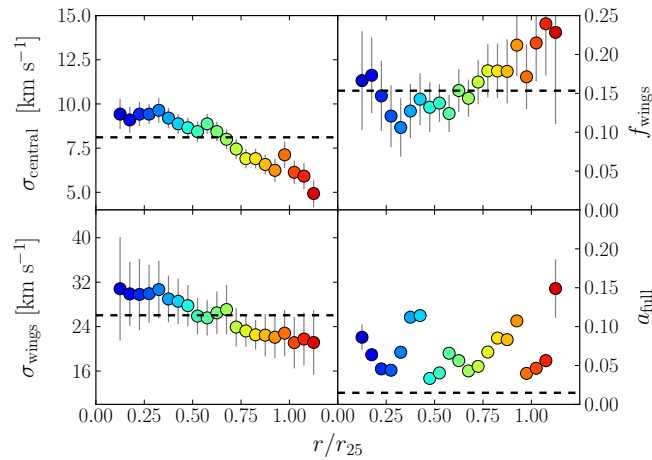


Figure 4.3c Variation of the superprofile parameters as a function of normalized radius for NGC 7793. The dashed black line shows the parameter value for the global superprofile (Chapter 3). We have plotted the equivalent a_{full} value of the global superprofile instead of a_{wings} , as measured in Chapter 3. The asymmetry of spatially-resolved profiles is higher than that of the global superprofile because smaller-scale asymmetries do not average out.

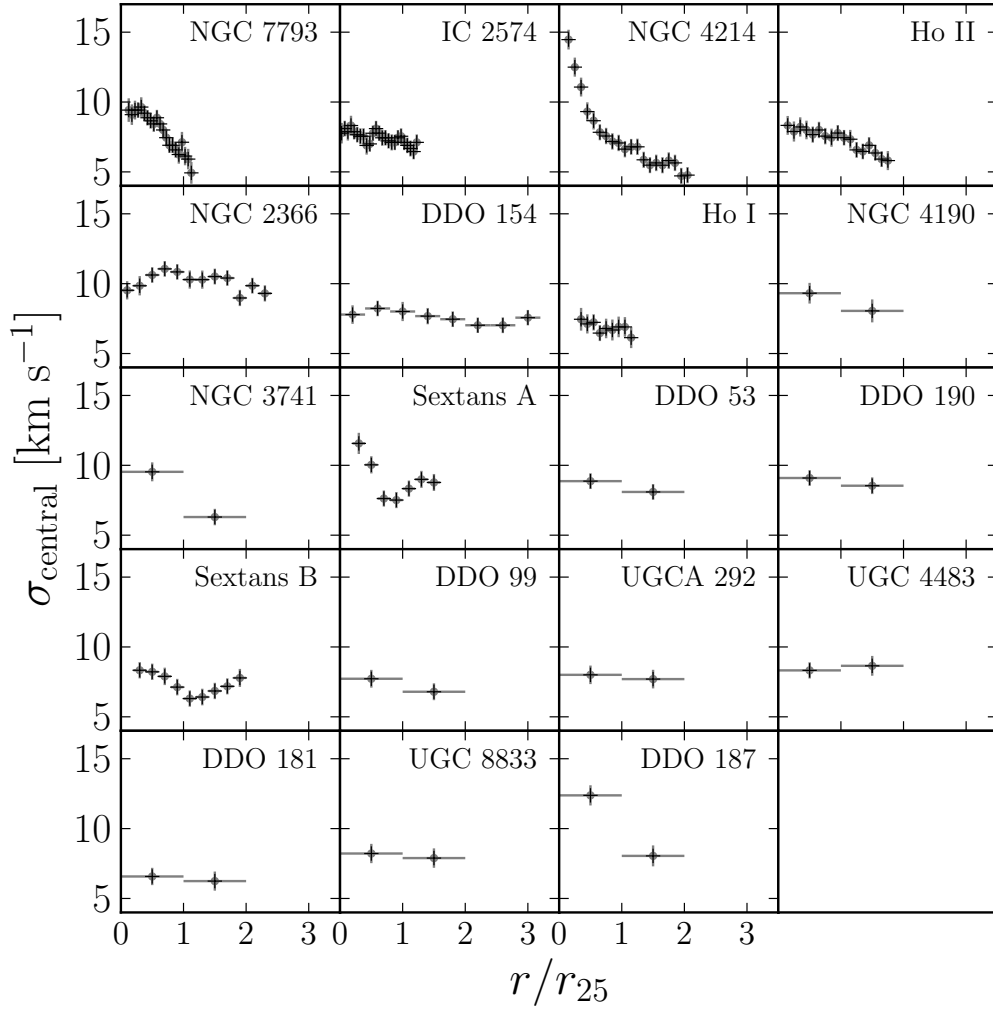


Figure 4.4 The velocity dispersion, σ_{central} , of the superprofiles generated in regions of constant radius. Each panel represents a single galaxy, and galaxies are ordered by decreasing $M_{\text{baryon,tot}}$. Within one panel, each point represents one superprofile. For those galaxies where we have generated superprofiles inside and outside r_{25} , we plot the two superprofiles at $r/r_{25} = 0.5$ and 1.5 , respectively. The velocity dispersion decreases smoothly with radius for the more massive galaxies, but shows erratic behavior for lower mass galaxies.

We have adopted six Σ_{SFR} bins for our analysis:

$$\begin{aligned}
 & \Sigma_{\text{SFR}} < 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2} \\
 10^{-4} & < \Sigma_{\text{SFR}} < 10^{-3.5} \\
 10^{-3.5} & < \Sigma_{\text{SFR}} < 10^{-3} \\
 10^{-3} & < \Sigma_{\text{SFR}} < 10^{-2.5} \\
 10^{-2.5} & < \Sigma_{\text{SFR}} < 10^{-2} \\
 10^{-2} & < \Sigma_{\text{SFR}}
 \end{aligned} \tag{4.5}$$

These values span the observed Σ_{SFR} range of our sample, but are small compared to typical Σ_{SFR} values for larger spirals, which can exceed $10^{-1} \text{ M}_{\odot} \text{ kpc}^{-2} \text{ yr}^{-1}$ in the central regions (e.g., Leroy et al., 2008).

For each galaxy, we generate superprofiles using pixels whose local Σ_{SFR} falls in each bin. We note that star formation rates in some of the lower-mass galaxies do not span the full Σ_{SFR} range sampled by our bins, and thus will have fewer than six superprofiles.

In Figure 4.5, we show histograms of the Σ_{SFR} values for the galaxies in our sample, ordered by decreasing $M_{\text{baryon,tot}}$. Each panel shows the distribution of inclination-corrected Σ_{SFR} values for pixels that fall above the $\text{H I } S/N > 5$ threshold for a single galaxy. The Σ_{SFR} bin edges given in Equation 4.5 are displayed as dashed vertical black lines.

In Figures 4.6a - 4.6c, we show an example of the Σ_{SFR} superprofiles for NGC 7793. The layout is similar to that used in the figures for the radially-resolved superprofiles (Figures 4.3a - 4.3c), with a few exceptions. In Figure 4.3a, the greyscale image is the Σ_{SFR} map measured with FUV+24 μm emission instead of Σ_{HI} as was used in Figure 4.6a. We have also plotted the parameters in Figure 4.6c as a function of Σ_{SFR} instead of radius.

In Figure 4.7, we highlight the behavior of σ_{central} as a function of radius in the sample. As with the radial superprofiles, many of the more massive galaxies in the sample have parameters that vary smoothly as a function Σ_{SFR} . In particular, both σ_{central} and σ_{wings} tend to increase with increasing Σ_{SFR} in the more massive galaxies (IC 2574, NGC 4214, Ho II, NGC 3741). However, this trend is not ubiquitous; a number of the galaxies show no strong trend or the opposite trend.

The Σ_{SFR} superprofiles for the sample are shown in § 4.7.2.

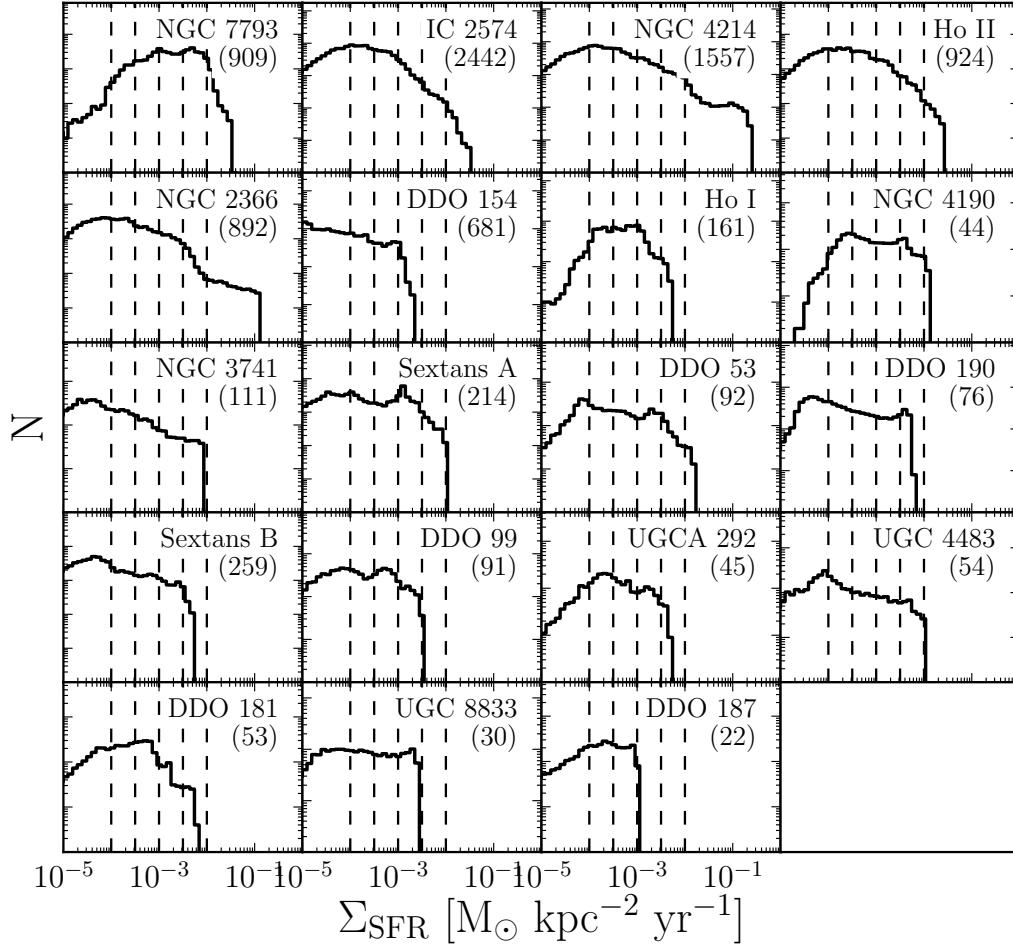


Figure 4.5 Histograms of inclination-corrected Σ_{SFR} values in each galaxy, in order of decreasing $M_{\text{baryon,tot}}$. Each panel represents the distribution of Σ_{SFR} values for pixels above the H I $S/N > 5$ threshold for a single galaxy. The number in parentheses below the galaxy name indicates the number of independent resolution elements above the $S/N > 5$ threshold for the entire galaxy. Note that not all galaxies have valid pixels in each bin.

4.3.4 Robustness and Verification

We performed a number of tests in Chapter 3 to ensure that the superprofiles do not exhibit artificial signals. In particular, we examined the effects of finite spatial resolution; finite velocity resolution; uncertainties in v_{peak} ; and noise. Of these effects, the only one whose uncertainties should not change when we move to spatially-resolved superprofiles is that for finite velocity resolution; we therefore adopt uncertainties from Chapter 3 for this effect. For the other three effects, we perform the same tests described in Chapter 3 on the spatially-resolved superprofiles. We discuss those tests and their results in this section.

4.3.4.1 Finite Spatial Resolution

Line widths in the central regions of galaxies can be affected by finite spatial resolution, as the velocity gradient across a single resolution element can be appreciable, leading to “beam smearing.” This affect is most problematic in massive galaxies with steeply rising rotation curves or high inclinations. In contrast, our sample is composed primarily of dwarfs with relatively small rotational velocities and shallow velocity gradients in the central regions. We therefore expect that beam smearing should not strongly influence our results, but the central regions of the more massive galaxies may be susceptible to increased effects from finite spatial resolution. As a check, we use models of NGC 2366 that includes the effects of beam smearing from Chapter 3. This galaxy has both a well-measured rotation curve (Oh et al., 2008) as well as a high inclination (63°). It should therefore exhibit some of the strongest effects of beam smearing in our sample.

For this test, we follow the same procedure outlined in Chapter 3 to produce model data cubes both with and without the presence of beam smearing (“true” and “convolved,” respectively). We use two models; both have a rotational curve that mimics the observed rotation curve, with a linear rise to $r_{\text{flat}} = 1.9$ kpc and $v_{\text{flat}} = 60$ km s $^{-1}$, as measured by Oh et al. (2008). For the first model, we assume that all line-of-sight spectra are Gaussian with an intrinsic velocity dispersion of 6 km s $^{-1}$. In the second model, we again assume that all line-of-sight spectra are Gaussian. However, to determine the Gaussian width of a line-of-sight spectrum at a given radius, we fit an exponential to the average second moment

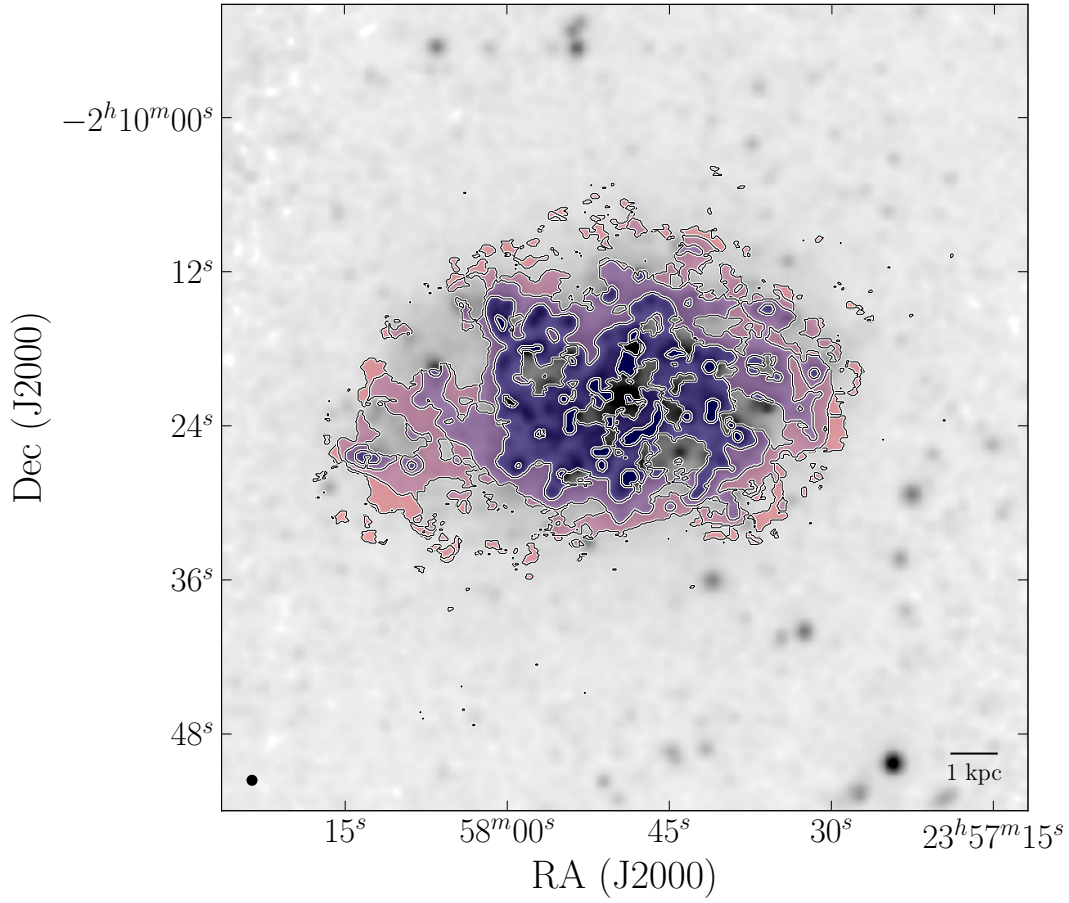


Figure 4.6a Σ_{SFR} regions in which superprofiles are generated for NGC 7793. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The shaded regions indicate which pixels have contributed to each radial superprofile, with red indicating low Σ_{SFR} and blue high Σ_{SFR} .

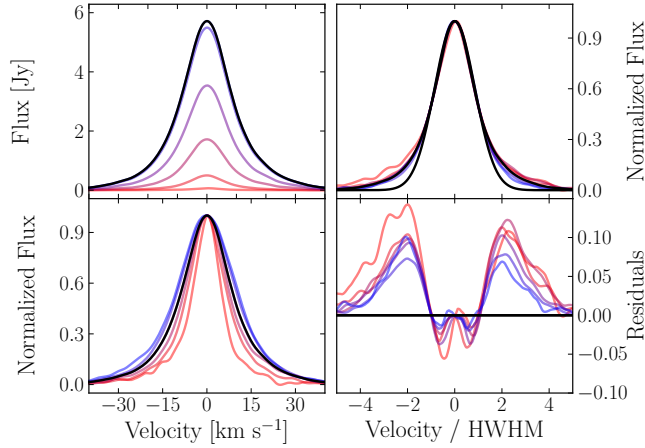


Figure 4.6b The Σ_{SFR} superprofiles in NGC 7793, where colors indicate the corresponding regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

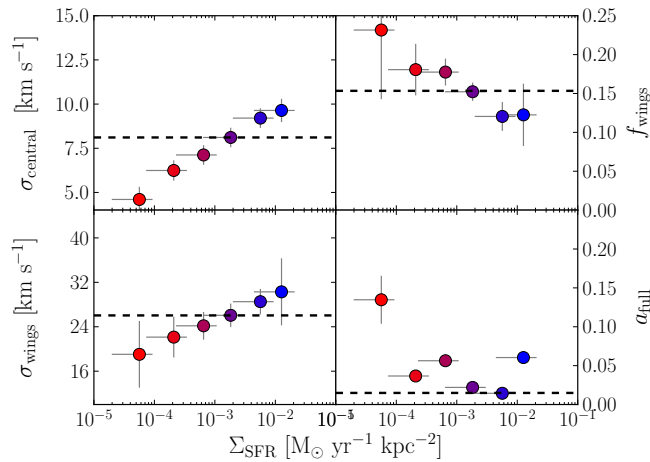


Figure 4.6c Variation of the Σ_{SFR} superprofile parameters as a function of Σ_{SFR} for NGC 7793. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). As before, we have plotted the equivalent a_{full} value of the global superprofile instead of a_{wings} , as measured in Chapter 3. Both σ_{central} and σ_{wings} increase with increasing Σ_{SFR} , while f_{wings} decreases with increasing Σ_{SFR} . The trends between a_{full} and Σ_{SFR} is less smooth.

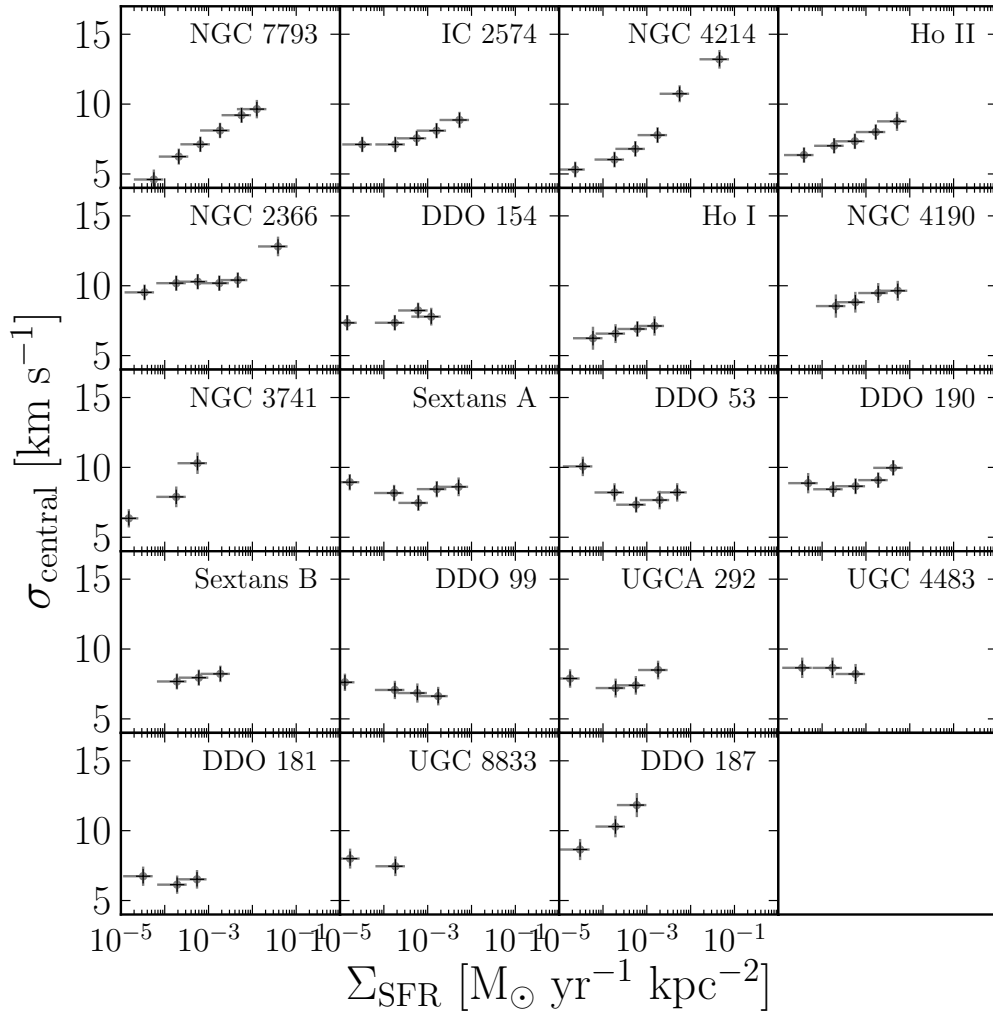


Figure 4.7 The velocity dispersion, σ_{central} , of the superprofiles generated in regions of constant Σ_{SFR} . Each panel represents a single galaxy, and galaxies are ordered by decreasing $M_{\text{baryon,tot}}$. Within one panel, each point represents one superprofile. The velocity dispersion increases smoothly with Σ_{SFR} for the more massive galaxies, but shows erratic behavior for lower mass galaxies.

value in radial annuli and adopt that scaling as the velocity dispersion.

Using these model cubes, we can generate superprofiles in radial bins from both the “true” and “convolved” cubes to assess the effects that beam smearing has at each radius. We show the difference between σ_{central} for the “convolved” and the “true” cubes in Figure 4.8. The upper panel shows σ_{central} values for the model with fixed velocity dispersion, and the lower panel shows σ_{central} values for the model with exponentially-declining velocity dispersion. Within each panel, the black line with filled markers represents σ_{central} from the “true” model in each radial bin. The dashed red line shows σ_{central} for the “convolved” data cube in the same radial bins. We have scaled the y -axis to show the approximate range of σ_{central} measured in our sample. We find that beam smearing has a $< 10\%$ effect on the width of line profiles for the first model, and $< 5\%$ for the second model. Finite spatial resolution also does not contribute a significant fraction of flux to the wings, so σ_{wings} and f_{wings} are not affected by beam smearing.

Because a good understanding of the rotation curve is necessary to assess the detailed effects of beam smearing in this fashion, we adopt the 0.5 km s^{-1} uncertainty on σ_{central} from Chapter 3.

4.3.4.2 Uncertainties in v_{peak}

The regions with the lowest Σ_{SFR} are often in the outskirts of galaxies where H I surface densities are also lower. At low H I surface densities, individual line-of-sight spectra tend to have lower S/N , therefore hindering the determination of v_{peak} . We have repeated the test detailed in Chapter 3 to assess the effects of v_{peak} uncertainties on the superprofiles as a function of radius. In this test, we use the Monte Carlo assessment of v_{peak} uncertainties for a representative sample of galaxies (NGC 2366, Sextans A, DDO 190, GR 8, and UGC 4483). For each selected pixel, we generate a fake superprofile ($S_{\text{fake}}(v)$) by co-adding Gaussian profiles with amplitude A_i determined by the S/N ratio of each pixel, offset μ_i drawn randomly from a Gaussian distribution with that pixel’s v_{peak} uncertainty as its standard deviation, and width of $\sigma = 6 \text{ km s}^{-1}$:

$$S_{\text{fake}}(v) = \sum_i A_i \exp \left[\frac{1}{2} \left(\frac{v - \mu_i}{6 \text{ km s}^{-1}} \right)^2 \right] \quad (4.6)$$

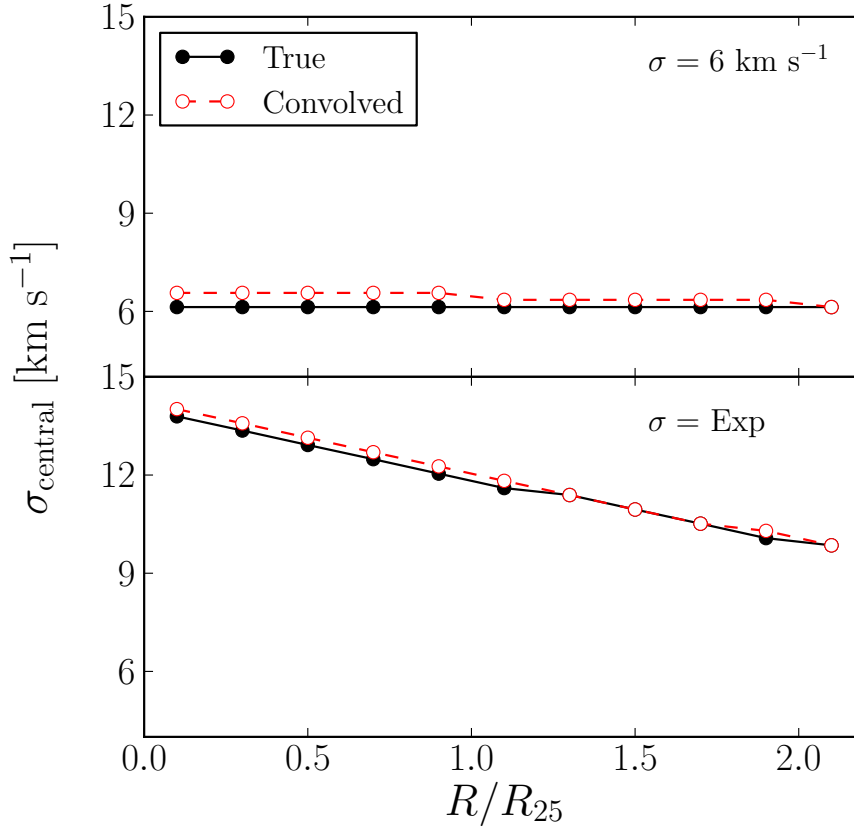


Figure 4.8 The effects of beam smearing on radial superprofiles for a model galaxy based on NGC 2366. The upper panel shows the effects on a model data cube with 6 km s^{-1} intrinsic velocity dispersion, and the lower is for one with an exponentially-declining intrinsic velocity dispersion. The black solid line with filled circles shows the “true” cube, unaffected by beam smearing. The red dashed line with unfilled circles shows the “convolved” cube, which has the effects of beam smearing included. We have scaled the y -axis to show the approximate range of measured σ_{central} values in our sample. At all radii, beam smearing increases σ_{central} by $< 10\%$. It therefore cannot account for the larger variation of observed σ_{central} values.

We then compare this superprofile to what would have been obtained in the absence of any v_{peak} uncertainties. We find that the differences between the “observed” fake superprofile and the “true” fake superprofile are $< 2\%$ in all cases. Therefore, v_{peak} uncertainties do not strongly affect the observed superprofiles, even in low S/N regions; we do not include uncertainties from this effect.

4.3.4.3 Noise

The noise of the final superprofile can also influence the determined parameters. We use our estimate of noise (Equation 4.1) to assess the approximate uncertainties on each superprofile parameter. For this test, we assume that the measured superprofile is the true superprofile. We then add an estimate of noise to each pixel, drawn from a Gaussian distribution whose width is determined by the estimated noise of that point. For this “noisy” superprofile, we again measure the σ_{central} , σ_{wings} , f_{wings} , and a_{full} parameters. We repeat this process 10,000 times and fit a Gaussian function to the range of allowed “noisy” parameters. We adopt the width of this Gaussian as the uncertainty due to noise.

4.3.4.4 Final Parameter Uncertainties

We include effects from finite velocity resolution using the tests presented in Chapter 3. These uncertainties should not change when we move to spatially-resolved scales.

For each superprofile, the final uncertainty for σ_{central} is given by:

$$\Delta\sigma_{\text{central}} = \sqrt{(0.5 \text{ km s}^{-1})^2 + (0.17 \text{ km s}^{-1})^2 + (\Delta\sigma_{\text{central,noise}})^2}. \quad (4.7)$$

Here, the first term represents the uncertainty due to spatial resolution; we have adopted the more conservative uncertainty from Chapter 3. The second term is taken from the finite velocity resolution tests in Chapter 3.

The final uncertainty for σ_{wings} is:

$$\Delta\sigma_{\text{wings}} = \sqrt{(0.13 \text{ km s}^{-1})^2 + (\Delta\sigma_{\text{wings,noise}})^2}. \quad (4.8)$$

The 0.13 km s^{-1} uncertainty is due to the effects of finite velocity resolution from Chapter 3.

The final uncertainty for f_{wings} is:

$$\Delta f_{\text{wings}} = \Delta f_{\text{wings,noise}}. \quad (4.9)$$

Neither finite spatial resolution or finite velocity resolution Chapter 3 affect f_{wings} by > 0.01 .

The final uncertainty for a_{full} is:

$$\Delta a_{\text{full}} = \sqrt{(0.003)^2 + (\Delta a_{\text{full,noise}})^2}, \quad (4.10)$$

where we have recalculated the standard deviation due to velocity resolution on Δa_{full} instead of a_{wings} based on the finite velocity resolution tests from Chapter 3.

4.4 H I *Kinematics as a Function of Local Galaxy Properties*

In Chapter 3, we compared global superprofile parameters to galaxy physical properties, averaged over the entire galaxy. In this paper, we assess the behavior of superprofile parameters in regions of constant projected radius or Σ_{SFR} , averaged over 200 pc scales. By deriving superprofiles in these subregions, we increase our sensitivity to any dependence of H I kinematics on local galaxy properties (i.e., Σ_{HI} , Σ_{SFR} , Σ_{baryon}).

To determine whether a correlation exists between a superprofile parameter and a physical property, we use the Spearman rank correlation coefficient. As described in Chapter 3, this statistic tests for a monotonically increasing ($r_S > 0$) or decreasing ($r_S < 0$) relationship between the two variables. The corresponding p_S value gives the probability of finding an r_S value equal to or more extreme than the observed r_S from a random sample. We choose $p_S = 0.01$ as a threshold for finding a significant correlation. The r_S and p_S values are given in Tables 4.3 for the radially-resolved superprofiles and in Table 4.4 for the Σ_{SFR} superprofiles.

We note that any trends observed between radial superprofiles and ISM properties are strongly dominated by the most massive galaxies in the sample, which often have high enough resolution to allow superprofiles to be constructed in a large number of radial annuli. In fact, as seen in Table 4.2 the four most massive dwarfs (NGC 7793, IC 2574, NGC 4214, and Ho II) contribute over 50% of the points to the radial correlation plots, whereas the smallest dwarfs typically have only two radial bins each (inside and outside

r_{25}). This overweighting of the larger galaxies is decreased when examining correlations in the Σ_{SFR} superprofiles, for which higher mass and lower mass galaxies contribute similar numbers of points. The superprofiles in subregions of constant Σ_{SFR} may therefore trace a more representative result for the entire sample compared to the superprofiles from radial subregions.

We explore how various local properties correlate first with measures of H I velocity (σ_{central} and σ_{wings} ; § 4.4.1) and second with measures of superprofile shape (f_{wings} and a_{full} ; § 4.4.2). We now present the different correlations, but largely defer discussion of their physical interpretation until § 4.5.

4.4.1 H I Velocities

We start by exploring the correlations of σ_{central} and σ_{wings} with a variety of local properties, keeping in mind that we expect some degree of correlation between σ_{central} and σ_{wings} , as σ_{wings} is restricted to values greater than σ_{central} by definition (Equation 4.3).

4.4.1.1 H I Velocities versus Surface Mass Density

In Chapter 3, we found that σ_{central} and σ_{wings} were correlated most strongly with Σ_{HI} , when averaged over the entire galaxy. In this section, we assess whether a similar correlation with Σ_{HI} holds locally when the properties of the H I kinematics are derived in subregions of constant normalized radius or Σ_{SFR} .

In Figure 4.9, we show σ_{central} , σ_{wings} , and $\sigma_{\text{wings}}/\sigma_{\text{central}}$ as a function of Σ_{HI} , calculated in spatially-resolved subregions. The right-hand panels show superprofiles calculated in radial subregions. Each galaxy contributes two or more points to this plot, with some galaxies contributing more than 20 (see Table 4.2). The points are color-coded by the normalized radius of the subregion (r/r_{25} , with blue indicating the central regions and red indicating the outskirts. For those galaxies where we have only generated superprofiles inside and outside r_{25} , we color the points either black or grey, respectively.

The left-hand panels of Figure 4.9 show the same parameters as those on the right, but for superprofiles calculated in Σ_{SFR} subregions. The points are color-coded by their Σ_{SFR}

bin (Equation 4.5), with blue indicating high Σ_{SFR} and red indicating low Σ_{SFR} . Both large and small galaxies contribute similar numbers of points to these panels compared to the right-hand panels, which are dominated by the largest galaxies.

We find significant correlations between Σ_{HI} and both σ_{central} and σ_{wings} for superprofiles generated in both radial and Σ_{SFR} subregions. The correlations are stronger in the radial subregions than the Σ_{SFR} subregions, as measured both by eye and by the Spearman correlation coefficient (see Tables 4.3 and 4.4). The correlations are stronger in the radial subregions because they are dominated by the most massive galaxies, which provide the most points and whose disks tend to follow smooth trends between radius and ISM properties. In both cases, however, neither σ_{central} nor σ_{wings} is strongly determined by Σ_{HI} ; the observed spread in σ_{central} at a given Σ_{HI} is comparable to the mean. We also find that the ratio between σ_{wings} and σ_{central} shows little structure with Σ_{HI} . Typically values are $\sigma_{\text{wings}}/\sigma_{\text{central}} \sim 2 - 3$.

Next, we examine correlations between HI velocities and Σ_{baryon} in Figure 4.10. The figure layout is the same as Figure 4.9, but for correlations with Σ_{baryon} instead of Σ_{HI} . The correlations between σ_{central} and σ_{wings} are stronger with Σ_{baryon} than with Σ_{HI} , for both radial and Σ_{SFR} subregions. As before, the r_S value is larger for the radial subregions, but again, this behavior likely results from the radial correlations being dominated by the most massive galaxies. We also find that σ_{central} shows a lower bound that increases with increasing Σ_{baryon} . Regions with high Σ_{baryon} do not have low σ_{central} values, while regions with low Σ_{baryon} can have either low or high σ_{central} . Similar behavior is seen for σ_{wings} , which may be a reflection of the fact that regions with higher σ_{central} values must by definition have higher σ_{wings} values.

4.4.1.2 HI Velocities versus Star Formation

We now address the behavior of HI velocities as a function of local star formation measures. We consider two measures of star formation: the local star formation intensity (Σ_{SFR}) and the ratio of available star formation energy to the HI mass that the energy couples to ($\Sigma_{\text{HI}}/\Sigma_{\text{SFR}}$). In Chapter 3, we did not find a correlation between σ_{central} and $\langle \Sigma_{\text{SFR}} \rangle$,

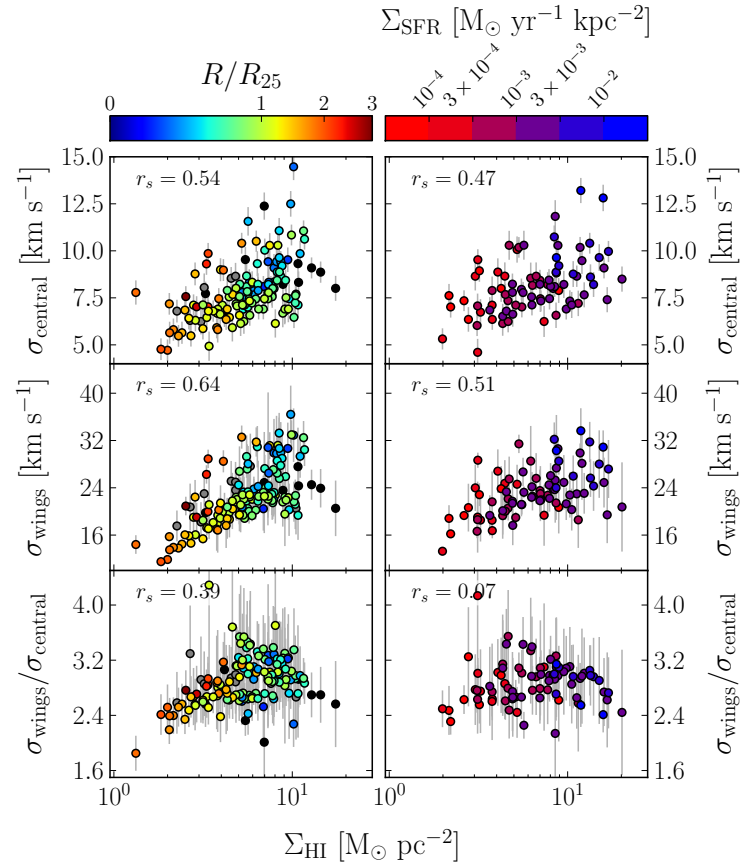


Figure 4.9 H I velocity measurements versus Σ_{HI} for spatially-resolved superprofiles. Each point indicates the Σ_{HI} and H I velocity measurement derived within one independent superprofile. The left-hand panels show σ_{central} , σ_{wings} , and $\sigma_{\text{wings}}/\sigma_{\text{central}}$ for superprofiles in radial subregions, with color indicating normalized radius. The lowest-mass galaxies have only two radial bins (inside and outside r_{25} , color-coded black and grey, respectively). The right-hand panels show the same measurements, but now for superprofiles in Σ_{SFR} subregions. In these panels, points are color-coded by the Σ_{SFR} bin into which they fall, with blue indicating high Σ_{SFR} and red indicating low Σ_{SFR} . Both σ_{central} and σ_{wings} show trends with Σ_{HI} , though they are more pronounced in the radial superprofiles.

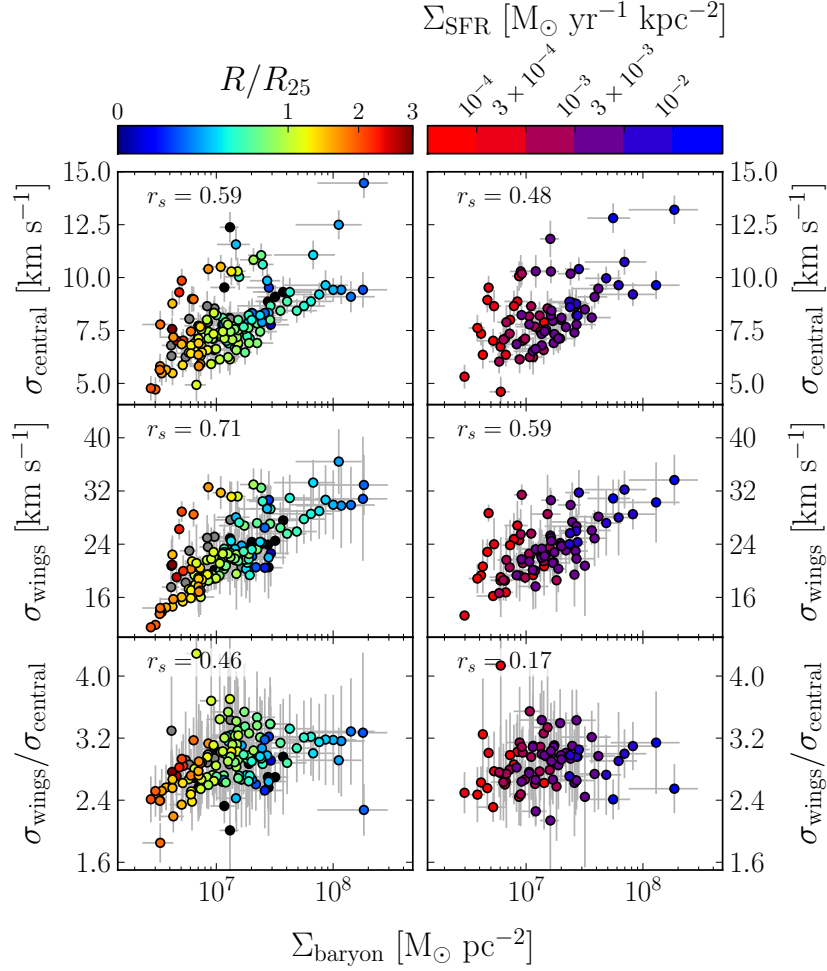


Figure 4.10 H I velocity measurements versus Σ_{baryon} for spatially-resolved superprofiles. Each point indicates the Σ_{baryon} and H I velocity measurement derived within one independent superprofile. The left-hand panels show σ_{central} , σ_{wings} , and $\sigma_{\text{wings}}/\sigma_{\text{central}}$ for superprofiles in radial subregions, with color indicating normalized radius. The lowest-mass galaxies have only two radial bins (inside and outside r_{25} , color-coded black and grey, respectively). The right-hand panels show the same measurements, but now for superprofiles in Σ_{SFR} subregions. In these panels, points are color-coded by the Σ_{SFR} bin into which they fall, with blue indicating high Σ_{SFR} and red indicating low Σ_{SFR} . Both σ_{central} and σ_{wings} show trends with Σ_{baryon} , though they are more pronounced in the radial superprofiles.

averaged over the entire galaxy, unless higher-mass galaxies were included.

In Figure 4.11 we show the behavior of H I superprofile velocities as a function of Σ_{SFR} . The layout of the figure is the same as for Figure 4.9. We find that Σ_{SFR} is correlated with both σ_{central} and σ_{wings} for superprofiles in both radial and Σ_{SFR} subregions. As for Σ_{HI} and Σ_{baryon} , the correlations are stronger for the radial subregions compared with the Σ_{SFR} subregions, because they are dominated by the four largest galaxies in the sample. The observed correlation between Σ_{SFR} and σ_{central} in the Σ_{SFR} subregions is strongly driven by the three highest Σ_{SFR} bins. When we calculate r_S for the lower three bins ($\Sigma_{\text{SFR}} < 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$), the correlations disappear entirely ($r_S = 0.02$ and $p_S = 0.86$, compared to $r_s = 0.42$ and $p_s < 0.001$ for the full range). At low Σ_{SFR} , either H I kinematics do not appear to be influenced by star formation, or the measurements of Σ_{SFR} have insufficient accuracy to reveal a correlation.

Even though it is strongly driven by the high Σ_{SFR} regions, the correlation between Σ_{SFR} and σ_{central} is new compared to Chapter 3. The local correlation was lost when averaged over the entire disk, as regions with both high and low star formation intensities were combined. In this case, we have sampled the H I kinematics and Σ_{SFR} on local scales and therefore would expect a stronger correlation between these properties, if they are connected. However, regions of with very low star formation intensity ($\Sigma_{\text{SFR}} < 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$) can still exhibit σ_{central} values of 10 km s^{-1} , comparable to those seen in higher Σ_{SFR} regions. The σ_{central} and σ_{wings} again show a lower bound at a given Σ_{SFR} , similar to that seen with Σ_{baryon} .

We next compare the H I velocities to $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$ in Figure 4.12. As stated before, this measurement provides an estimate of the energy available from star formation per unit gas mass, rather than a strict star formation efficiency measurement. Again, we find that σ_{central} and σ_{wings} are correlated with $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$, but with weaker correlation coefficients compared to Σ_{SFR} . However, the connection between star formation and σ_{central} is not one-to-one; σ_{central} values at low $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$ can be as high as 10 km s^{-1} . Additionally, σ_{central} exhibits an increasing lower bound with increasing $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$, which could imply a minimum efficiency at which star formation affects the surrounding H I.

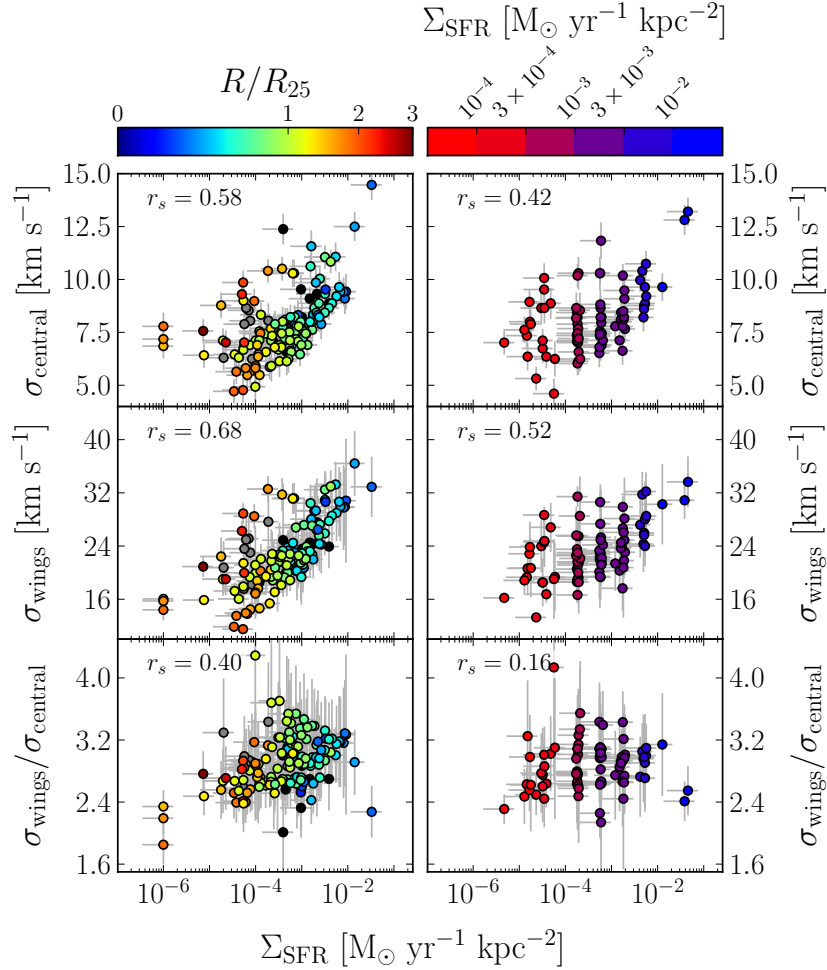


Figure 4.11 H I velocity measurements versus Σ_{SFR} for spatially-resolved superprofiles. Each point indicates the Σ_{SFR} and H I velocity measurement derived within one independent superprofile. The left-hand panels show σ_{central} , σ_{wings} , and $\sigma_{\text{wings}}/\sigma_{\text{central}}$ for superprofiles in radial subregions, with color indicating normalized radius. The lowest-mass galaxies have only two radial bins (inside and outside r_{25} , color-coded black and grey, respectively). The right-hand panels show the same measurements, but now for superprofiles in Σ_{SFR} subregions. In these panels, points are color-coded by the Σ_{SFR} bin into which they fall, with blue indicating high Σ_{SFR} and red indicating low Σ_{SFR} . The vertical lines of points in the left-hand panels are an artifact of the Σ_{SFR} binning; the horizontal jitter is due to a different distribution of Σ_{SFR} values in each bin. Both σ_{central} and σ_{wings} show trends with Σ_{SFR} , though they are more pronounced in the radial superprofiles. We also observe a lower limit to σ_{central} that increases with Σ_{SFR} .

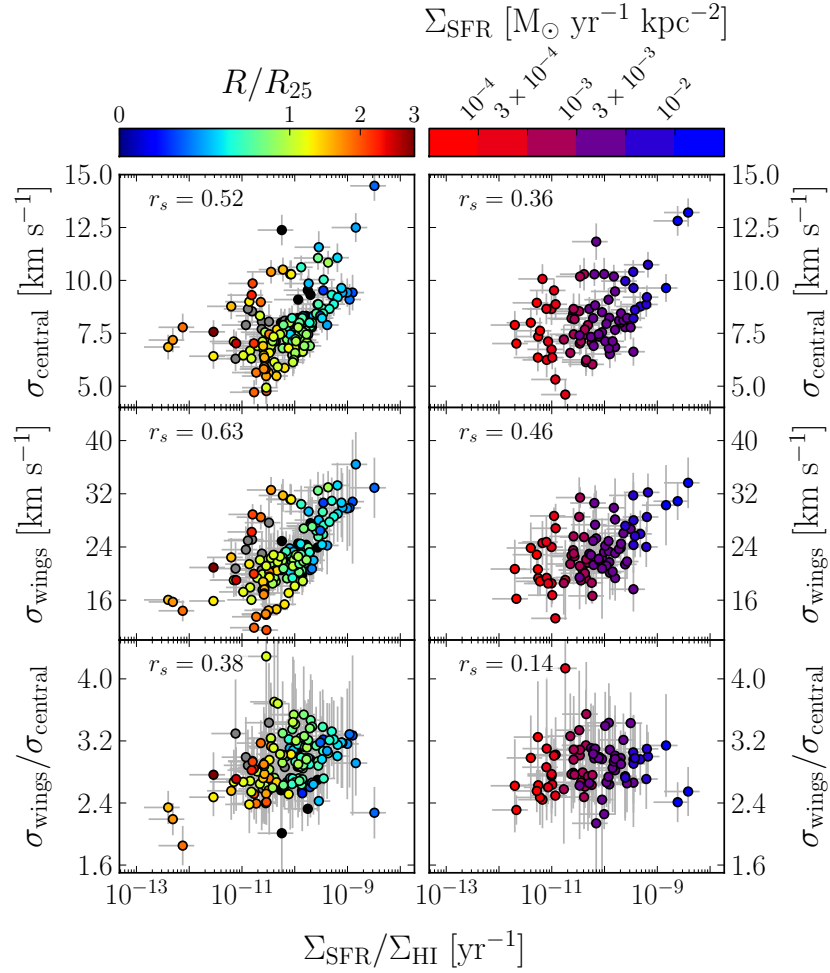


Figure 4.12 H I velocity measurements versus $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$ for spatially-resolved superprofiles. Each point indicates the $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$ and H I velocity measurement derived within one independent superprofile. The left-hand panels show σ_{central} , σ_{wings} , and $\sigma_{\text{wings}}/\sigma_{\text{central}}$ for superprofiles in radial subregions, with color indicating normalized radius. The lowest-mass galaxies have only two radial bins (inside and outside r_{25} , color-coded black and grey, respectively). The right-hand panels show the same measurements, but now for superprofiles in Σ_{SFR} subregions. In these panels, points are color-coded by the Σ_{SFR} bin into which they fall, with blue indicating high Σ_{SFR} and red indicating low Σ_{SFR} . Both σ_{central} and σ_{wings} show trends with $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$.

4.4.2 Superprofile Shapes

We now address whether the shapes of the spatially-resolved superprofiles are connected to local ISM properties. In particular, we examine the fraction of gas in the wings of the superprofiles (f_{wings}) and the asymmetry of the superprofiles (a_{full}). In Chapter 3, we found that f_{wings} increased with SFR/M_{HI} , averaged on global scales, and that the asymmetry of the profiles, measured with a_{wings} , decreased with increasing total SFR and galaxy mass. We now assess whether similar correlations hold for superprofiles generated in radial bins or regions of similar Σ_{SFR} . As with the H I velocities discussed in § 4.4.1, we examine correlations both with surface mass density (§ 4.4.2.1) and with measures of star formation (§ 4.4.2.2).

We note that the f_{wings} and a_{full} parameters may not be tracing the same effects in the resolved superprofiles as in the global superprofiles from Chapter 3. In the global superprofiles, line-of-sight spectra with a range of velocity dispersions were averaged together. The final superprofile was therefore a composite of H I profiles with different velocity dispersions. Some H I in the wings of those superprofiles could have been due to H I line-of-sight spectra with larger velocity dispersions compared to the average. Second, we measure the full asymmetry of the superprofiles (a_{full}) in this paper instead of the asymmetry of the wings (a_{wings}). This difference is unlikely to be major, since the measurement of asymmetry in the global superprofiles was strongly weighted by the wings.

4.4.2.1 Surface Mass Density

We start by examining correlations between superprofile shape and surface mass density. We note that in Chapter 3, however, we found no correlations between surface density and either f_{wings} or the wing asymmetry (as measured with a_{wings}). Nonetheless, any local correlations may have been obscured when averaging over the entire disk.

In Figure 4.13 we show the superprofile shape parameters as a function of Σ_{HI} . The layout is similar to Figure 4.9, but we now plot f_{wings} and a_{full} for superprofiles derived in subregions of constant radius or Σ_{SFR} . Very little structure is apparent in either f_{wings} or a_{full} with increasing Σ_{HI} . We note that a_{full} has a p -value $p_S < 0.01$ for the radial subregions,

but the corresponding correlation coefficient is very low ($r_S = 0.26$), indicating that the two quantities are not strongly correlated. The two quantities are not significantly correlated for the Σ_{SFR} subregions.

In Figure 4.14, we show the same figure but for Σ_{baryon} instead of Σ_{HI} . As with Σ_{HI} , the superprofile shapes are not strongly influenced by Σ_{baryon} . The radial subregions show significant correlations as measured by their p_S value, but as before, the corresponding correlation coefficients themselves are low. The correlations disappear entirely for the Σ_{SFR} subregions. Because neither Σ_{HI} nor Σ_{baryon} show strong or consistent correlations with superprofile shape, surface mass density does not drive the properties of the velocity of the wings.

4.4.2.2 Star Formation

We now compare the superprofile shapes with measures of star formation. As before, we examine correlations with both Σ_{SFR} and $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$.

In Figure 4.15, we show f_{wings} and a_{full} for superprofiles generated in radial and Σ_{SFR} subregions. The layout is the same as Figure 4.13. The HI superprofiles tend to have $f_{\text{wings}} \sim 0.1$, which suggests that average HI spectra are typically non-Gaussian in most ISM conditions.

Again, there are no strong correlations between these parameters and Σ_{SFR} , indicating that there is no monotonic relationship between superprofile shape and star formation intensity. The smallest values of f_{wings} and a_{full} do appear to occur in regions of low star formation intensity ($\Sigma_{\text{SFR}} < 10^4 \text{ M}_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$), with higher values at moderate Σ_{SFR} . We also observe an upper bound to f_{wings} that decreases with increasing Σ_{SFR} , but this behavior may reflect the lower bound between σ_{central} and Σ_{SFR} (§ 4.4.1.2).

In Figure 4.16, we show the superprofile shapes versus $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$. As with the previous figures, there are no obvious trends between these parameters and $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$. A similar upper bound for f_{wings} as a function of $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$ is present, but it could again be an artifact of the lower bound in the σ_{central} versus $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$ figure.

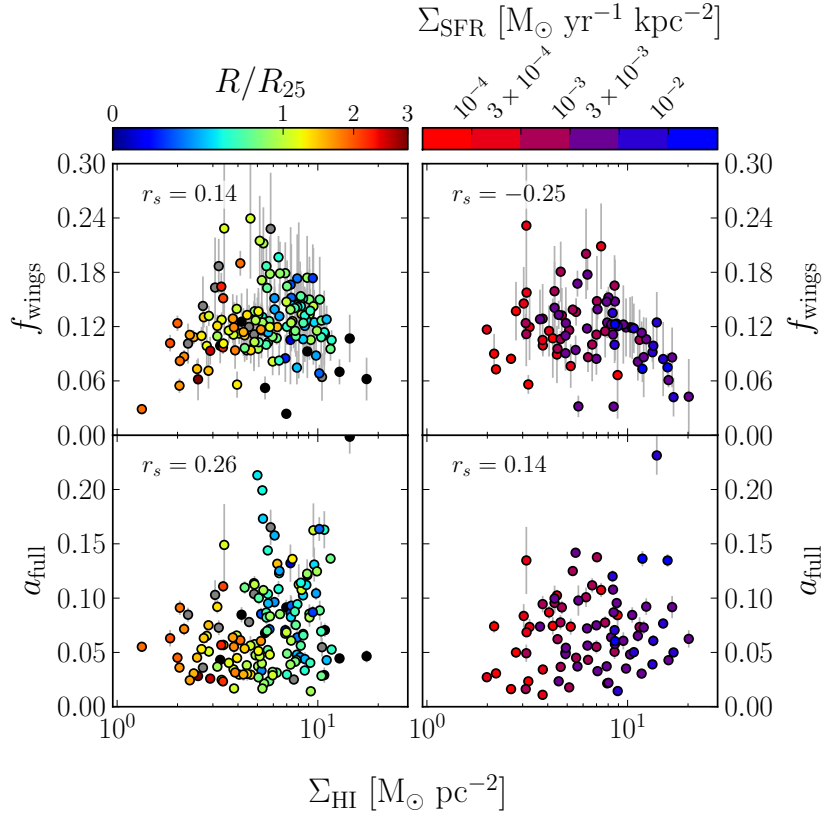


Figure 4.13 H I superprofile shape parameters versus Σ_{HI} for spatially-resolved superprofiles. Each point indicates the Σ_{HI} measurement and superprofile shape parameter derived for one independent superprofile. The left-hand panels show f_{wings} and a_{full} for superprofiles in radial subregions, with color indicating normalized radius. The lowest-mass galaxies have only two radial bins (inside and outside r_{25} , color-coded black and grey, respectively). The right-hand panels show the same measurements, but now for superprofiles in Σ_{SFR} subregions. In these panels, points are color-coded by the Σ_{SFR} bin into which they fall, with blue indicating high Σ_{SFR} and red indicating low Σ_{SFR} . The vertical lines of points are an artifact of the Σ_{SFR} binning; the horizontal jitter is due to a different distribution of Σ_{SFR} values in each bin.

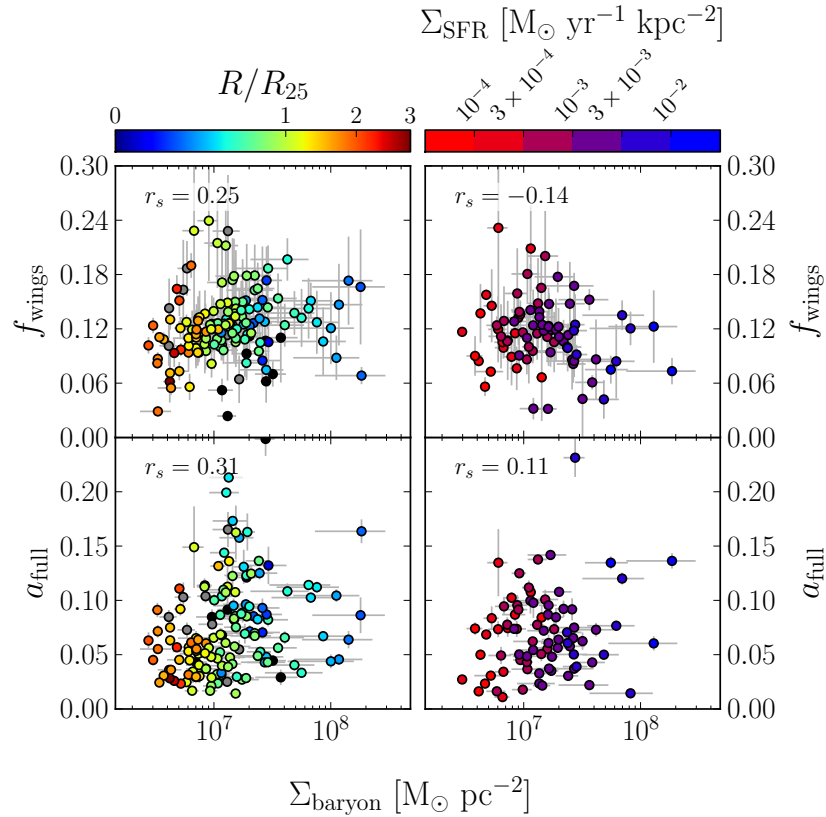


Figure 4.14 H I superprofile shape parameters versus Σ_{baryon} for spatially-resolved superprofiles. Each point indicates the Σ_{baryon} measurement and H I superprofile parameter derived for one independent superprofile. The left-hand panels show f_{wings} and a_{full} for superprofiles in radial subregions, with color indicating normalized radius. The lowest-mass galaxies have only two radial bins (inside and outside r_{25} , color-coded black and grey, respectively). The right-hand panels show the same measurements, but now for superprofiles in Σ_{SFR} subregions. In these panels, points are color-coded by the Σ_{SFR} bin into which they fall, with blue indicating high Σ_{SFR} and red indicating low Σ_{SFR} . The vertical lines of points are an artifact of the Σ_{SFR} binning; the horizontal jitter is due to a different distribution of Σ_{SFR} values in each bin.

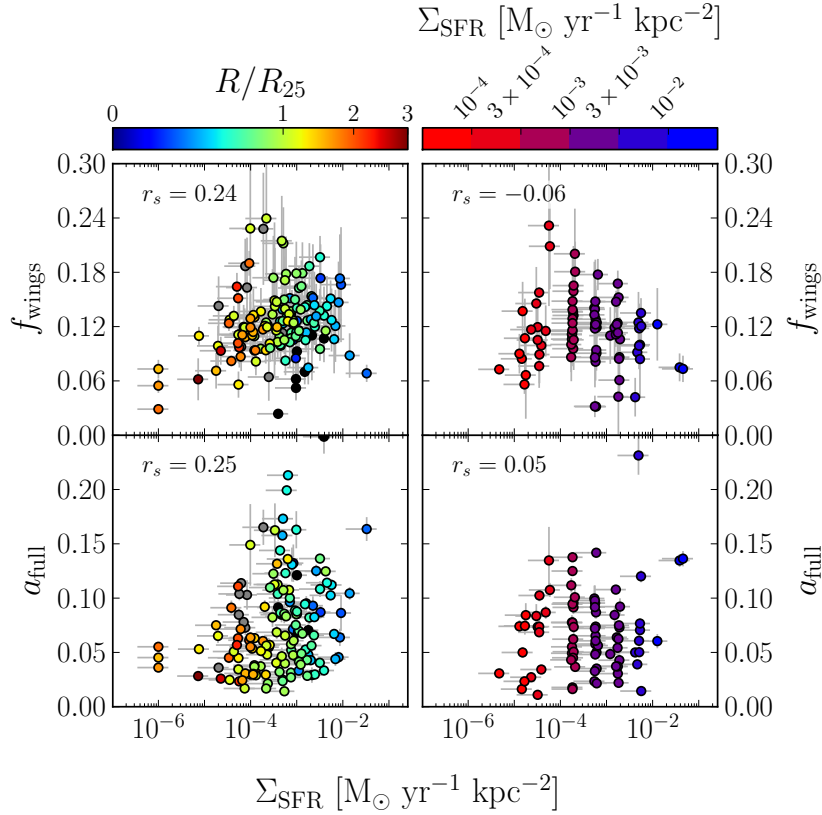


Figure 4.15 H I superprofile shape parameters versus $\Sigma_{\text{H I}}$ for spatially-resolved superprofiles. Each point indicates the $\Sigma_{\text{H I}}$ measurement and H I superprofile parameter derived for one independent superprofile. The left-hand panels show f_{wings} and a_{full} for superprofiles in radial subregions, with color indicating normalized radius. The lowest-mass galaxies have only two radial bins (inside and outside r_{25} , color-coded black and grey, respectively). The right-hand panels show the same measurements, but now for superprofiles in Σ_{SFR} subregions. In these panels, points are color-coded by the Σ_{SFR} bin into which they fall, with blue indicating high Σ_{SFR} and red indicating low Σ_{SFR} . The vertical lines of points are an artifact of the Σ_{SFR} binning; the horizontal jitter is due to a different distribution of Σ_{SFR} values in each bin.

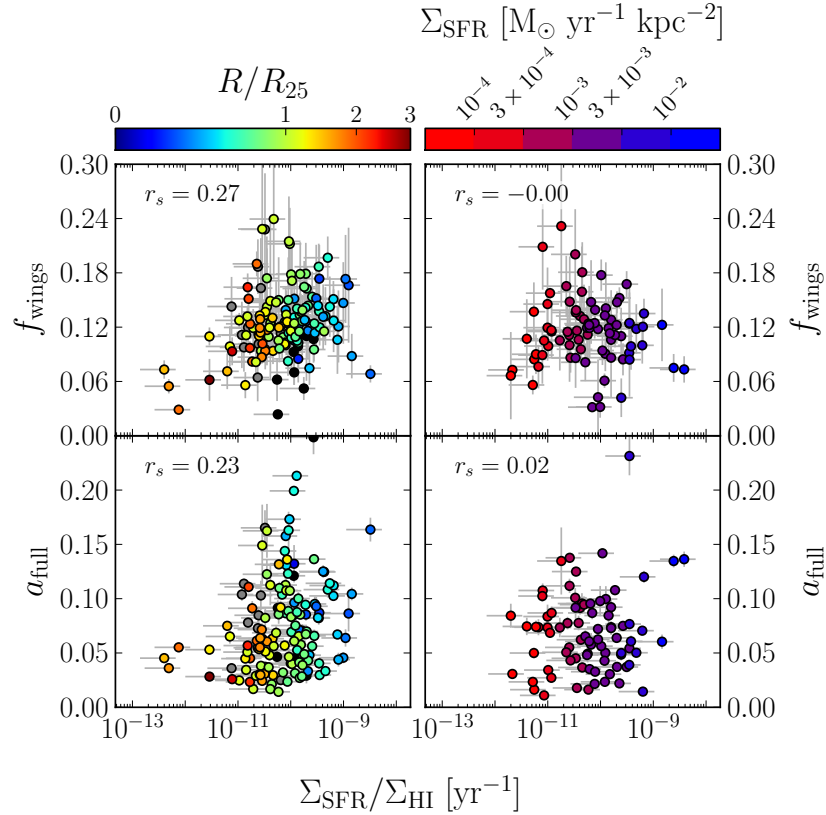


Figure 4.16 H I superprofile shape parameters versus $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$ for spatially-resolved superprofiles. Each point indicates the $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$ measurement and H I superprofile parameter derived for one independent superprofile. The left-hand panels show f_{wings} and a_{full} for superprofiles in radial subregions, with color indicating normalized radius. The lowest-mass galaxies have only two radial bins (inside and outside r_{25} , color-coded black and grey, respectively). The right-hand panels show the same measurements, but now for superprofiles in Σ_{SFR} subregions. In these panels, points are color-coded by the Σ_{SFR} bin into which they fall, with blue indicating high Σ_{SFR} and red indicating low Σ_{SFR} .

Table 4.3: Spearman correlation coefficient r_S and probability p_S between superprofile parameters and physical properties for the radial superprofiles. Significant correlations are shown in bold.

Property	σ_{central}		σ_{wings}		f_{wings}		a_{full}	
	r_S	p_S	r_S	p_S	r_S	p_S	r_S	p_S
Σ_{HI}	0.537	<0.001	0.638	<0.001	0.140	0.090	0.263	0.001
Σ_{baryon}	0.590	<0.001	0.714	<0.001	0.251	0.002	0.309	<0.001
Σ_{SFR}	0.577	<0.001	0.678	<0.001	0.242	0.003	0.250	0.002
$\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$	0.518	<0.001	0.626	<0.001	0.271	<0.001	0.234	0.004

Table 4.4: Spearman correlation coefficient r_S and probability p_S between superprofile parameters and physical properties for the Σ_{SFR} superprofiles. Significant correlations are shown in bold.

Property	σ_{central}		σ_{wings}		f_{wings}		a_{full}	
	r_S	p_S	r_S	p_S	r_S	p_S	r_S	p_S
Σ_{HI}	0.466	<0.001	0.507	<0.001	-0.249	0.025	0.137	0.224
Σ_{baryon}	0.484	<0.001	0.587	<0.001	-0.142	0.205	0.107	0.341
Σ_{SFR}	0.422	<0.001	0.525	<0.001	-0.058	0.605	0.052	0.645
$\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$	0.358	0.001	0.463	<0.001	-0.004	0.975	0.023	0.836

4.5 Discussion

In § 4.4, we calculated the correlations between superprofile parameters and local ISM properties. The r_S correlation coefficients and corresponding p_S significance values for the correlations discussed in § 4.4 are listed in Table 4.3 for the radial subregions and in Table 4.4 for the Σ_{SFR} subregions. In general, the correlations are weaker for the Σ_{SFR} subregions

compared to the radial subregions.

We find that measures of H I turbulent velocity, traced by σ_{central} , and wing velocity, traced by σ_{wings} , are correlated with all physical properties we have inspected (Σ_{HI} , Σ_{baryon} , Σ_{SFR} , and $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$). The H I turbulent velocities also tend to show a lower bound for a given Σ_{SFR} or Σ_{baryon} .

Because σ_{wings} and σ_{central} are correlated, we focus primarily on the correlations between the width of the central peak (σ_{central}) and local ISM properties. The parameters describing the shapes of the superprofiles, f_{wings} and a_{full} , do not show strong correlations with any of these properties, though there are weak correlations with measures of local SFR.

In this section, we discuss the physical meaning behind these correlations. We begin with correlations between the central peak of the superprofile and ISM properties in § 4.5.1. We then discuss correlations with σ_{wings} , f_{wings} , and a_{wings} in § 4.5.2.

4.5.1 The Central H I peak

H I turbulent velocities are often thought to be caused by feedback from star formation. Tamburro et al. (2009) found that star formation provides enough energy to drive H I turbulence inside r_{25} for relatively massive disk galaxies, but that the relationship between Σ_{SFR} and turbulence breaks down both in the outskirts of spiral galaxies or in dwarf galaxies where star formation rates are low. For our sample, which is dominated by systems in the latter regime, we find that the width of the central peak of the H I velocity dispersion correlates most strongly with Σ_{baryon} , and less strongly with measures of star formation. We first discuss the origins and limitations of the correlation of σ_{central} with Σ_{SFR} , and then discuss the stronger correlation with Σ_{baryon} .

4.5.1.1 Turbulent H I Kinematics and Star Formation

We find significant correlations between σ_{central} and Σ_{SFR} , for both types of subregions (Figure 4.11, Tables 4.3 and 4.4). However, the observed $\sigma_{\text{central}}\text{-}\Sigma_{\text{SFR}}$ correlation for the superprofiles calculated in radial bins is driven primarily by the most massive galaxies in the sample, which contribute the largest numbers of points; if we eliminate the four most

massive galaxies, the correlation coefficient drops from 0.58 to 0.42, though both values still have $p_S < 0.001$. In contrast, for the $\sigma_{\text{central}}\text{-}\Sigma_{\text{SFR}}$ correlation traced by superprofiles in subregions of constant Σ_{SFR} , both smaller and larger galaxies contribute similar numbers of points, and thus may be more representative of the overall behavior in our sample. For the Σ_{SFR} -based subregions, the correlation between σ_{central} and Σ_{SFR} is weaker and is only seen when the highest SFR intensity bins ($\Sigma_{\text{SFR}} > 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$) are included. The $\Sigma_{\text{SFR}} < 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ threshold occurs at approximately r_{25} in the largest dwarfs in our sample, as seen both in Figure 4.11 and in Tamburro et al. (2009) for H I kinematics inside r_{25} in larger galaxies, so the fact that the correlations break down at around this Σ_{SFR} mirrors the Tamburro et al. (2009) results.

These results indicate that at low Σ_{SFR} , H I kinematics do not appear to be strictly driven by star formation properties. Superprofiles generated in regions of low star formation can show velocity dispersions as high as 10 km s^{-1} , values similar to their counterparts in regions of higher star formation.

Even at higher Σ_{SFR} , the H I velocity dispersions are not uniquely defined by Σ_{SFR} . The relationship between σ_{central} and Σ_{SFR} has large scatter at low star formation intensities and inconsistent behavior within individual galaxies. Although the more massive galaxies in the sample tend to show increasing σ_{central} values with increasing Σ_{SFR} , the behavior of σ_{central} compared to Σ_{SFR} is more erratic in the low mass dwarfs. Some have no strong trends between σ_{central} and Σ_{SFR} (e.g., DDO 154, Sextans A, UGCA 292), while others show the complete opposite trend as seen in the more massive spirals (e.g., DDO 53), with decreasing σ_{central} with increasing Σ_{SFR} .

There are a number of reasons why σ_{central} may not couple strongly to the local Σ_{SFR} . First, the discrepancy may be due to a mismatch between the timescale of the FUV+24 μm star formation tracer and the timescale on which star formation energy is injected. We assess this possibility in Chapter 5 of this thesis using time-resolved star formation histories. It may also be due to a mismatch in physical scale. If SF drives turbulence over an area larger than a subregion, then the turbulence and SFR may appear decoupled. In such a case, we may see stronger trends for galaxy-wide superprofiles (as in Chapter 3 or Chapter 5) where all the SF and turbulent energy is considered. The discrepancy may also originate from the

fact that star formation energy may couple more strongly to H I energy instead of turbulent velocity alone.

While the local star formation intensity does not appear to set the H I velocity dispersion, it does appear to provide a floor below which σ_{central} does not fall. This behavior can be seen as the clear lower bound in Figure 4.11, which approximately follows

$$\sigma_{\text{central}} \sim 6.8 \text{ km s}^{-1} \left(\frac{\Sigma_{\text{SFR}}}{10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}} \right)^{0.14}. \quad (4.11)$$

The local star formation intensity may influence the smallest allowed velocity dispersion in a region, even if it does not solely drive the H I velocity dispersions.

4.5.1.2 Turbulent H I Energy

In addition to examining the correlations between σ_{central} and Σ_{SFR} , we also compare the turbulent H I energy to the energy provided by SF. This comparison provides a more robust connection between ISM properties and SF because the star formation energy may couple at similar efficiencies in regions that have different H I masses.

As in Chapter 3, we estimate the energy contained in the central H I peak, $E_{\text{HI,central}}$ as:

$$E_{\text{HI,central}} = \frac{3}{2} M_{\text{SP}} (1 - f_{\text{wings}}) (1 - f_{\text{cold}}) \sigma_{\text{central}}^2. \quad (4.12)$$

Here, M_{SP} is the total mass of the superprofile in $\text{M}_{\odot}$, given by $M_{\text{SP}} = 2.36 \times 10^5 D^2 F_{\text{SP}} \Delta v$, for a distance D in Mpc and an integrated superprofile flux $F_{\text{SP}} \Delta v$ in Jy km s^{-1} . The factor of 3/2 accounts for motion in three dimensions, assuming isotropy. The total mass in the central peak is given by $M_{\text{SP}} (1 - f_{\text{wings}})$. We exclude H I in the wings of each superprofile because it does not follow the Gaussian velocity structure of the central peak. We estimate that a fraction $f_{\text{cold}} = 0.15$ of this mass is cold H I and has kinematics that are poorly represented by σ_{central} . The true amount and kinematics of cold H I are unknown, but limits on f_{cold} in dwarf galaxies range between 1 – 20% (e.g., Young et al., 2003; Warren et al., 2012). This value also matches the approximate fraction of cold H I in the SMC (< 15%; Dickey et al., 2000). Because the kinematics of cold H I are likely not turbulent and may not be connected to star formation in the same way as warm H I, we exclude this estimated fraction of cold gas from our energy calculation.

If the H I is turbulent, its energy can be dissipated approximately over one turbulent timescale, τ_D , defined by Mac Low (1999) as:

$$\tau_D \simeq 9.8 \text{ Myr} \left(\frac{\lambda}{100 \text{ pc}} \right) \left(\frac{\sigma}{10 \text{ km s}^{-1}} \right)^{-1} \quad (4.13)$$

where λ is the turbulent driving scale and σ is the H I velocity dispersion. Following Chapter 3, we have approximated $\lambda = 100 \text{ pc}$ and $\sigma = \sigma_{\text{central}}$. To maintain the observed turbulent kinetic energy, sufficient energy must be replenished over this timescale.

4.5.1.3 Available Star Formation Energy

We now compare the turbulent kinetic H I energy to that provided by star formation, E_{SF} , over one turbulent timescale, τ_D :

$$E_{\text{SF}} = \eta_{\text{SN}} (\text{SFR} \times \tau_D) 10^{51} \text{ ergs}, \quad (4.14)$$

Here, η_{SN} is the number of SN per unit stellar mass formed; we adopt $\eta_{\text{SN}} = 1.3 \times 10^{-2} \text{ SN } M_{\odot}^{-1}$ based on a Kroupa (2001) IMF with a $120 M_{\odot}$ upper mass limit. This equation assumes that the star formation rate is constant across a $10 - 20 \text{ Myr}$ interval, so it may be problematic for dwarf galaxies, which often have non-uniform recent SFHs (e.g., McQuinn et al., 2010; Weisz et al., 2011). It also assumes the SFR is averaged over the past $\sim 10 - 100 \text{ Myr}$, without allowing for variations in SFH. However, star formation can provide energy for up to $\sim 50 \text{ Myr}$ after a burst, so these assumption may not be strongly in error. We also note that the stochastic sampling of the IMF and cluster mass function in regions of low star formation can introduce scatter into SFR estimates from FUV or H α tracers (Weisz et al., 2012). However, compared with H α , FUV estimates of star formation are more likely to provide correct estimates of the SFR as they rely on both O and B stars instead of only those with $M \gtrsim 15 M_{\odot}$ (Lee et al., 2011; Kennicutt & Evans, 2012).

4.5.1.4 Efficiency of Coupling Star Formation Energy to Kinetic H I Energy

With estimates of both $E_{\text{HI,central}}$ and E_{SF} , we next derive the range of efficiencies that are consistent with our measurements. If star formation is the only driver of H I velocity dispersions, then the conversion efficiency from star formation energy to H I kinetic energy

is given by $\epsilon \equiv E_{\text{HI,central}}/E_{\text{SF}}$. The actual efficiency could be lower if additional drivers also contribute to the kinetic H I energy. The conversion efficiency has been limited by a number of various studies, including those focusing on H I holes (e.g., Weisz et al., 2009a; Warren et al., 2012) and simulations (e.g., Tenorio-Tagle et al., 1991; Thornton et al., 1998). However, estimates of ϵ vary widely in these studies, from as low as $< 1\%$ to up to 50%.

We start by examining the behavior of $E_{\text{HI,central}}$ and E_{SF} as a function of Σ_{SFR} in Figure 4.17. For this figure, we normalize the energies by area, as larger radial annuli often have a larger area of contributing star formation but with lower intensities. We plot Σ_{HI} (top panels), the energy surface density of the H I central peak ($\Sigma_{E,\text{HI,central}}$; middle panels), and the star formation energy surface density ($\Sigma_{E,\text{SF}}$; bottom panels) as a function of Σ_{SFR} . The left-hand panels represent the superprofiles generated in radial subregions; points are colored by r/r_{25} . The right-hand panels show the superprofiles generated in subregions of constant Σ_{SFR} ; points are colored by Σ_{SFR} .

Figure 4.17 shows that $\Sigma_{E,\text{SF}}$ and $\Sigma_{E,\text{HI}}$ both decline with increasing Σ_{SFR} . However, their ranges span very different orders of magnitude. To indicate this difference in range, we have also plotted a black vertical line indicating one order of magnitude in the lower right corner of each panel. The H I energy surface density, which depends on both Σ_{HI} and σ_{central} , covers $\lesssim 2$ orders of magnitude, while the star formation energy density spans ~ 4 orders of magnitude. If star formation couples to H I with a universal efficiency, then we expect both $\Sigma_{E,\text{SF}}$ and $\Sigma_{E,\text{HI}}$ to span approximately the same number of orders of magnitude.

We can recast the data from Figure 4.17 by examining the correlation between E_{SF} and E_{HI} directly. We plot this comparison in Figure 4.18 for both the correlation between E_{SF} and E_{HI} and for the inferred energy coupling efficiency $\epsilon \equiv E_{\text{HI}}/E_{\text{SF}}$. Each point represents a single superprofile, and points are colored by r/r_{25} for the radial subregions (left panels) and by Σ_{SFR} for the Σ_{SFR} subregions (right panels). The top panels show E_{HI} versus E_{SF} , while the bottom panels show ϵ versus Σ_{SFR} . Unphysical or theoretically-forbidden efficiencies ($\epsilon > 1$ or $\epsilon > 0.1$) are shown in dark or light grey, and lines of constant efficiency are shown as dashed grey lines.

The data in Figure 4.18 clearly show that the coupling efficiency ϵ is lowest at the high SFR intensities characteristic of the inner disks of galaxies. At low SFR intensities

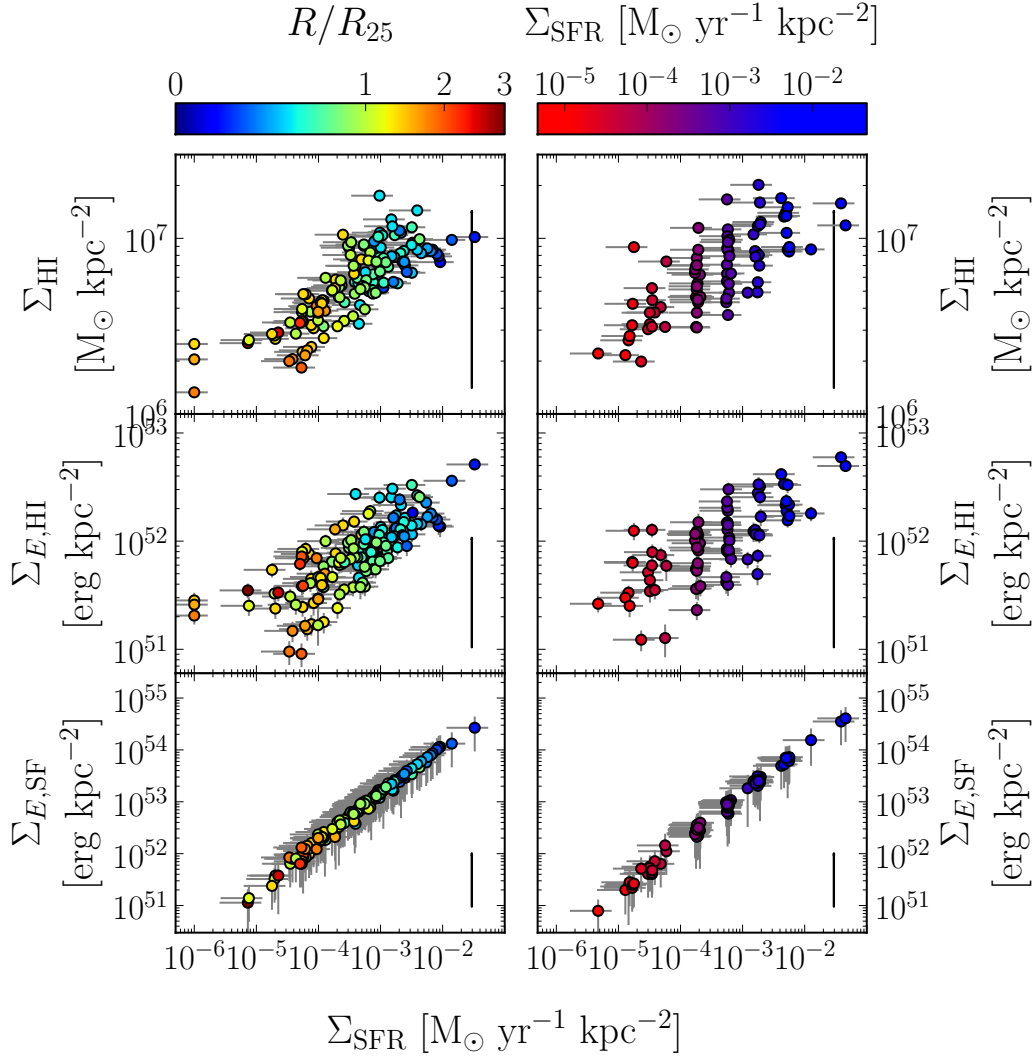


Figure 4.17 Σ_{HI} (upper panels), $\Sigma_{\text{E,HI}}$ (middle panels), and $\Sigma_{\text{E,SF}}$ (lower panels) as a function of Σ_{SFR} . Each point represents one spatially-resolved superprofile. The left-hand panels show measurements for superprofiles in radial subregions (colored by normalized radius), and the right-hand panels show measurements for superprofiles in subregions of constant Σ_{SFR} (colored by Σ_{SFR}). The vertical black line in the lower right corner of each panel represents one order of magnitude, indicating that $\Sigma_{\text{E,SF}}$ covers a much larger range than either Σ_{HI} or $\Sigma_{\text{E,HI}}$.

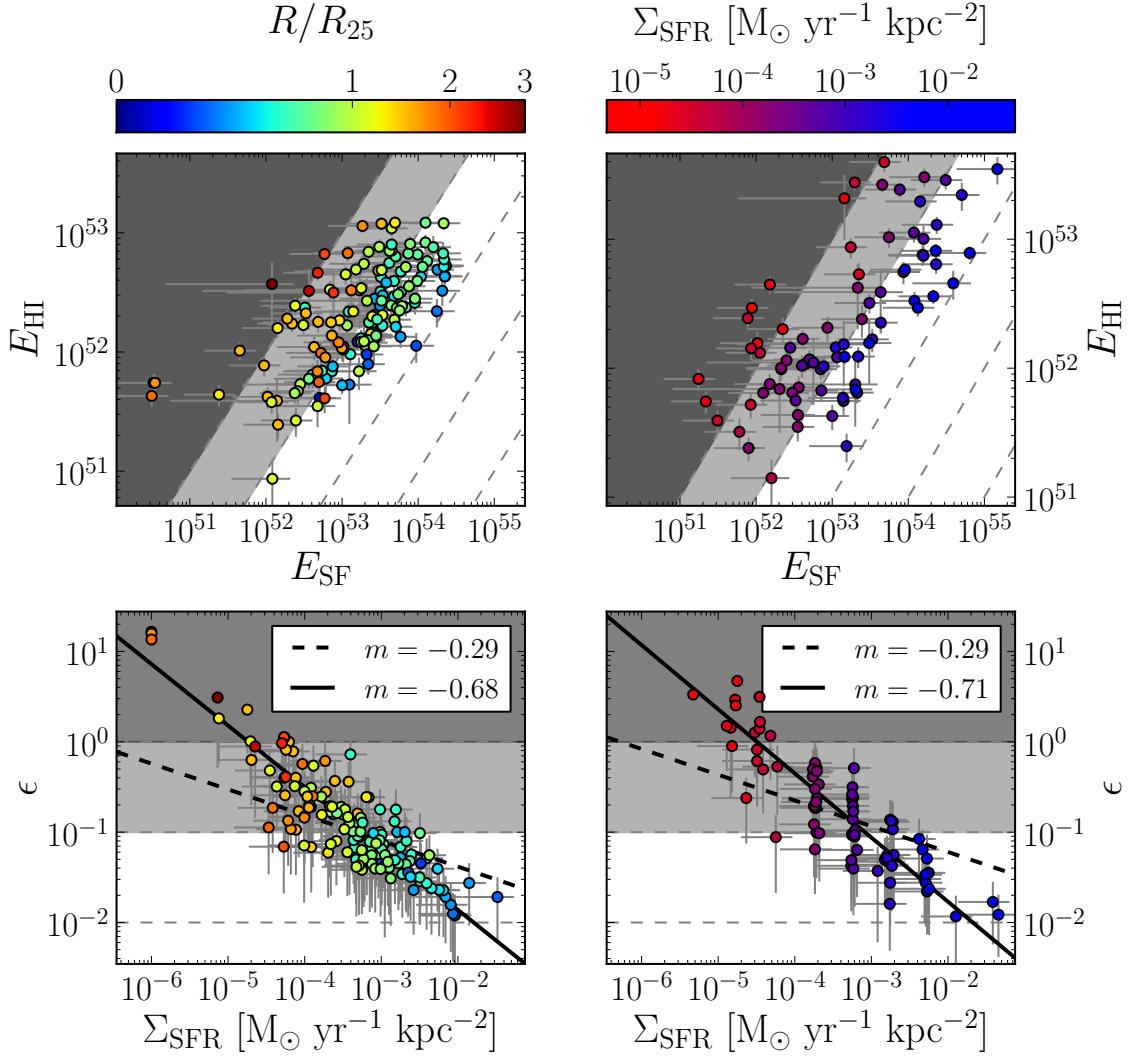


Figure 4.18 Comparison of H I and SF energies and coupling efficiencies for the spatially-resolved sample. The upper panels show E_{HI} versus E_{SF} , and the lower panels show $\epsilon \equiv E_{\text{HI}}/E_{\text{SF}}$. The left panels represent measurements from the superprofiles in radial subregions (colored by normalized radius), and the right panels show measurements from superprofiles in subregions of constant Σ_{SFR} (colored by Σ_{SFR}). The shaded regions represent regions where $\epsilon > 1$ (dark grey) and $\epsilon > 0.1$ (light grey). In the lower panels, we have overlaid the scaling relation between ϵ and Σ_{SFR} from simulations by Joung et al. (2009) as the thick dashed line. We also overlay the best-fit scaling relation to our data as the black solid line. In our data, ϵ has a steeper dependence on Σ_{SFR} than in the Joung et al. (2009) simulations, which were for higher star formation intensities and more massive galaxies.

($\Sigma_{\text{SFR}} \lesssim 10^{-4}$), ϵ often has theoretically-forbidden ($\epsilon > 0.1$ Thornton et al., 1998) or unphysical values ($\epsilon > 1$). If star formation were the sole driver of H I velocity dispersions, we might expect to see efficiencies that were constant. Instead, the strong apparent increase of efficiency with decreasing Σ_{SFR} may simply be due to the decrease of star formation energy with Σ_{SFR} while H I energy remains relatively constant due to another driving mechanism unrelated to SF. It also seems unlikely that the efficiencies conspire to produce the observed well-defined trend.

The observed trend of decreasing efficiencies with increasing Σ_{SFR} has also been seen in numerical simulations by Joung et al. (2009)¹, who found that $\epsilon \propto \Sigma_{\text{SFR}}^{-0.29}$. We show this scaling as the thick dashed black line in the lower panels of Figure 4.18, with the caveat that we have normalized the relation to match our data range. The Joung et al. (2009) scaling relation from the simulations is shallower than the observed relationship between Σ_{SFR} and ϵ in our sample. We also overlay the linear regression to the data as the solid black line, as given by $\log \epsilon = m \log (\Sigma_{\text{SFR}}/\Sigma_0) + b$; the best-fit regression corresponds to $\epsilon = (\Sigma_{\text{SFR}}/\Sigma_0)^{-0.68 \pm 0.03}$ and $\epsilon = (\Sigma_{\text{SFR}}/\Sigma_0)^{-0.71 \pm 0.04}$ for the superprofiles generated in subregions of constant radius or star formation intensity, respectively. The normalization $\Sigma_0 = (6.0 \pm 1.3) \times 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ for the constant radius subregions, and $\Sigma_0 = (6.4 \pm 1.8) \times 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ for the constant Σ_{SFR} subregions. For both types of subregion, the relation between Σ_{SFR} and ϵ is steeper than the relationship found by Joung et al. (2009). However, the Joung et al. (2009) simulations focused on more intense star formation regimes than our sample, spanning 1 – 512 times the SFR of the Milky Way. In addition, the scaling relations adopted in the Joung et al. (2009) simulations may not be appropriate for lower-mass galaxies like those in our sample. For example, Joung et al. (2009) assumed that $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.4}$, a value appropriate for the larger spirals in their simulations, but in the lower-mass SMC, Bolatto et al. (2011) found a much steeper relation of $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{2.2}$, a scaling more appropriate for our low-mass sample. In spite of the different SFR regimes and input assumptions, however, the observed behavior of declining efficiency with increasing Σ_{SFR} is still qualitatively similar to the Joung et al. (2009) simulations.

¹The exponent on this scaling is different than that published in Joung et al. (2009), but the author agreed with the change (Joung, private communication).

A declining coupling efficiency with increasing Σ_{SFR} is not theoretically unreasonable. The ISM is multiphase, and the neutral medium we trace here is probably less directly coupled to star formation than the dense molecular phase, which precedes star formation, or the hotter ionized phase, which is an immediate result of star formation. For example, if the energy of star formation, in the form of stellar winds and SN feedback, goes primarily into shock heating and producing ionized outflows, then any coupling to the neutral medium must occur primarily on the interfaces between the expanding SN-driven bubbles and the neutral gas reservoir, suggesting a relatively weak coupling consistent with what is seen here. At high enough Σ_{SFR} , SN-driven outflows may be strong enough to break out of the galactic disk, allowing more of the star formation energy to escape (e.g., Dekel & Silk, 1986). In addition, Lopez et al. (2011) have shown that hot gas in the intense star forming region 30 Doradus can leak out of the surrounding shell, consistent with this picture.

The star formation energy may also couple more strongly to the warm ionized phase of the ISM. Indeed, studies of $\text{H}\alpha$ in dwarf galaxies indicate that the ionized gas shows both larger velocity dispersions and a larger dynamic range compared with H I (e.g., van Eymeren et al., 2010; Moiseev & Lozinskaya, 2012). For example, Sextans A contains a shell of ionized gas with expansion velocities of $\sim 60 \text{ km s}^{-1}$, much higher than surrounding H I velocity dispersions (Martin, 1998). One could imagine that as the SFR intensity decreases, a smaller fraction of the SN-driven bubbles actively undergo blowout, thus guaranteeing that most of the SN energy is deposited in the disk and increasing the coupling efficiency between star formation and H I energies. Indeed, extraplanar diffuse ionized gas has been seen primarily in spirals whose disks exceed a given Σ_{SFR} threshold (Rossa & Dettmar, 2003), consistent with the picture that a stronger coupling to the ionized phase (and therefore a weaker coupling to H I) exists at higher Σ_{SFR} .

The turbulent dissipation timescale in dwarf galaxies could potentially be longer than the fiducial $\sim 10 \text{ Myr}$ found by Mac Low (1999). At low SFRs, SNe are sparsely distributed across the disk, implying that the driving scale of turbulence in these systems could be larger as remnants could propagate farther through the disk. The increased scale heights of dwarf galaxies compared to larger spiral disks mean that SNe are still contained within the disk to larger radii than in more massive galaxies. The scale height therefore provides

an upper limit to the driving scale, as energy can escape from the disk once the radius of the SNe is equal to the scale height. The scale heights of dwarf galaxies are a few times larger than more massive spiral counterparts (e.g., Banerjee et al., 2011). This difference only provides a factor of a few increase in the energy available from star formation, which is not enough to compensate for implied efficiencies of $\epsilon \gtrsim 1$.

If star formation has nothing to do with setting turbulent H I velocity dispersions, we would also expect to see declining efficiencies with increasing Σ_{SFR} . For a fixed H I turbulent energy, we would expect $\epsilon \propto \Sigma_{\text{E,SF}}^{-1}$, implying a similar scaling between ϵ and Σ_{SFR} . This scaling is steeper than the observed $\epsilon \propto \Sigma_{\text{SFR}}^{-0.64}$ from Figure 4.18, so it is likely that star formation does have some influence on H I turbulent velocity dispersions. However, the fact that efficiencies reach unphysically high values at low star formation intensities indicates that Σ_{SFR} cannot be the sole driver of H I velocity dispersions. This scaling is also hampered by the fact that local ISM conditions also scale with star formation; for example, Σ_{HI} and Σ_{SFR} are correlated. We explore other drivers of turbulence in § 4.5.1.5 and 4.5.1.6.

4.5.1.5 *Turbulent H I Kinematics and Surface Mass Density*

Although the H I velocity dispersion correlates with the local Σ_{SFR} at high star formation intensities, it is even more strongly correlated with Σ_{baryon} (Tables 4.3 and 4.4). The mismatch between star formation energy and H I energy, especially at low star formation intensities, supports the idea that H I velocity dispersions are driven at least partially by other processes.

The fact that σ_{central} correlates most strongly with Σ_{baryon} may indicate that H I velocity dispersions are driven by some type of gravitational instability in the low Σ_{SFR} , low Σ_{baryon} regime that dominates our sample. However, the solid-body rotation curves of low-mass galaxies do not provide the large shearing motions that are thought to be necessary to drive most gravitational instabilities (e.g., Kim & Ostriker, 2007; Agertz et al., 2009). A number of these gravitational instabilities also require the presence of strong spiral arms (e.g., Roberts, 1969; Lin & Shu, 1964), which are likewise not present in the majority of our sample. In addition, our earlier analysis of the global kinematics (Chapter 3) showed that

one of these gravitational instabilities, as outlined by Wada et al. (2002), does not provide enough energy to drive H I velocity dispersions.

Simple energy scaling arguments for gravitational instabilities suggests that σ_{central} should increase as $\Sigma_{\text{baryon}}^{0.5}$ for an isothermal disk with fixed scale height (e.g., van der Kruit, 1981). However, a MCMC fit (see Foreman-Mackey et al., 2012) to the σ_{central} and Σ_{baryon} data yields

$$\sigma_{\text{central}} = (7.6 \pm 0.9) \left(\frac{\Sigma_{\text{baryon}}}{10^7 \text{ M}_{\odot} \text{ kpc}^{-2}} \right)^{0.13 \pm 0.01}, \quad (4.15)$$

with a slope three times shallower than expected. This discrepancy may be due to the influence of the dark matter component within the disk, or to variable scale heights in our sample. Using the equation for scale height given by Ott et al. (2001):

$$h_z = 579 \text{ pc} \left(\frac{\sigma_{\text{gas}}}{10 \text{ km s}^{-1}} \right)^2 \left(\frac{N_{\text{HI}}}{10^{21} \text{ cm}^{-2}} \right)^{-1} \left(\frac{\rho_{\text{HI}}}{\rho_t} \right), \quad (4.16)$$

where σ_{gas} is the velocity dispersion, N_{HI} is the H I column density, and ρ_{HI} and ρ_t are the H I and total mass densities of the disk, we derive scale heights ranging between $\sim 50\text{--}900$ pc for the subregions. However, the idea of a “scale height” may not be appropriate for the smallest dwarfs in our sample, which show very irregular H I distributions and high σ/w_{20} ratios for disks. We note that this slope remains the same if we use the Σ_{SFR} superprofiles instead of the radially-resolved ones. Both the fact that gravitational drivers are inefficient in these systems (Chapter 3) as well as the mismatch between the expected and measured scaling of σ_{central} with Σ_{baryon} imply that gravity is not a strong factor in driving H I turbulence.

4.5.1.6 Other Possible Turbulent Drivers

Many of the other proposed non-stellar drivers of turbulence, such as the magnetorotational instability (MRI), require shear from differential rotation to extract energy from the gravitational potential and convert it to turbulence. Unfortunately, the rotation curves of dwarf galaxies are often solid-body and therefore lack the necessary shear. We note that H I in dwarf galaxies show similar velocity dispersions to those measured in the outer regions of spirals, where shear is present. Because the MRI is expected to be less efficient in this regime, but H I velocity dispersions are similar, one can question the idea that MRI is a

driver of H I velocity dispersions in spirals as well. On the other hand, non-circular motions in galaxies could potentially provide a source of shear to extract energy for turbulence, but the average amplitude of non-circular motions ($\lesssim 5 \text{ km s}^{-1}$; Trachternach et al., 2008; Oh et al., 2011) is smaller than the typical H I velocity dispersions, thus requiring efficiencies in excess of 100%.

Recently, mass accretion has been proposed as a driver of turbulence in galaxies (Klessen & Hennebelle, 2010). In this scenario, infalling gas converts its kinetic energy to turbulent energy with some efficiency:

$$\epsilon_{\text{acc}} \equiv \left| \frac{\dot{E}_{\text{decay}}}{\dot{E}_{\text{in}}} \right| = \frac{M_{\text{gas}} \sigma^3}{\lambda \dot{M}_{\text{in}} v_{\text{in}}^2}, \quad (4.17)$$

where $\dot{E}_{\text{decay}}$ and $\dot{E}_{\text{in}}$ are the rates of turbulent energy decay and energy input, respectively. Here, M_{gas} is the mass of turbulent gas, σ^2 is the turbulent velocity dispersion, and λ the turbulent decay length. $\dot{M}_{\text{in}}$ and v_{in} represent the mass accretion rate and the velocity of infalling gas. The authors calculated the required coupling efficiencies for accretion-driven turbulence in 11 THINGS galaxies, under the assumption that $\dot{M}_{\text{in}} = \dot{M}_{\text{SF}}$ (i.e., that all infalling gas is being converted to stars) and $v_{\text{in}} = v_{\text{rot}}$. They found that the efficiencies were $\epsilon \lesssim 10\%$ for the 8 spirals in their sample, including the outer disks, but the 3 of the 4 dwarfs that overlap with our sample required $\epsilon > 1$ to drive observed levels of turbulence (IC 2574, NGC 4214, and Ho I). While this method may be a viable source of energy for turbulence in the outer disks of spirals, it does not appear to function effectively in dwarfs.

We note that SN bubbles or H II regions could induce expanding gas motions, resulting in infalling material that could drive turbulence through a similar mechanism (“galactic fountain”; e.g., Shapiro & Field, 1976). In spiral galaxies, this idea is supported by the existence of extraplanar gas at anomalous velocities in some systems (e.g., Fraternali et al., 2001, 2002; Barbieri et al., 2005; Boomsma et al., 2008). Expanding ISM material has also been detected in both typical and starbursting dwarf galaxies (e.g., NGC 2366, NGC 4861, NGC 1569, NGC 4214; Schwartz & Martin, 2004; van Eymeren et al., 2009a,b, 2010). However, the timescale for this expanding gas to fall back to the disk is unclear, as ionized gas structures can be found in regions far from any current star formation (e.g., Hunter et al., 1993), thus hampering any energy calculations. In addition, the fact that less than half the

dwarfs in the Hunter et al. (1993) sample showed evidence of expanding shells indicates that galactic fountains are unlikely to be responsible for accretion-driven turbulence in all dwarf galaxies.

Dynamical interactions with dark matter subhalos have recently been proposed as a cause for H I holes or both gaseous and stellar substructure in extended galaxy disks (e.g., Bekki & Chiba, 2006; Kazantzidis et al., 2008). These interactions could potentially be a source of energy for turbulence in low Σ_{SFR} regions if energy could be extracted and transferred to the gas. Because the H I gas will dissipate its turbulent energy over ~ 10 Myr, the interactions must be at least this frequent to sustain observed levels of turbulence. Followup simulations have concluded that impacts from dark matter subhalos are an unlikely cause of H I holes (e.g., Kannan et al., 2012), but interactions that increase velocity dispersion are not necessarily restricted only to the energetic events necessary for hole creation. Halo impacts on the disk can increase gas velocity perpendicular the disk of order $\sim 5 - 10$ km s $^{-1}$, but the effect is local (e.g., Kannan et al., 2012).

As a first test of this idea, we compare the gravitational potential energy of the galaxy, E_{GPE} , to the energy required to maintain the observed velocity dispersion, $E_{\text{turb}} = \dot{E}_{\text{turb}}\tau_D$, since a redshift of $z = 1$. To first order, we can estimate the gravitational potential energy of a halo with an isothermal density profile as:

$$E_{\text{GPE}} = \frac{GM_{200}^2}{R_{200}} = (10GH)^{2/3}M_{200}^{5/3}, \quad (4.18)$$

where G is the gravitational constant, H is the Hubble constant (70 km s $^{-1}$ Mpc $^{-1}$; Komatsu et al., 2011), and M_{200} and R_{200} are the mass and radius of the halo when the average density reaches 200 times the critical density of the universe. The dissipation rate of turbulent energy associated with a mass M_{HI} for a given velocity dispersion σ is

$$\dot{E}_{\text{turb}} = \eta_v k M_{\text{HI}} \sigma^3, \quad (4.19)$$

where $\eta_v = 0.21/\pi$ and k is related to the driving length scale of turbulence by $k = 2\pi/\lambda$ (Mac Low, 1999).

We can compare the energy required to maintain a velocity dispersion of 10 km s $^{-1}$ since a redshift of $z = 1$ to the gravitational potential energy of the halo by taking the ratio of

E_{turb} to E_{GPE} . If we assume that $M_{\text{HI}} = f_{\text{gas}} M_{\text{baryon}}$ and $M_{200} = M_{\text{baryon}}/f_{\text{baryon}}$, we can re-write the ratio $\dot{E}_{\text{turb}} \times t/E_{\text{GPE}}$ as:

$$\epsilon = 0.078 \left(\frac{f_{\text{gas}}}{0.5} \right) \left(\frac{f_{\text{baryon}}}{0.0066} \right)^{5/3} \left(\frac{M_{\text{baryon}}}{10^8 \text{ M}_{\odot}} \right)^{-2/3} \left(\frac{\sigma}{10 \text{ km s}^{-1}} \right)^3 \left(\frac{\lambda}{100 \text{ pc}} \right). \quad (4.20)$$

In this case, we have assumed $f_{\text{gas}} = 0.5$, a value compatible with the M_{HI} and M_{baryon} measurements of our sample. Estimates for f_{baryon} for the range of M_{star} in our sample are $0.01 - 0.1 f_{\text{cosmic}}$ (Trujillo-Gomez et al., 2011), where f_{cosmic} is the cosmic baryon fraction of the universe (i.e., $\Omega_{\text{baryon}}/\Omega_{\text{matter}}$); we choose the median $f_{\text{baryon}} = 0.05 f_{\text{cosmic}}$. We use $H = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, as consistent with the seventh year WMAP results (Komatsu et al., 2011).

The ratio of E_{turb} to E_{GPE} is 0.078 for halos with $M_{\text{baryon}} = 10^8 \text{ M}_{\odot}$, the mean stellar mass of our sample, and increases for the lower-mass dwarfs in our sample with smaller M_{baryon} . If energy can be extracted from the gravitational potential of the galaxy (i.e., due to interactions between the disk and dark matter subhalos), the ratio given in Equation 4.20 must at the very least be less than the canonical fraction of mass in subhalos smaller than a given halo mass (10%; e.g., Klypin et al., 1999; Ghigna et al., 2000). Since dark matter is collisionless and can only affect the disk gravitationally, one would expect the efficiency of extracting energy to be very low. It would also depend on the interaction rate between subhalos and the gaseous disk, as not all subhalos have orbits that pass through the H I disk (e.g., Kannan et al., 2012). This method may be potentially feasible for massive galaxies, with larger gravitational potentials, but is unlikely to provide enough energy in the lower-mass galaxies where other potential drivers of turbulence (e.g., the MRI or gravitational instabilities) are unable to function.

4.5.1.7 Implications

H I velocity dispersions in dwarf galaxies are very similar to those of spirals. In this paper, we have examined a number of potential sources of energy for turbulent velocity dispersions (star formation, known gravitational instabilities, the MRI, and accretion-driven turbulence) and found that no single one is able to consistently sustain the observed velocity dispersions in all regions of dwarf galaxies. If some instability could extract energy from the rotational

energy of the galaxies, it would require efficiencies on the order of $\epsilon \sim (\sigma_{\text{central}}/v_{\text{rot}})^2$, which ranges from $\epsilon \sim 0.4 - 10\%$ for a median $\sigma_{\text{central}} = 7.8 \text{ km s}^{-1}$ and the range of $v_{\text{rot}} \sim w_{20}/2$ values of our sample. These efficiencies are not unreasonable, but the mechanism to extract this energy is unknown.

In addition, it is not necessary to limit the energy for turbulence to a single source. Instead, it may come from a number of sources, e.g.:

$$E_{\text{total}} = \epsilon_{\text{SF}} E_{\text{SF}} + \epsilon_{\text{grav}} E_{\text{grav}} + \epsilon_{\text{accr}} E_{\text{accr}} + \dots \quad (4.21)$$

for contributions from star formation, gravitational, accretion energies, and other sources, respectively, but disentangling the required efficiencies for each energetic component is beyond the scope of this paper.

It is also possible that the observed velocity dispersions are thermal in nature, instead of turbulent. A UV background could potentially drive thermal velocity dispersions to $\sim 6 \text{ km s}^{-1}$ (Schaye, 2004; Tamburro et al., 2009), but is unlikely to explain the higher velocity dispersions of $\sim 10 \text{ km s}^{-1}$. If some other mechanism is able to heat H I to higher temperatures (i.e., the decay of previous turbulent energy into thermal energy), the combination of low metallicity from inefficient SF and the low pressure due to low surface density means that H I is likely to exist primarily in the warm phase. We can test this by assuming that existing SF couples to the surrounding H I gas at a 10% efficiency, producing H I with a turbulent velocity dispersion σ_{turb} , with thermal broadening at a level σ_{thermal} making up the remainder of the observed velocity dispersion. By adding the two velocity dispersions in quadrature to obtain observed σ_{central} values (i.e., $\sigma_{\text{central}}^2 = \sigma_{\text{thermal}}^2 + \sigma_{\text{turb}}^2$), we estimate the necessary σ_{thermal} as:

$$\sigma_{\text{thermal}} = \left(\sigma_{\text{central}}^2 - 0.1 \frac{2 \Sigma_{\text{E,SF}}}{\Sigma_{\text{HI}}} \right)^{1/2}. \quad (4.22)$$

Here, 0.1 represents a fiducial coupling efficiency between SF energy and H I turbulent energy. This approximation is valid only in low Σ_{SFR} regimes, as observed efficiencies can be $\lesssim 0.1$ in higher Σ_{SFR} regions.

In Figure 4.19 we plot the implied σ_{thermal} and corresponding implied temperature T as a function of Σ_{SFR} for superprofiles in regions of constant radius (top) and constant

Σ_{SFR} (bottom). The implied T values span a wide range, from 100 – 16000 K, with many σ_{thermal} values requiring temperatures in the unstable regime of the phase diagram (e.g., Wolfire et al., 1995). In the Milky Way, roughly 50% of H I has been observed to have temperatures in this unstable regime (Heiles, 2001; Heiles & Troland, 2003), so it may not be unrealistic to expect similar results in other galaxies. A small number of superprofiles have implied temperatures greater than 10^4 K, approximately the maximum temperature expected for H I (e.g., Wolfire et al., 1995). The Mach numbers implied by σ_{thermal} and σ_{turb} are typically subsonic for estimates of σ_{thermal} from Equation 4.22 or from assuming that all H I has $T = 7000$ K. If the H I were cold ($T = 100$ K), however, the Mach numbers indicate supersonic turbulent motions for the superprofiles.

For the low column densities and larger scale heights of dwarf galaxies, we might expect the majority of H I to be in the warm phase, with $T \sim 10^4$ K. The low metallicity characteristic of these galaxies plus lower gas densities means that n^2 cooling processes are less efficient, and thus gas will remain in the warm phase for longer times. Therefore, it may not be unreasonable to expect that H I velocity dispersions are primarily thermal in low Σ_{SFR} regions. However, implied temperatures greater than 10^4 K suggest that both turbulence due to star formation and thermal broadening are unable to explain the velocity dispersion of *all* H I line profiles.

In summary, we have determined that *none* of the proposed drivers of turbulence alone can function effectively in dwarf galaxies where the typical Σ_{SFR} is low. In all cases, more energy is required than can be provided by any driver alone. If the velocity dispersions are indeed due to turbulence, the only apparent solution is that the turbulent energy is not being dissipated at the expected rate. It is therefore unclear what mechanism is driving the turbulence in the low- Σ_{SFR} regime. However, thermal broadening can potentially provide broadening at the observed levels of velocity dispersion, but the connection between thermal velocity dispersions and star formation is not necessarily clear when both high and low Σ_{SFR} regions are taken into account.

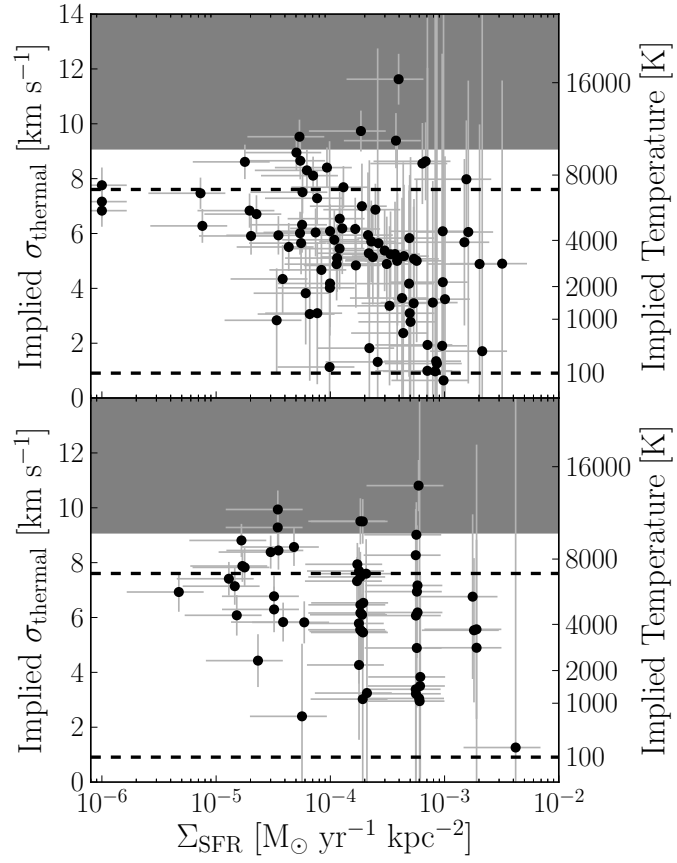


Figure 4.19 Implied thermal velocity dispersions and corresponding temperatures for superprofiles in regions of constant radius (top panel) and constant Σ_{SFR} (bottom panel), assuming a coupling efficiency of 0.1 between star formation and H I energy. The horizontal dashed lines are the two stable temperatures expected for H I (Wolfire et al., 1995). We have shaded $T > 10^4$ K, where H I is not expected to exist.

4.5.2 The Superprofile Wings

We find that only a small fraction ($\lesssim 15\%$) of the H I gas exists at high velocities compared to σ_{central} . These small fractions indicate either small systematic non-Gaussianity inherent in H I line profiles (e.g., Petric & Rupen, 2007) or may be due to small amounts of H I gas accelerated to high velocities by SN feedback. However, we see no significant trend between f_{wings} and the local star formation intensity. The only possible trend is an indication that f_{wings} has lower scatter at higher star formation intensities, which may be due only to the small number of measurements at these extreme values. While the lack of strong correlations suggests only a tenuous connection between high velocity gas and star formation or a poor mismatch of the spatial and temporal scales to which are measurements are sensitive, the lack of a clear lifetime for high velocity gas makes any firm conclusions difficult, given that the presence of high velocity gas may be restricted to timescales either much shorter or longer than the timescale associated with FUV+24 μm SFR estimates. We investigate this possibility further in Chapter 5 of this thesis.

Like the width of the central peak of the superprofiles, σ_{wings} also tends to increase with increasing measures of mass surface density and/or star formation. If this trend is interpreted physically, this behavior is consistent with the idea that star formation drives bulk H I motions to faster velocities, for some fraction of the H I disk. However, σ_{wings} is correlated with σ_{central} by definition (Equation 4.3), so superprofiles with higher σ_{central} values must necessarily have higher σ_{wings} values as well.

In Chapter 3, we proposed that the asymmetry of the wings had more scatter in lower mass galaxies due to star formation. In that scenario, individual star formation regions drove asymmetric H I motions, so galaxies with fewer star formation regions had a higher chance of retaining asymmetry in the superprofile. If that were the case, we might expect to see increased asymmetry in the spatially resolved superprofiles with increased measures of star formation, as traced by either Σ_{SFR} or $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$. In general, the a_{full} parameter does not show the expected trends, though some individual galaxies do show increasing a_{full} with increasing Σ_{SFR} (i.e., IC 2574, NGC 4214, DDO 53).

The asymmetry of the superprofiles may therefore be due to other factors, such as

infalling or outflowing H I. The trend of decreasing scatter in a_{wings} with increasing SFR found in Chapter 3 could also be attributed to the fact that galaxies with lower total SFRs tend to be lower mass, with shallower potentials that are more conducive to sloshing motions that could induce the observed asymmetry. For example, the velocity field of UGC 4483 has been shown to be consistent with rotation plus $\sim 5 \text{ km s}^{-1}$ radial motions (Lelli et al., 2012). As stated before, average non-circular motions are $\lesssim 5 \text{ km s}^{-1}$ in THINGS dwarf galaxies in our sample (Trachternach et al., 2008; Oh et al., 2011). If these motions are not uniform across the galaxy disk, they could produce asymmetries that propagate to the superprofiles.

4.5.3 *Universality in H I profile shapes*

As proposed in Petric & Rupen (2007) and discussed in Chapter 3, average H I line profiles tend to show very similar shapes when normalized to the same width. We now determine if the spatially-resolved superprofiles also have similar shapes. In Figure 4.20, we show the resolved superprofiles after scaling to the same amplitude and HWHM. Both radial superprofiles (left) and Σ_{SFR} superprofiles (right) are shown. We find similar behavior for the spatially-resolved superprofiles as in Chapter 3 and Petric & Rupen (2007). The primary differences manifest in the wing regions, with some galaxies showing more flux in the wings compared to others. This finding supports the idea that the H I emission tends to follow a non-Gaussian profile shape.

4.6 *Conclusions*

We have presented average H I spectra on spatially-resolved scales in a number of nearby dwarf galaxies from VLA-ANGST and THINGS. To produce these superprofiles, we have co-added H I line-of-sight spectra after removal of the rotational velocity for regions determined both by radius and by the local Σ_{SFR} . Like the global superprofiles presented in Chapter 3, the spatially-resolved superprofiles typically exhibit a narrow central peak with higher velocity wings to either side.

As with the global superprofiles, the shape of the spatially-resolved H I superprofiles, when scaled to the same HWHM, is very similar from galaxy to galaxy. The majority of the

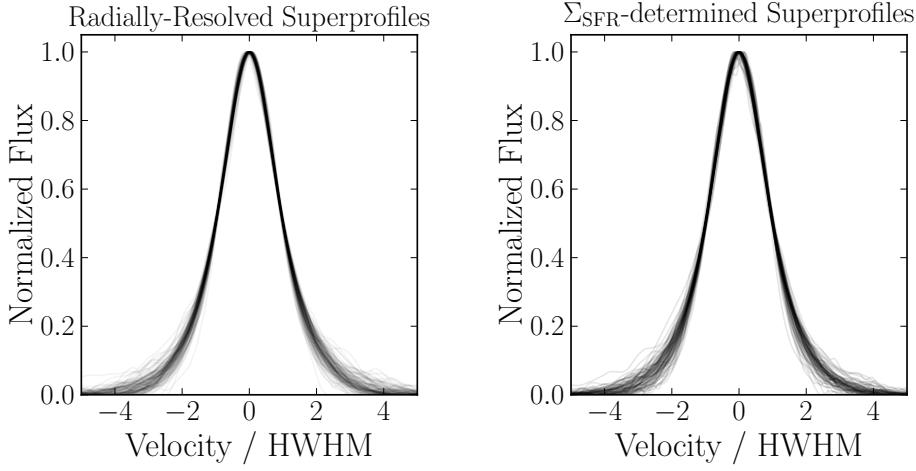


Figure 4.20 Superprofiles scaled to the same amplitude and HWHM for our sample. The left panel shows all superprofiles from radial subregions, while the right shows the all superprofiles from subregions of constant Σ_{SFR} . Each line represents a single superprofile, and has been plotted with a transparency value. Darker regions indicate more overlapping superprofiles. In both cases, the superprofiles have very similar shapes when scaled to the same HWHM, with the majority of fluctuations in the wing regions. The similarity of average H I line shapes suggests that the intrinsic H I profiles may not be Gaussian.

differences in shape are in the wings of the superprofiles. The similarity in shape supports the idea discussed in Chapter 3 that average H I profiles are non-Gaussian.

We follow the interpretation in Chapter 3 and characterize the central peak as turbulent with a width σ_{central} . We interpret the higher-velocity wings as representing anomalous H I motions, and characterize their *rms* velocity (σ_{wings}) and the fraction of H I in the wings (f_{wings}). We also measure the asymmetry of the full superprofile, a_{full} . By comparing these parameters to the spatially-resolved physical properties, we have found a number of correlations.

- σ_{central} : The width of the central peak shows correlations with all physical properties we have measured (Σ_{HI} , Σ_{baryon} , Σ_{SFR} , and $\Sigma_{\text{SFR}}/\Sigma_{\text{HI}}$). The correlations with star formation are strongly driven by the highest Σ_{SFR} regions in our sample. At $\Sigma_{\text{SFR}} < 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, H I velocity dispersions do not appear to be connected to Σ_{SFR} and can even be as high as 10 km s^{-1} . However, star formation does appear to set a lower threshold below which velocity dispersions cannot fall.

- σ_{wings} : The *rms* velocity of the wings is also correlated with all physical properties we have measured. This behavior could indicate that star formation can drive surrounding H I to faster velocities. However, it may be caused by correlations between our parameters; higher σ_{central} values produce higher σ_{wings} values by definition.
- f_{wings} : We do not find strong correlations between f_{wings} and physical properties, which may indicate that the wings of the H I profiles are not due to star formation but instead reflect an intrinsic H I profile shape.
- a_{full} : The asymmetry of the full superprofiles does not appear to be connected with local ISM properties, and therefore may be due to other effects, such as warps or inflowing gas.

We have also compared the energy from star formation to the H I kinetic energy in the central turbulent peak of the superprofiles over one turbulent timescale. As previously observed, the coupling efficiency must increase with radius in large dwarfs if star formation is the sole driver of H I kinematics. Similarly, the coupling efficiency between star formation energy and H I kinetic energy decreases as a function of Σ_{SFR} . Otherwise, the efficiencies are realistic ($\epsilon < 0.1$) only in regions where $\Sigma_{\text{SFR}} > 5 \times 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$.

Star formation therefore does not appear to be the sole driver of H I kinematics in dwarf galaxies, though our data suggest that it does influence them. Star formation may also provide a lower threshold to the surrounding H I velocity dispersions. It is therefore likely that some other physical mechanism is inducing turbulent motions in regions of low star formation, or that the velocity dispersions are thermal in nature. However, many of the proposed drivers of turbulence cannot function efficiently in the systems studied in this paper, but simulations of dwarf galaxies are necessary to estimate the effectiveness of other instabilities in a non-shearing, low Σ_{SFR} regime.

4.7 *Spatially-Resolved Superprofiles for the Entire Sample*

In this section, we present the spatially-resolved superprofiles for the entire sample. In § 4.7.1, we show the superprofiles derived in subregions of constant radius, and in § 4.7.2 we show the superprofiles derived in subregions of constant Σ_{SFR} . In both sections, the figures are ordered by decreasing galaxy $M_{\text{baryon,tot}}$.

4.7.1 *Radial Superprofiles*

In the following pages, we present the superprofiles generated in subregions of constant radius. For a single galaxy, the figures are the same as Figures 4.3a - 4.3c. Galaxies are shown in order of decreasing $M_{\text{baryon,tot}}$, with the exception of NGC 7993, which was previously shown in the text.

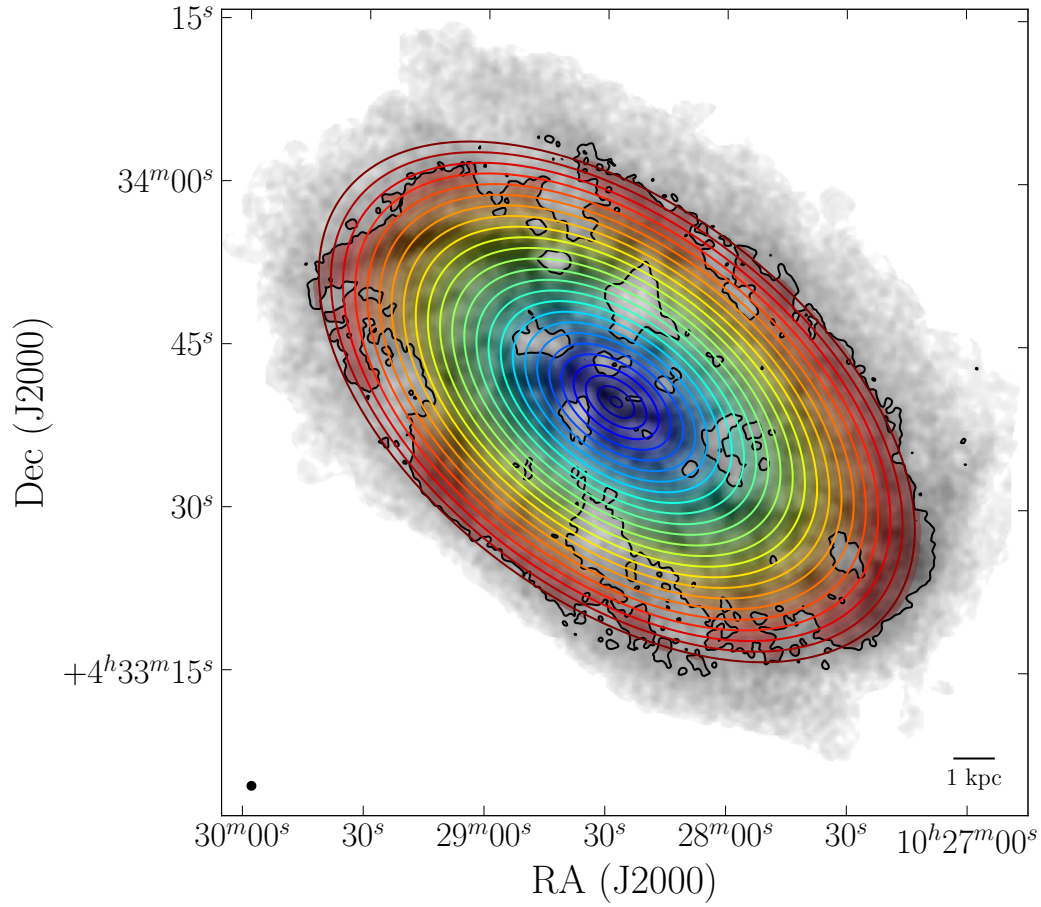


Figure 4.21a Radial annuli in which radial superprofiles are generated for IC2574. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

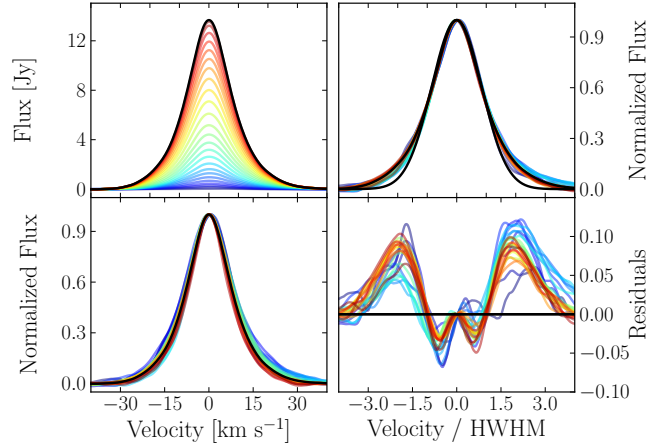


Figure 4.21b The radial superprofiles in IC 2574, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

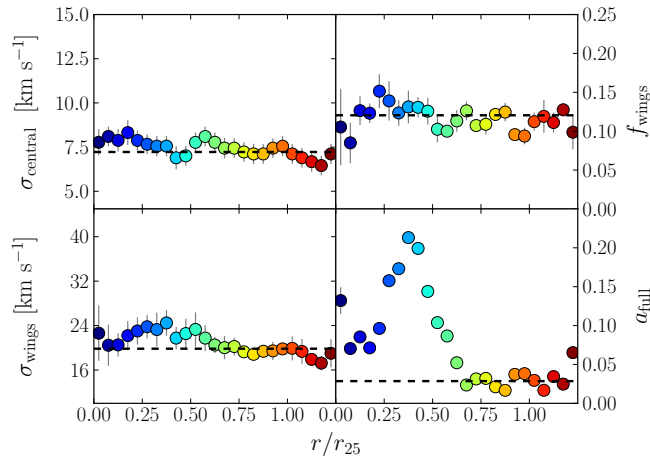


Figure 4.21c Variation of the superprofile parameters as a function of normalized radius for IC 2574. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

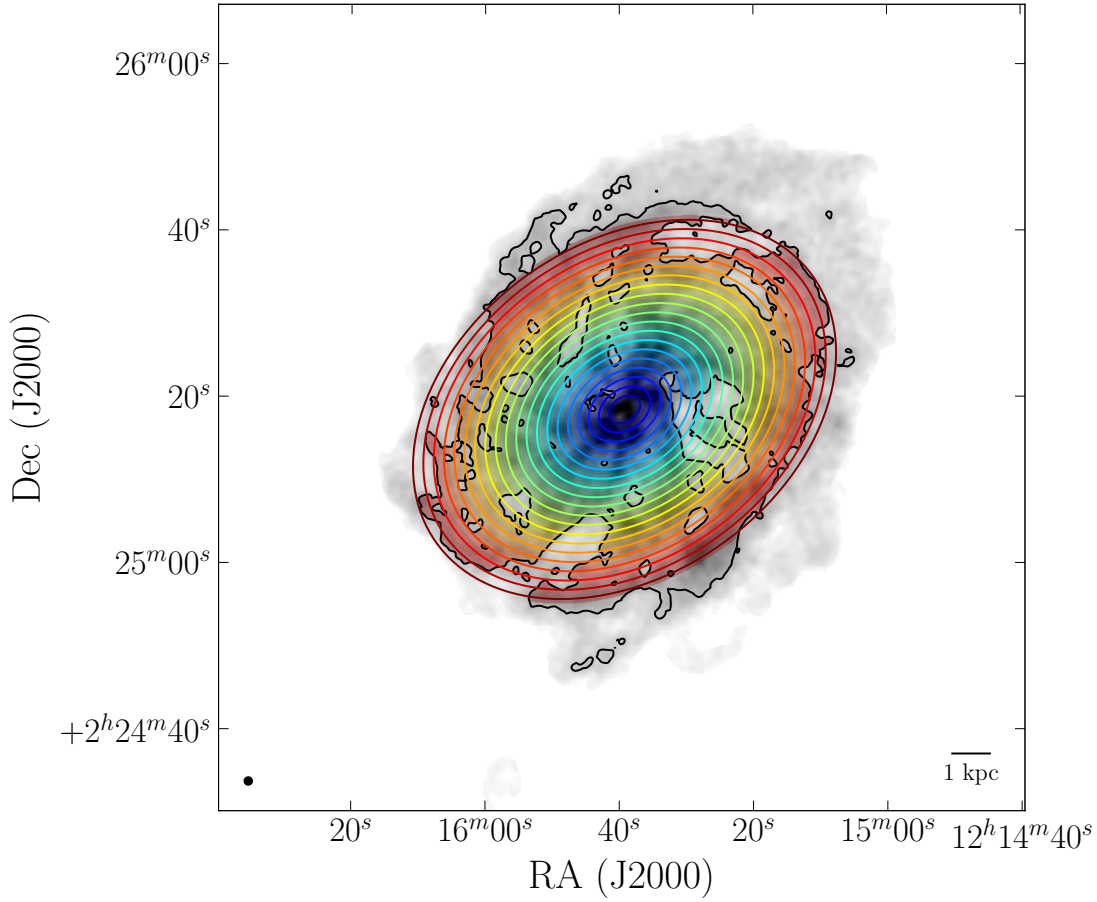


Figure 4.22a Radial annuli in which radial superprofiles are generated for NGC 4214. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

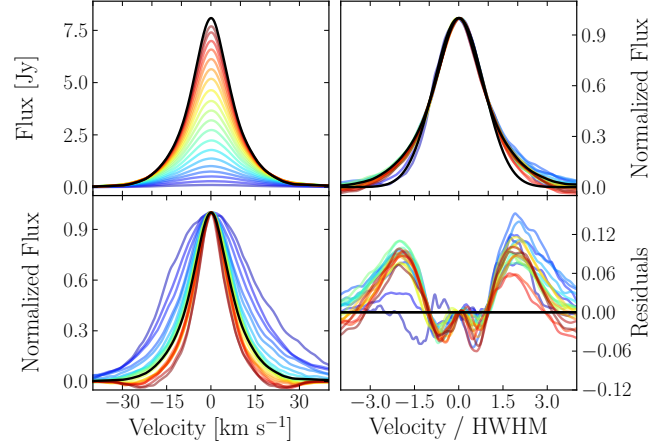


Figure 4.22b The radial superprofiles in NGC 4214, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

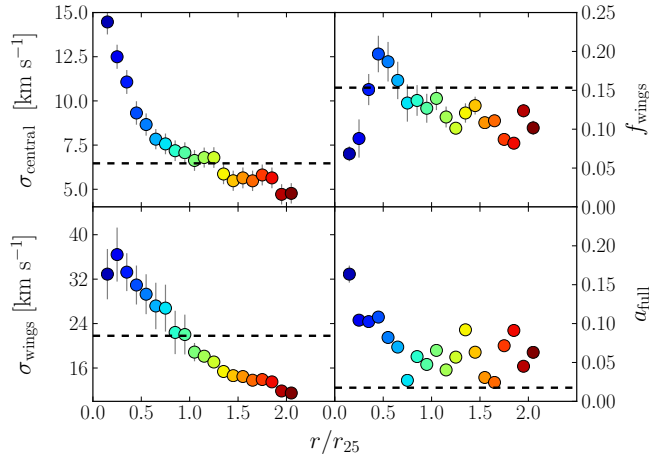


Figure 4.22c Variation of the superprofile parameters as a function of normalized radius for NGC 4214. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

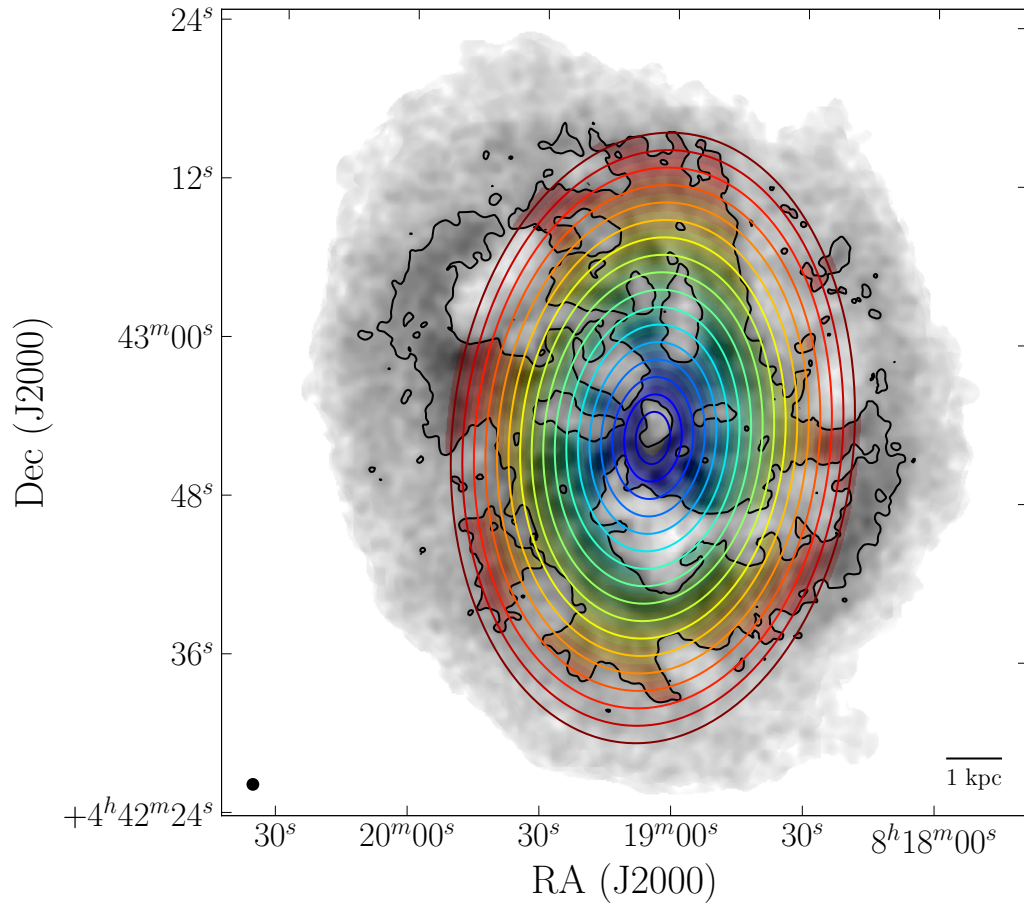


Figure 4.23a Radial annuli in which radial superprofiles are generated for Ho II. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

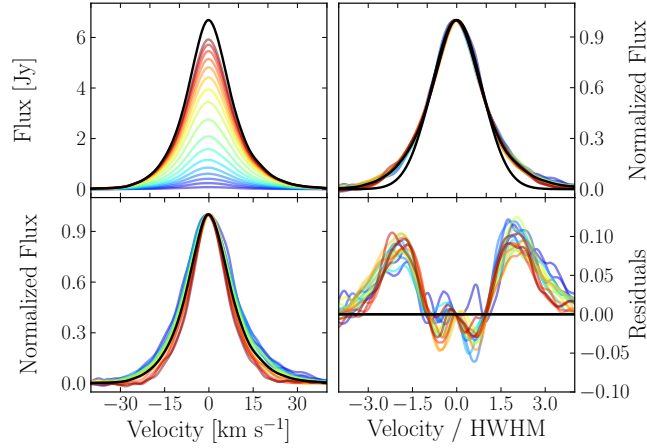


Figure 4.23b The radial superprofiles in Ho II, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

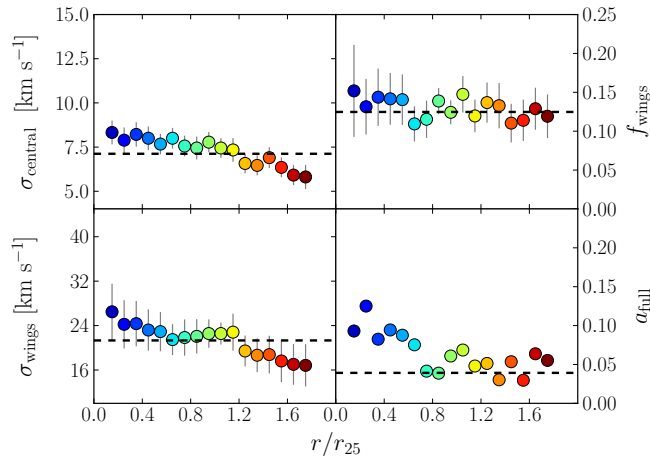


Figure 4.23c Variation of the superprofile parameters as a function of normalized radius for Ho II. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

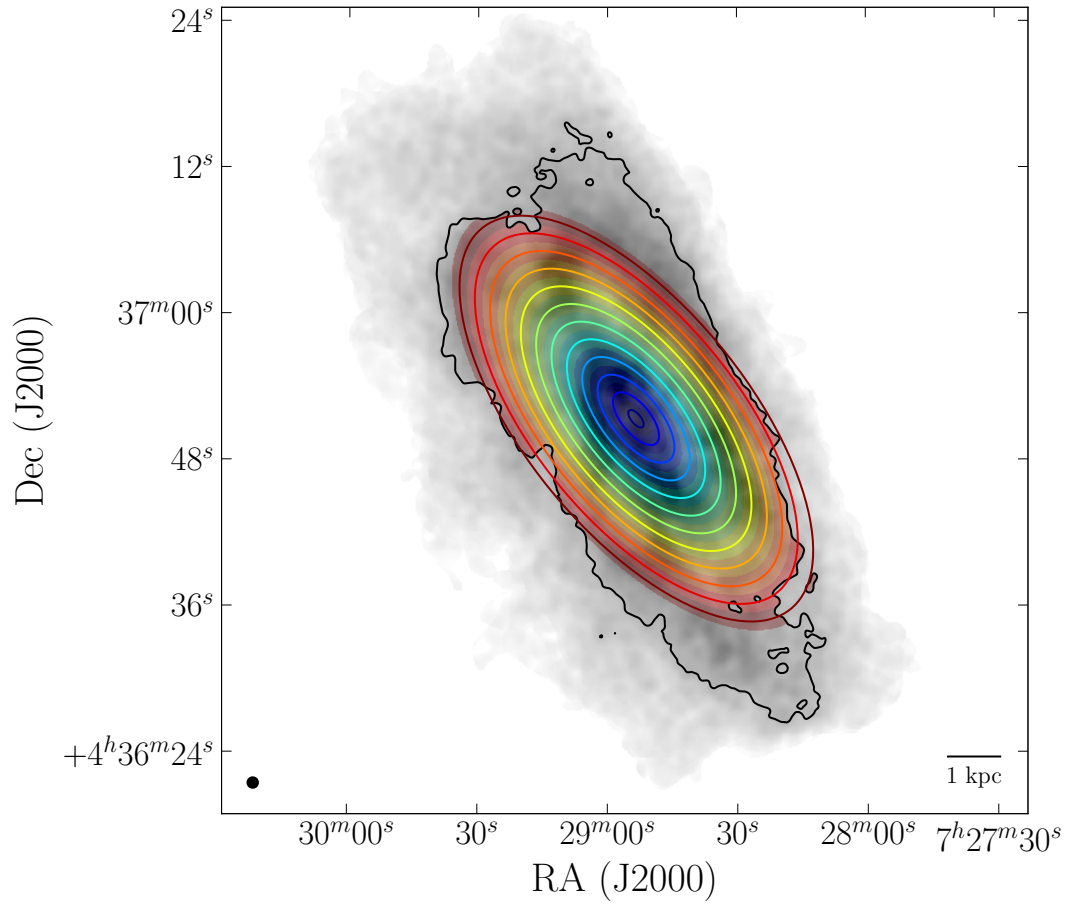


Figure 4.24a Radial annuli in which radial superprofiles are generated for NGC 2366. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

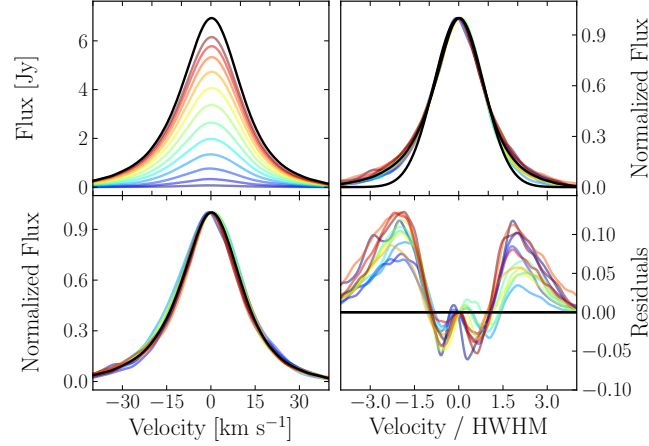


Figure 4.24b The radial superprofiles in NGC 2366, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

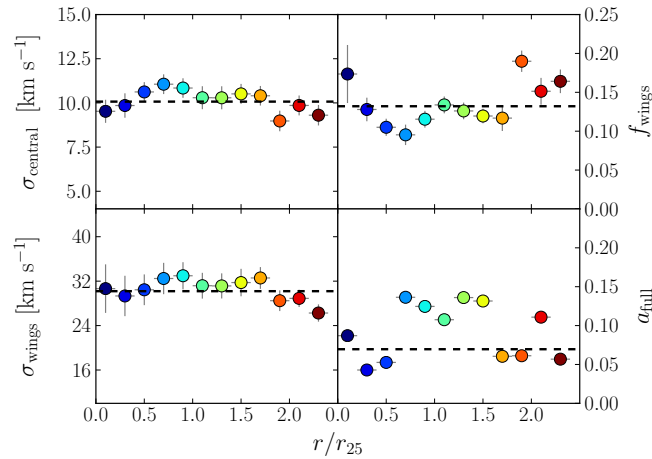


Figure 4.24c Variation of the superprofile parameters as a function of normalized radius for NGC 2366. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

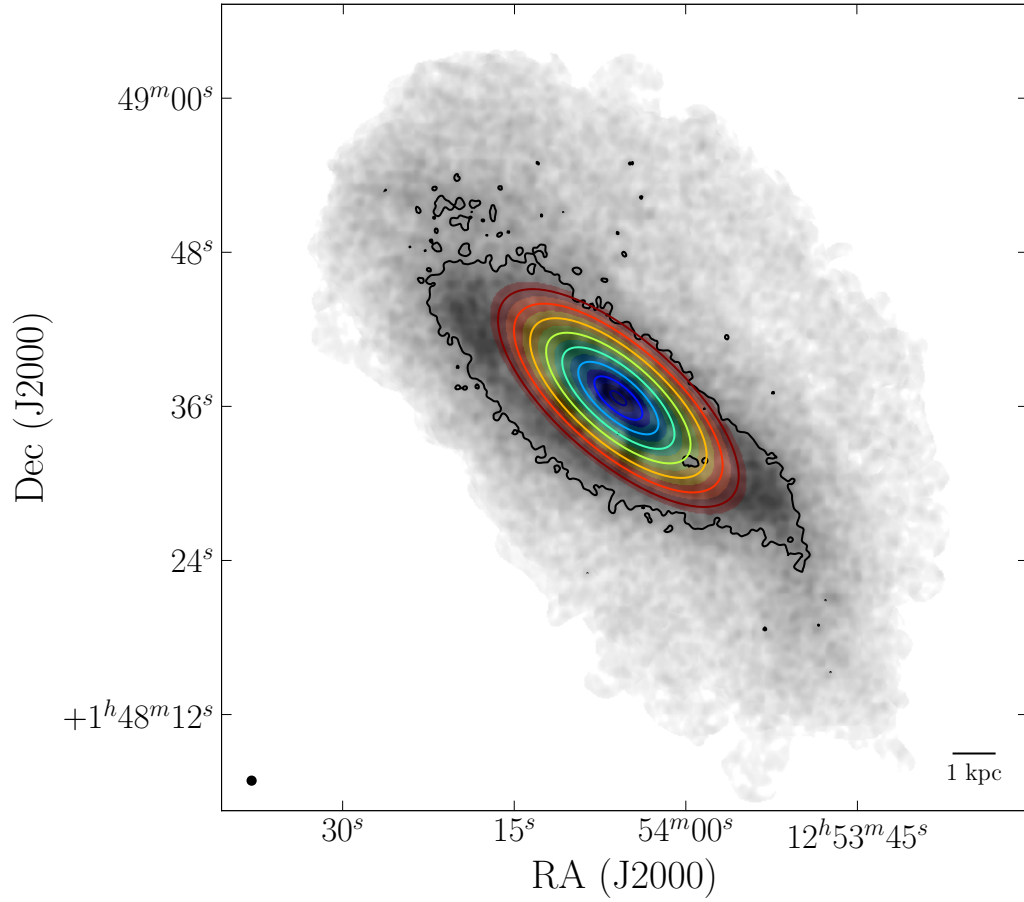


Figure 4.25a Radial annuli in which radial superprofiles are generated for DDO 154. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

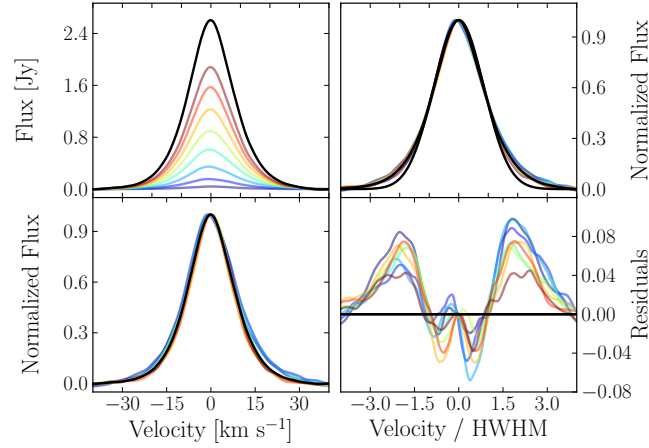


Figure 4.25b The radial superprofiles in DDO 154, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

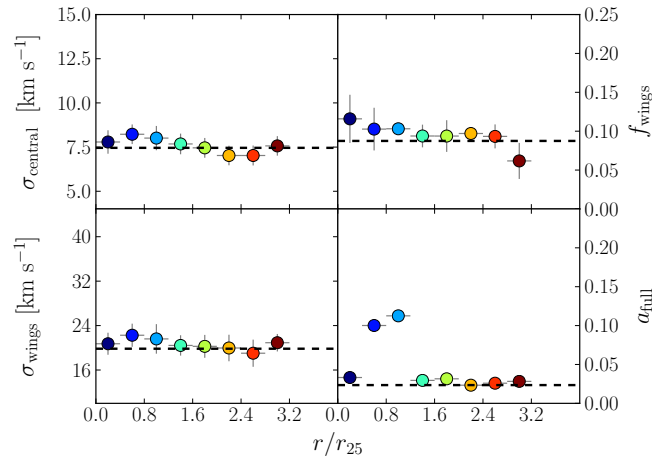


Figure 4.25c Variation of the superprofile parameters as a function of normalized radius for DDO 154. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

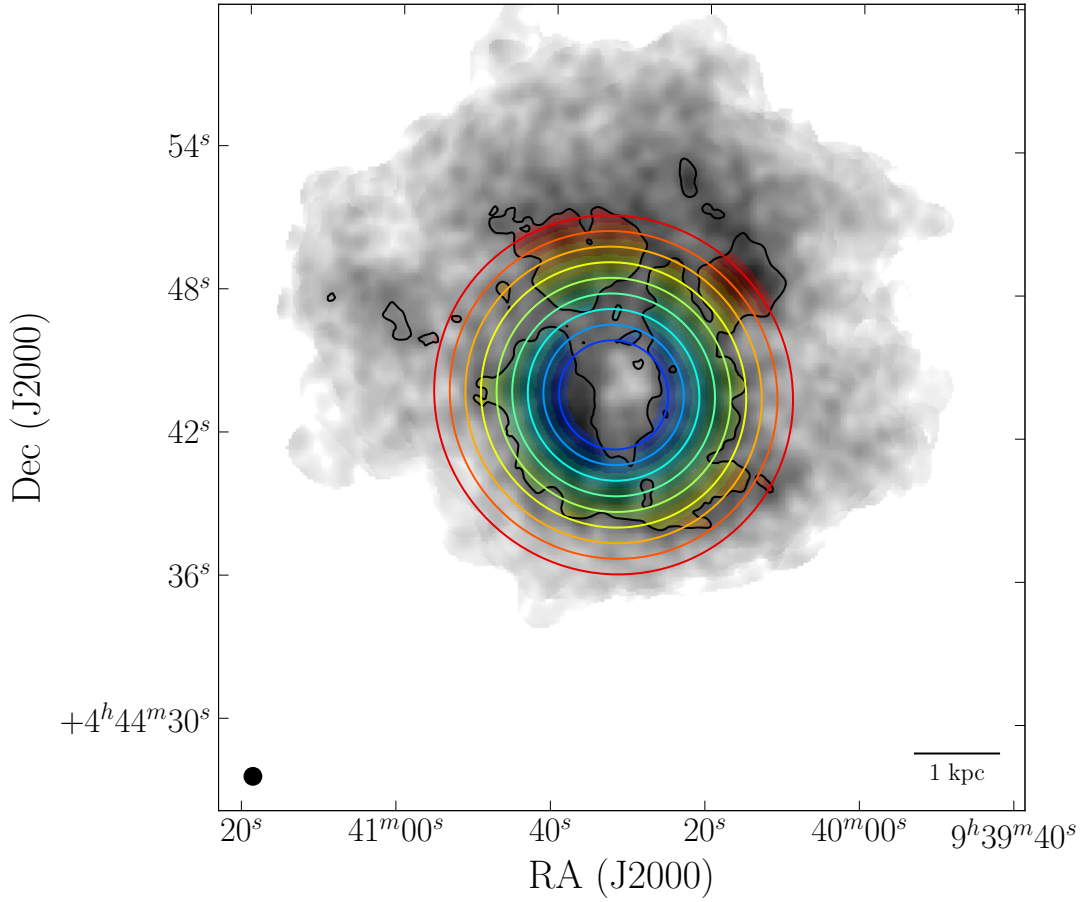


Figure 4.26a Radial annuli in which radial superprofiles are generated for Ho I. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

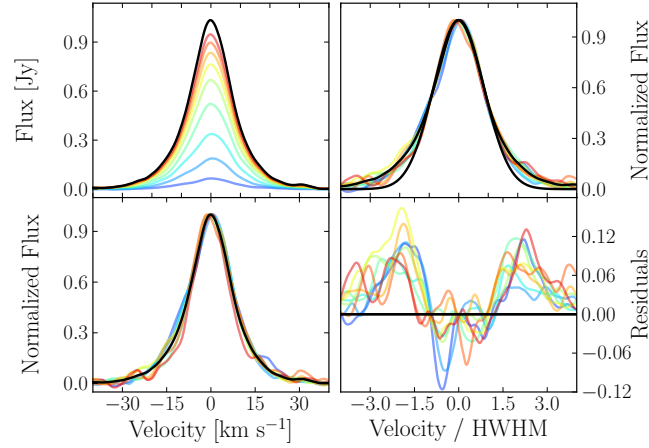


Figure 4.26b The radial superprofiles in Ho I, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

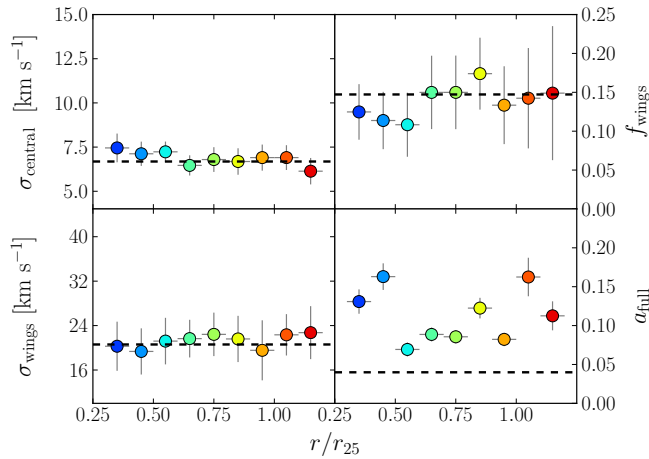


Figure 4.26c Variation of the superprofile parameters as a function of normalized radius for Ho I. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

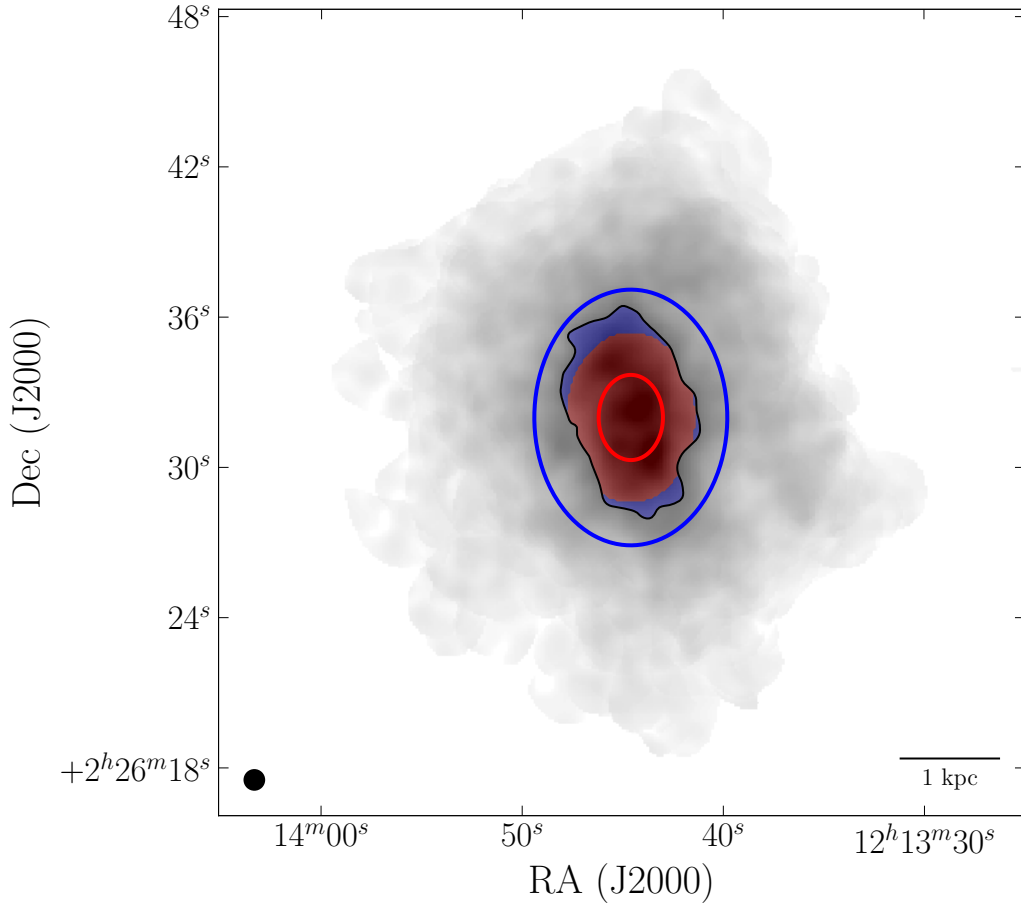


Figure 4.27a Radial annuli in which radial superprofiles are generated for NGC 4190. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

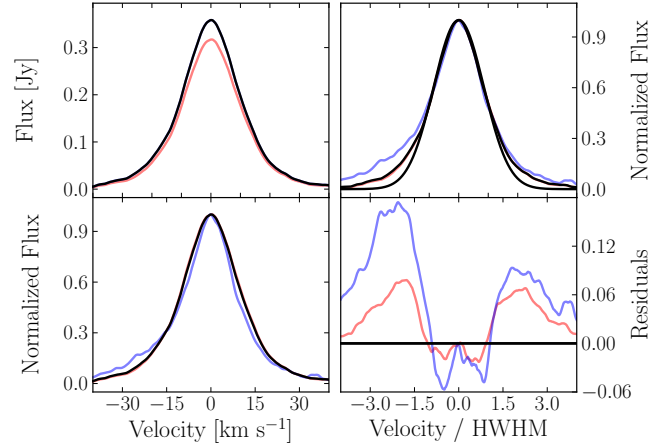


Figure 4.27b The radial superprofiles in NGC 4190, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

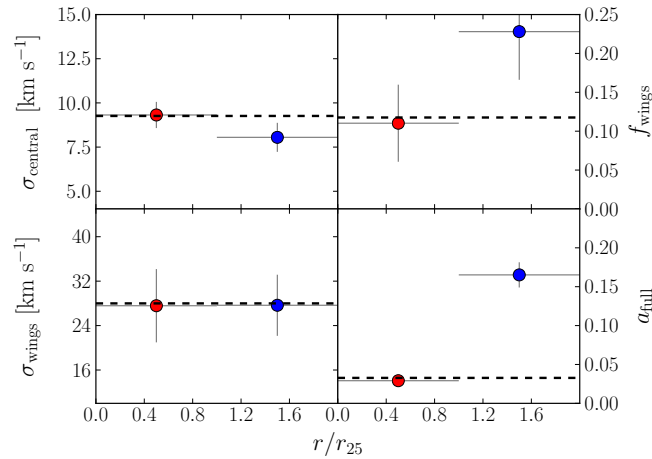


Figure 4.27c Variation of the superprofile parameters as a function of normalized radius for NGC 4190. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

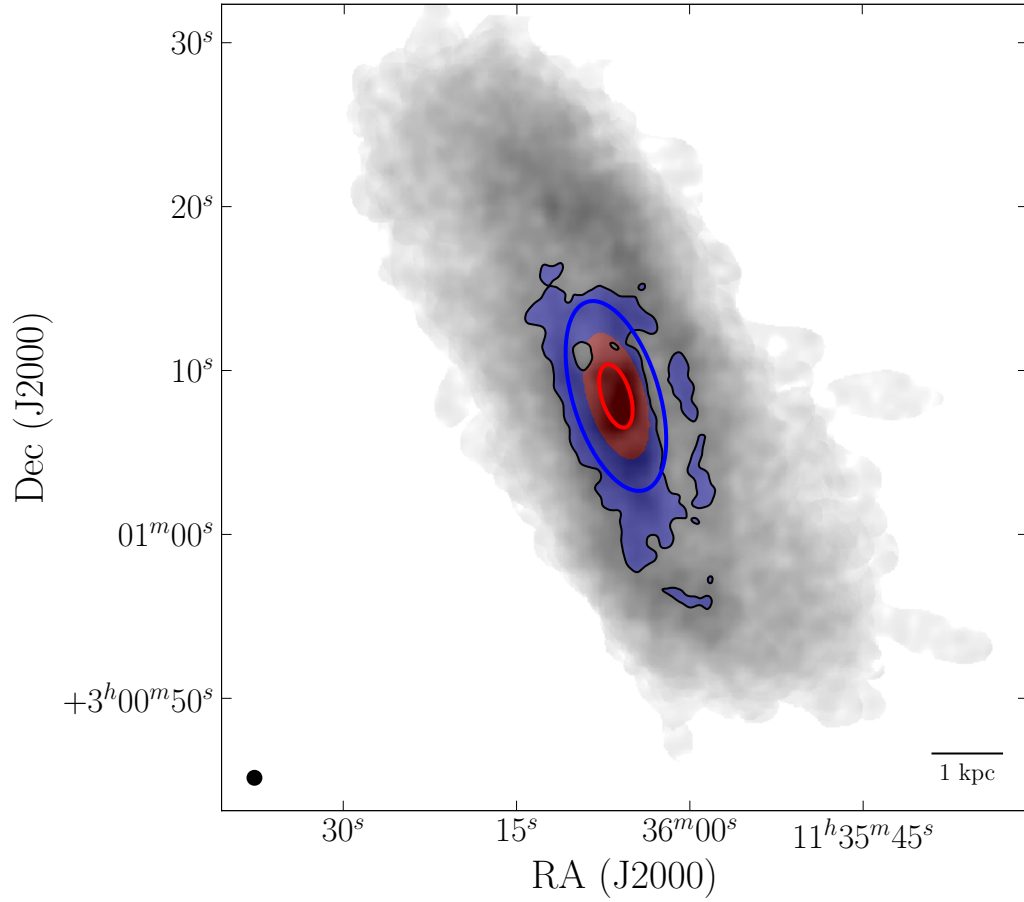


Figure 4.28a Radial annuli in which radial superprofiles are generated for NGC 3741. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

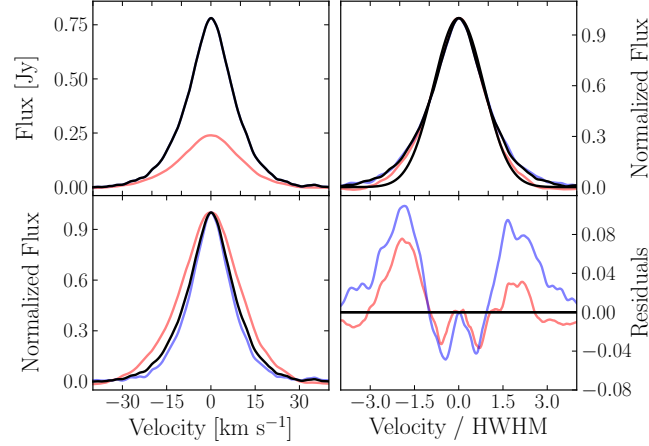


Figure 4.28b The radial superprofiles in NGC 3741, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

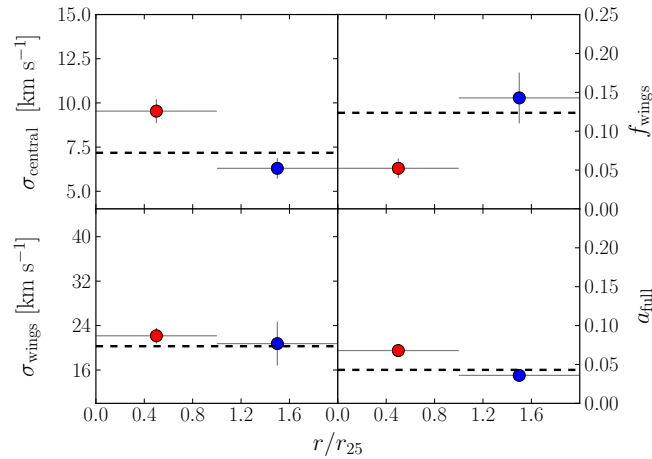


Figure 4.28c Variation of the superprofile parameters as a function of normalized radius for NGC 3741. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

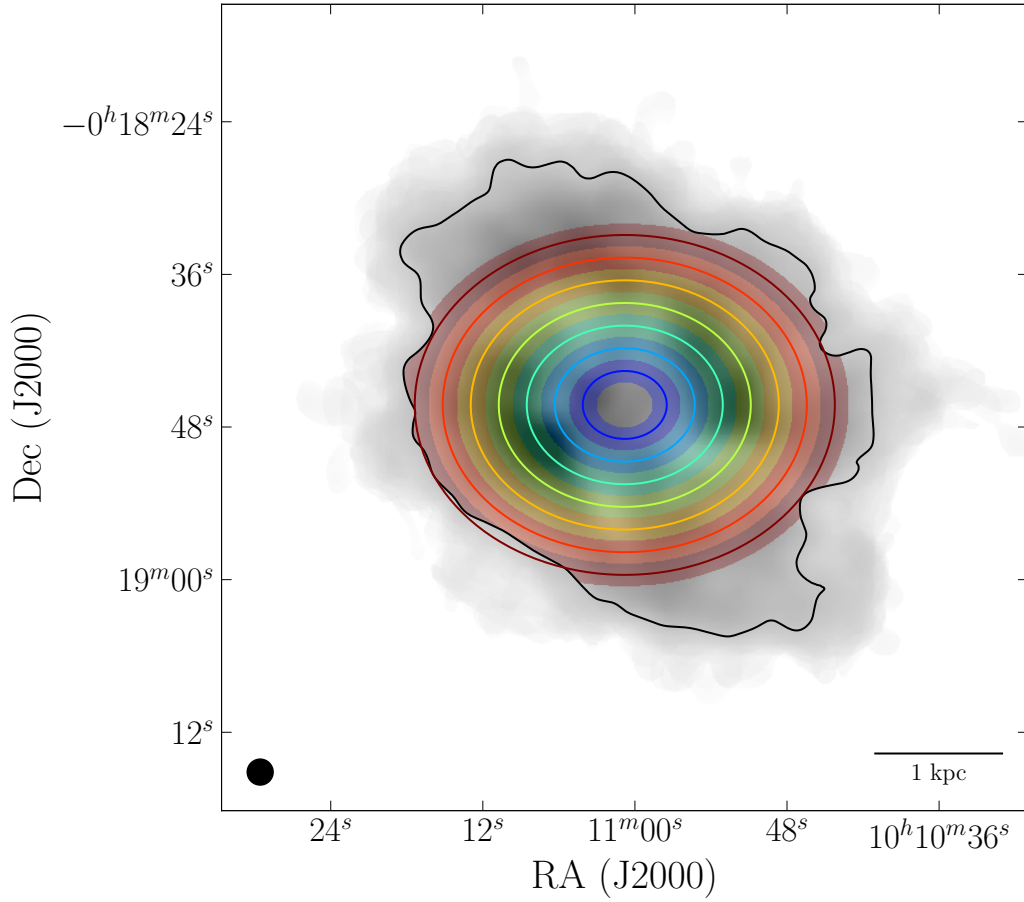


Figure 4.29a Radial annuli in which radial superprofiles are generated for Sextans A. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

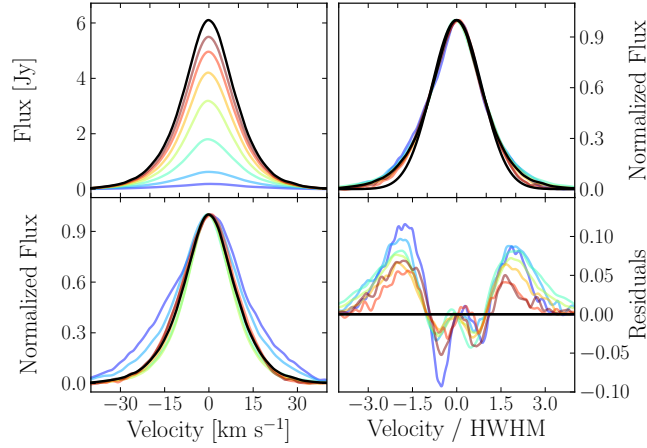


Figure 4.29b The radial superprofiles in Sextans A, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

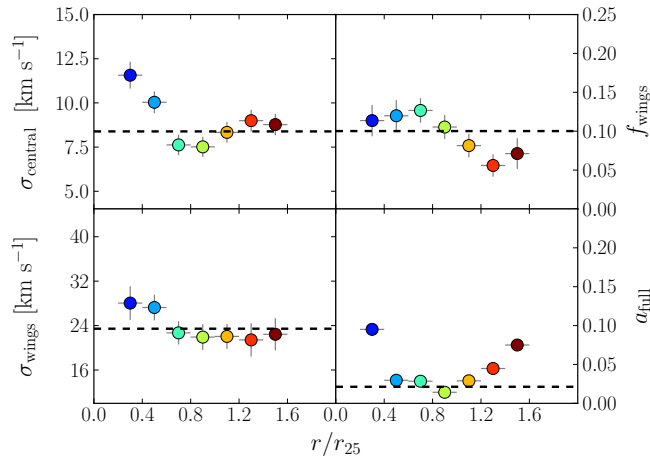


Figure 4.29c Variation of the superprofile parameters as a function of normalized radius for Sextans A. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

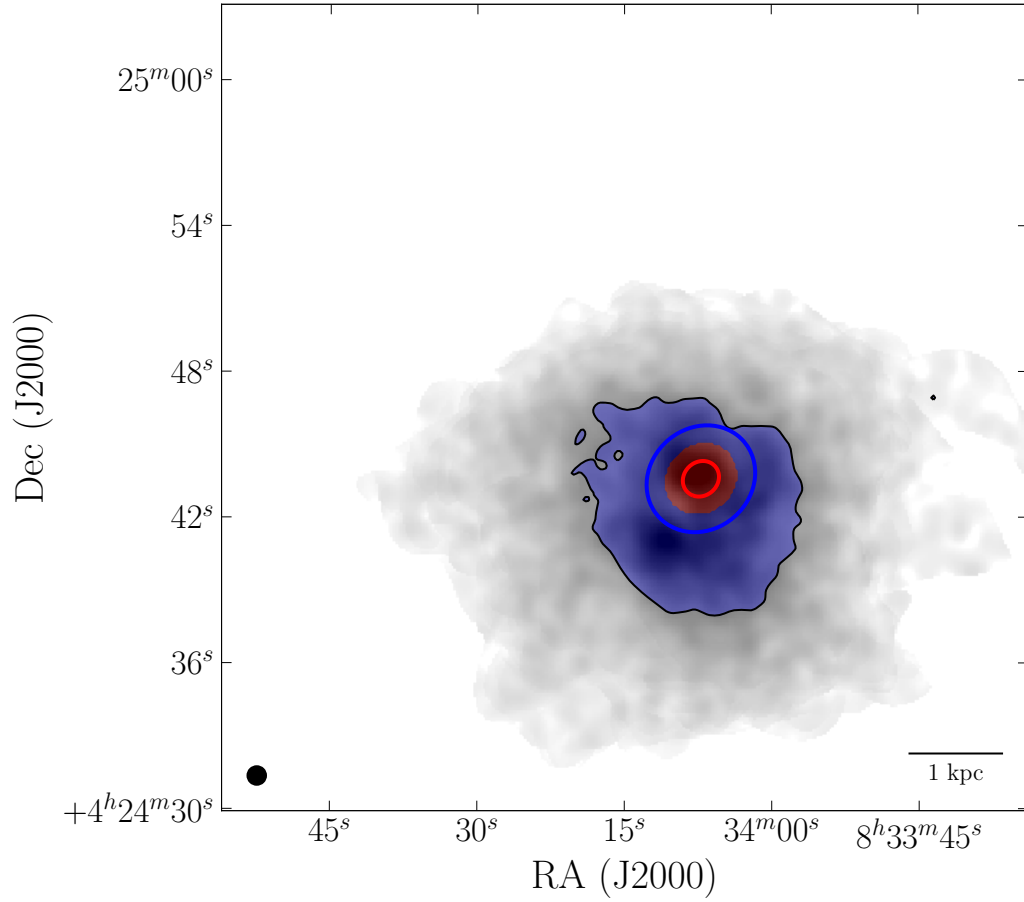


Figure 4.30a Radial annuli in which radial superprofiles are generated for DDO 53. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

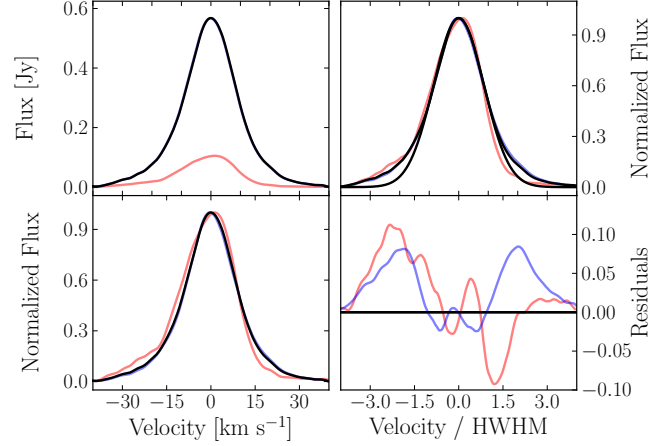


Figure 4.30b The radial superprofiles in DDO 53, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

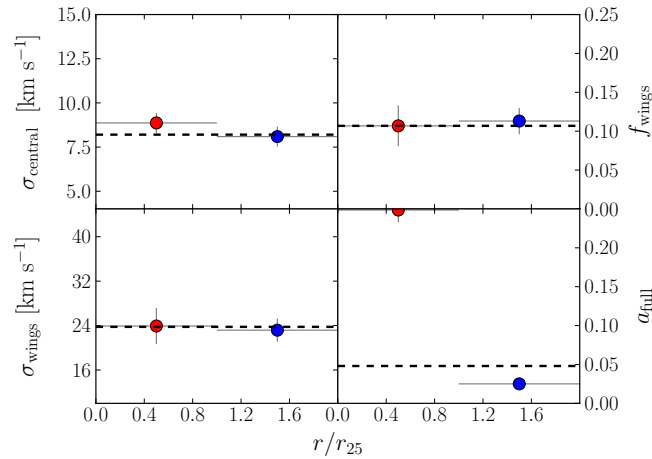


Figure 4.30c Variation of the superprofile parameters as a function of normalized radius for DDO 53. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

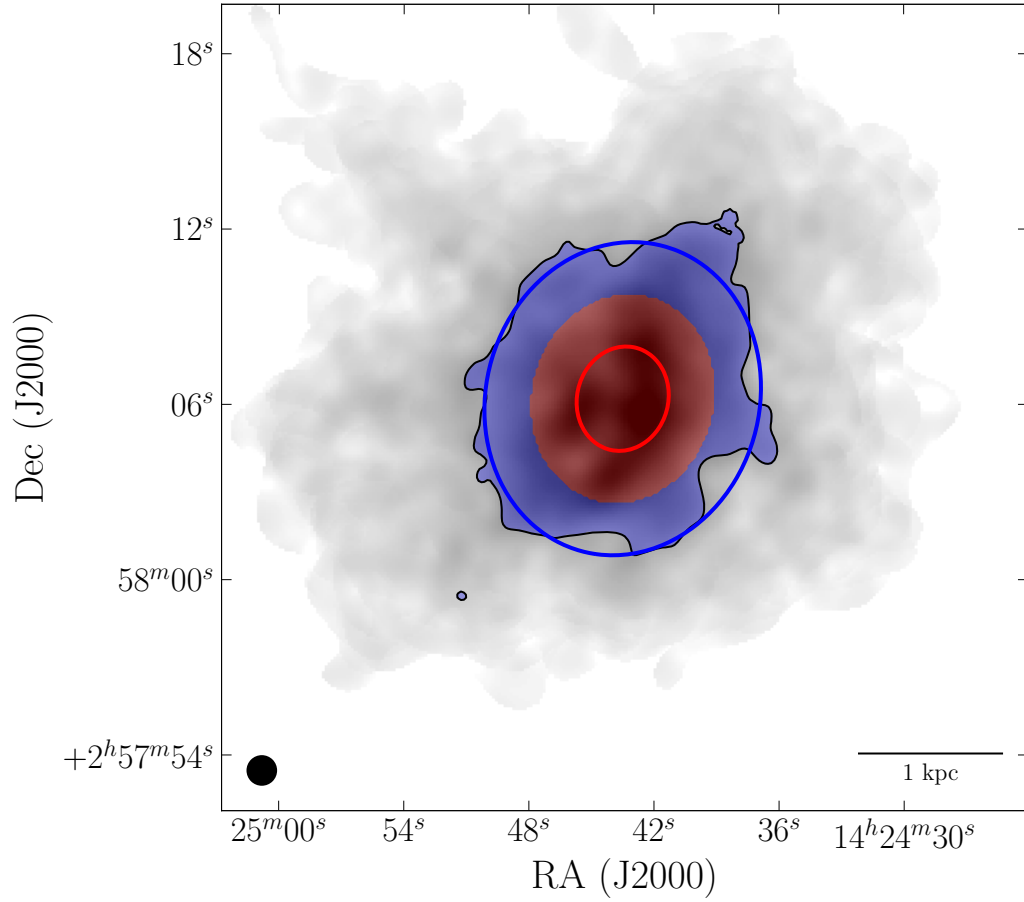


Figure 4.31a Radial annuli in which radial superprofiles are generated for DDO 190. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

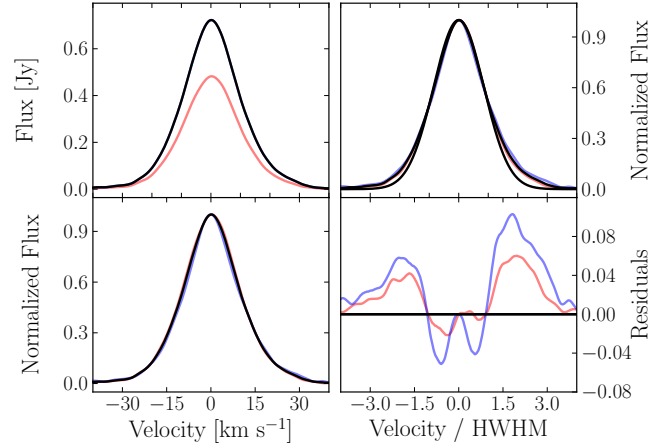


Figure 4.31b The radial superprofiles in DDO 190, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

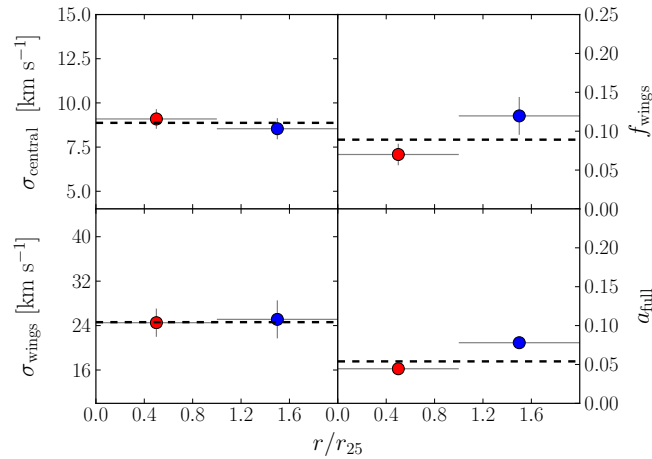


Figure 4.31c Variation of the superprofile parameters as a function of normalized radius for DDO 190. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

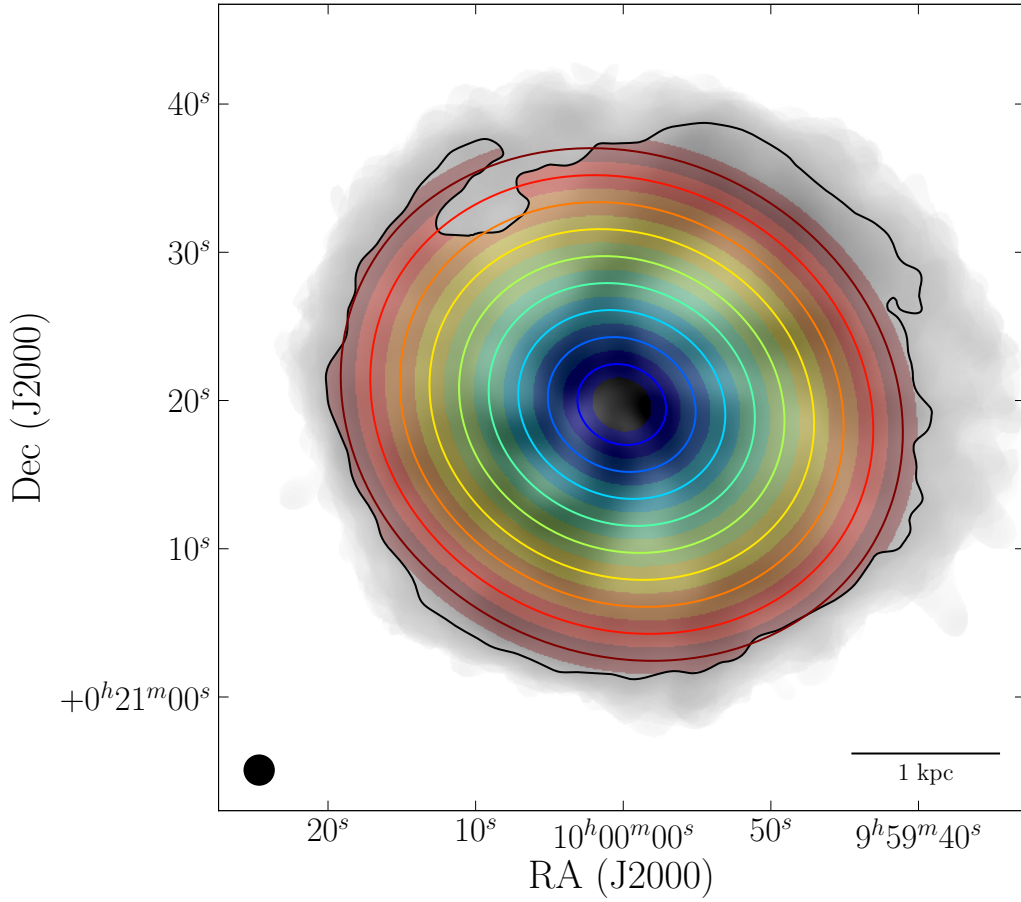


Figure 4.32a Radial annuli in which radial superprofiles are generated for Sextans B. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

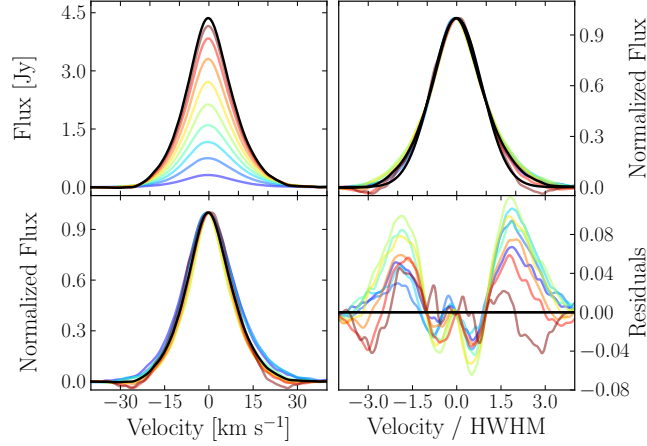


Figure 4.32b The radial superprofiles in Sextans B, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

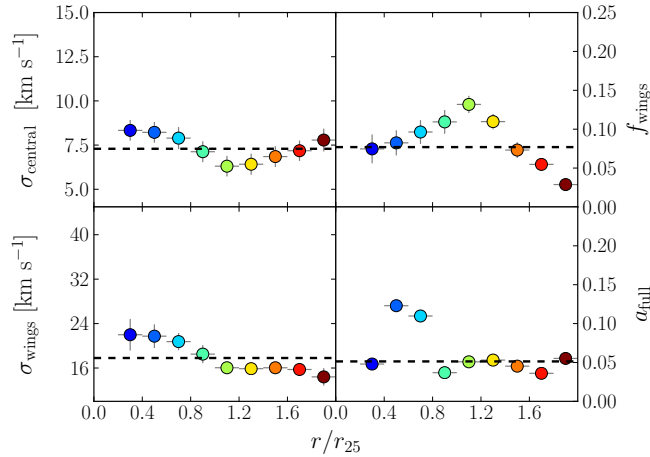


Figure 4.32c Variation of the superprofile parameters as a function of normalized radius for Sextans B. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

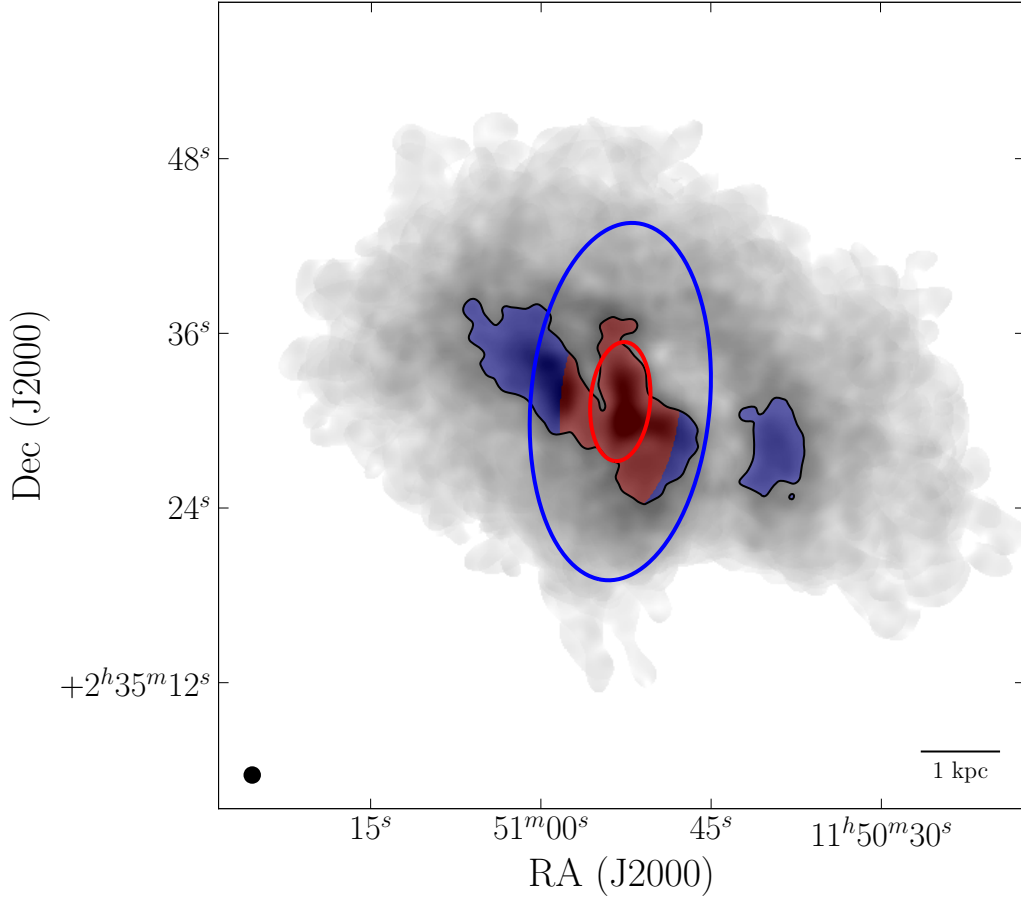


Figure 4.33a Radial annuli in which radial superprofiles are generated for DDO 99. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

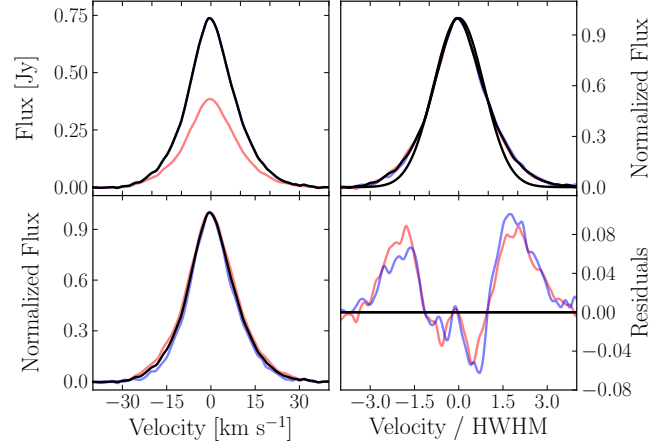


Figure 4.33b The radial superprofiles in DDO 99, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

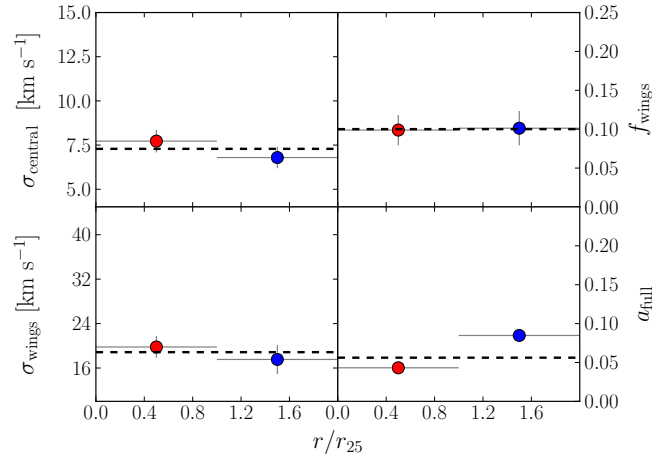


Figure 4.33c Variation of the superprofile parameters as a function of normalized radius for DDO 99. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

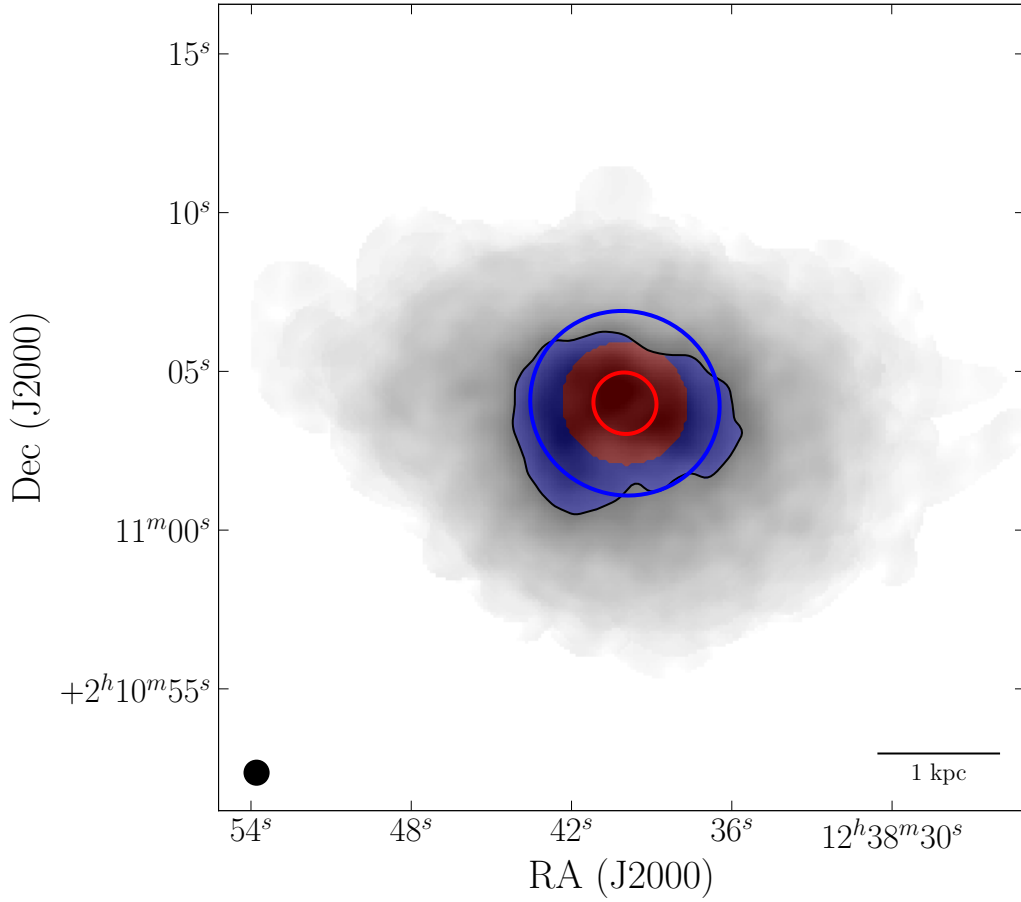


Figure 4.34a Radial annuli in which radial superprofiles are generated for UGCA 292. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

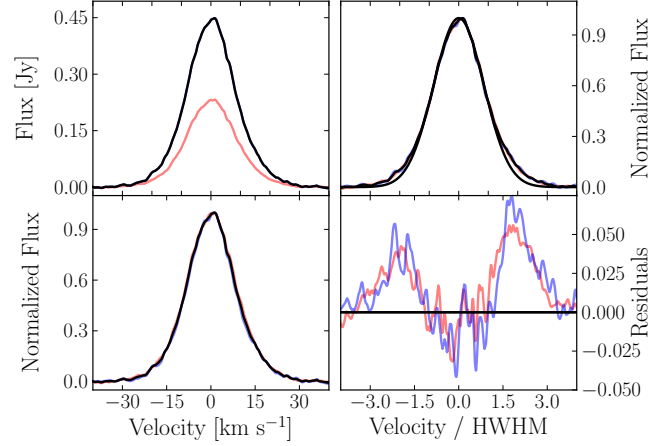


Figure 4.34b The radial superprofiles in UGCA 292, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

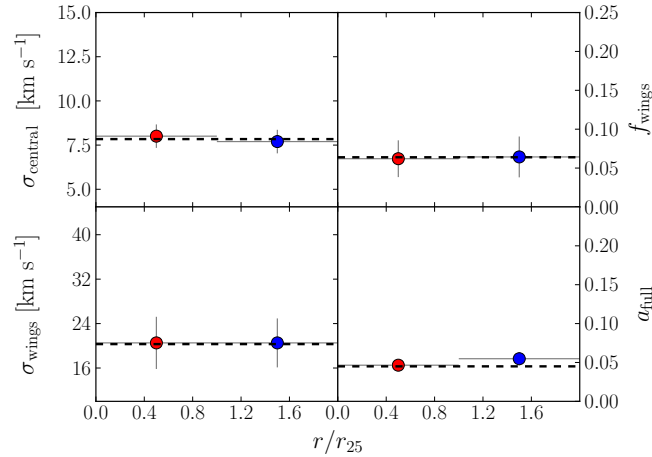


Figure 4.34c Variation of the superprofile parameters as a function of normalized radius for UGCA 292. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

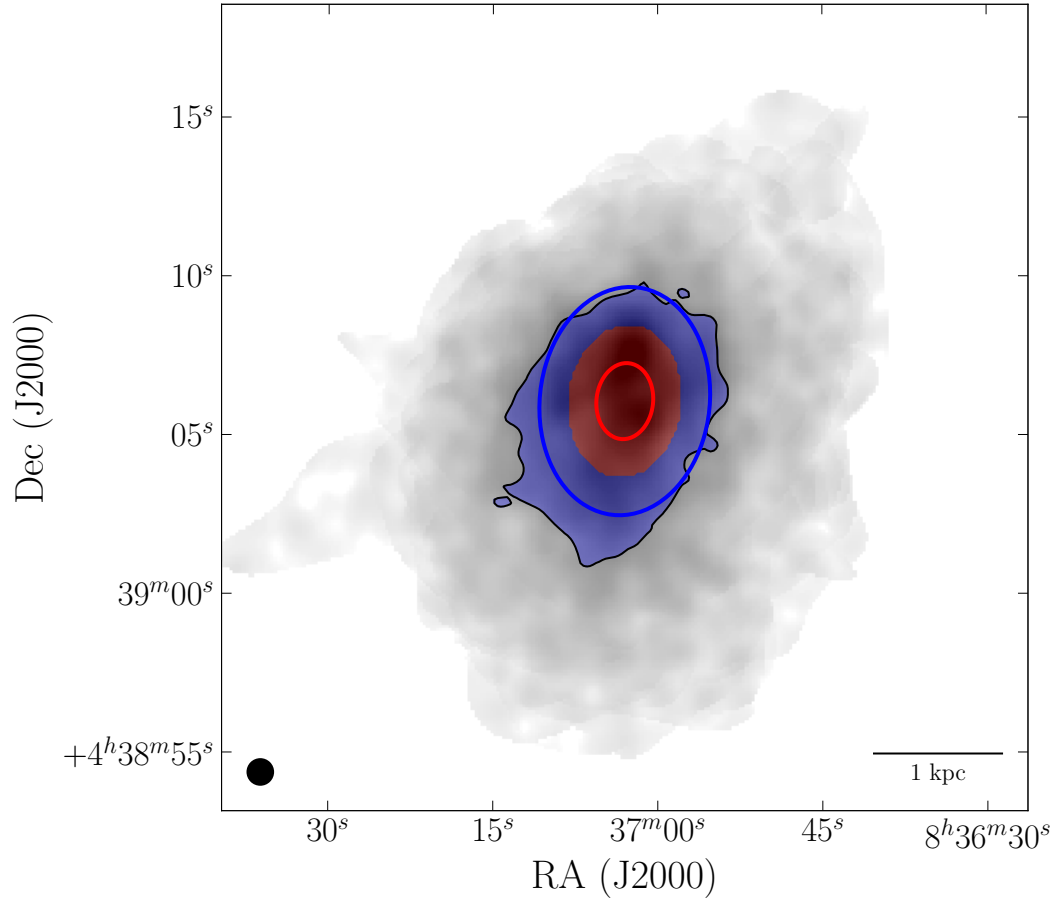


Figure 4.35a Radial annuli in which radial superprofiles are generated for UGC 4483. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

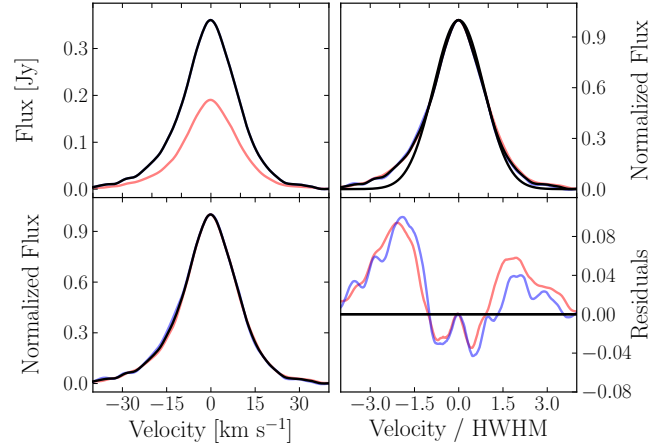


Figure 4.35b The radial superprofiles in UGC 4483, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

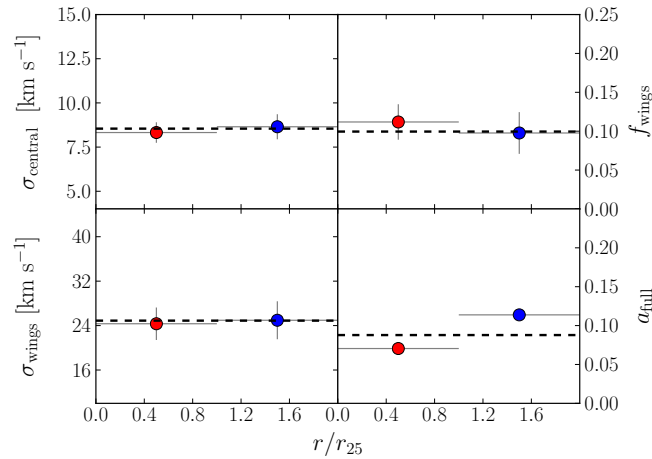


Figure 4.35c Variation of the superprofile parameters as a function of normalized radius for UGC 4483. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

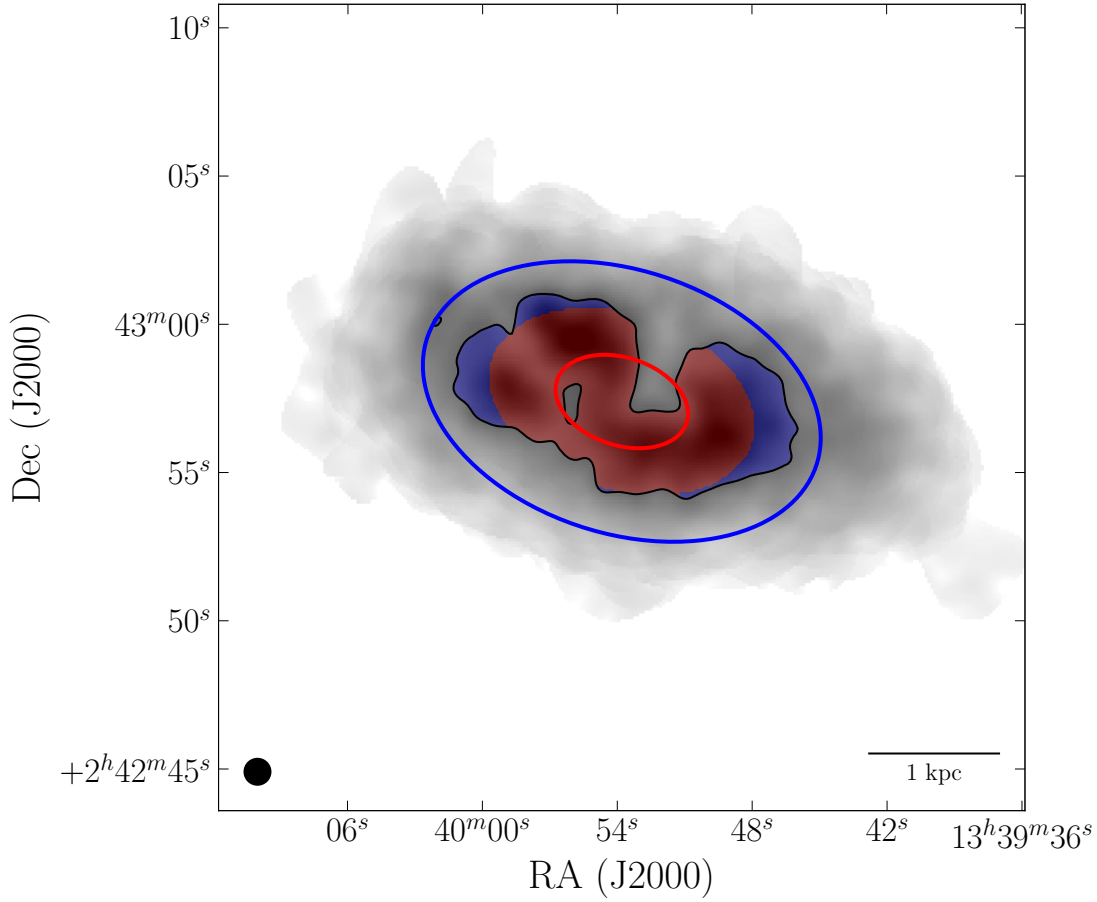


Figure 4.36a Radial annuli in which radial superprofiles are generated for DDO 181. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

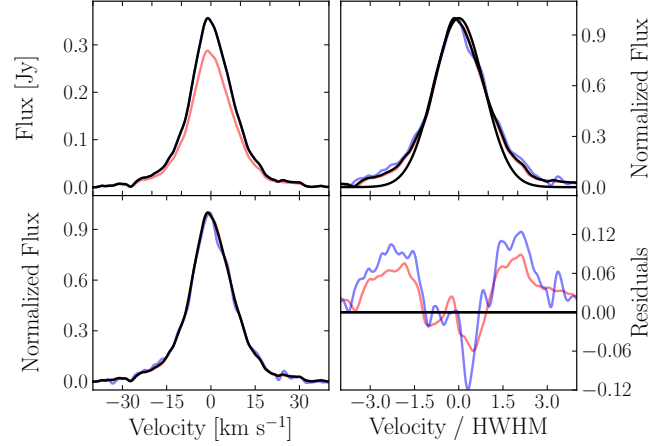


Figure 4.36b The radial superprofiles in DDO 181, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

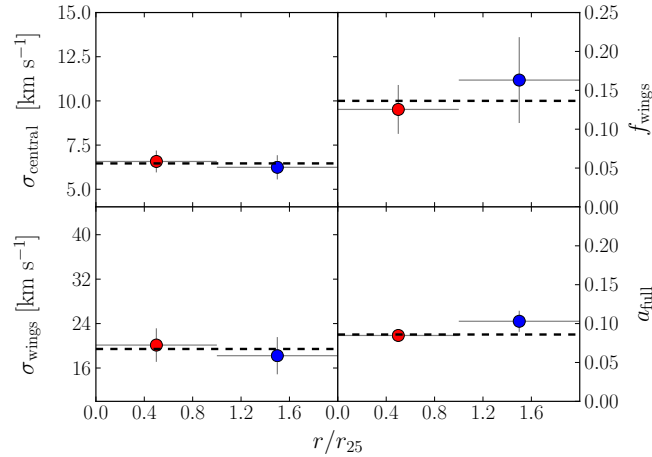


Figure 4.36c Variation of the superprofile parameters as a function of normalized radius for DDO 181. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

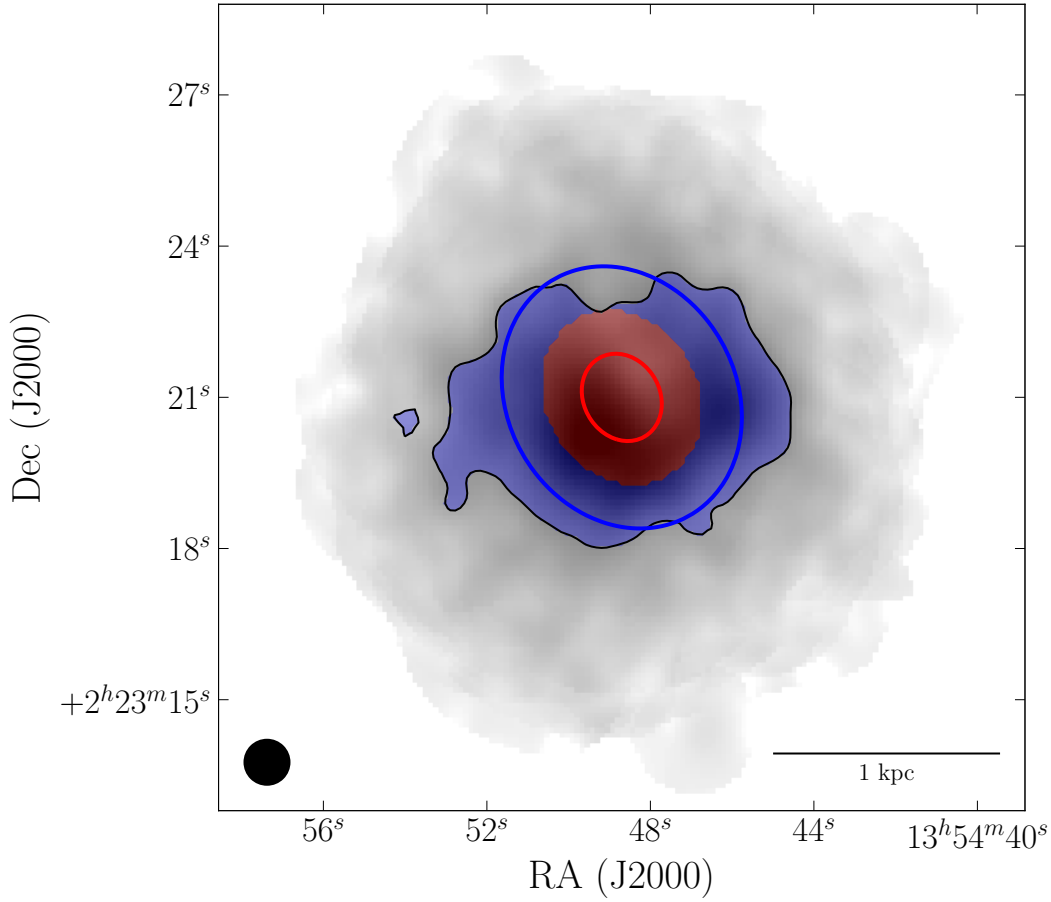


Figure 4.37a Radial annuli in which radial superprofiles are generated for UGC 8833. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

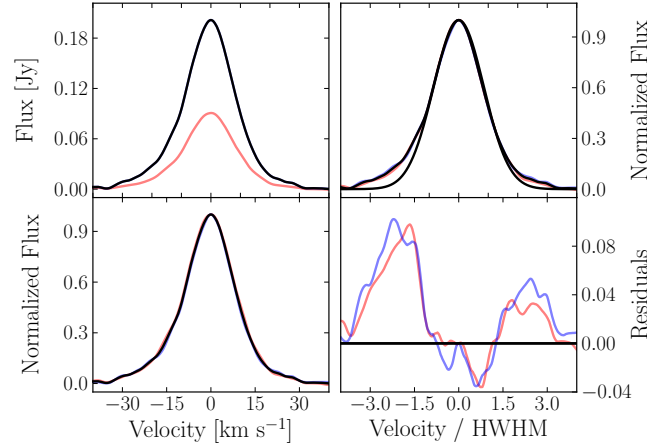


Figure 4.37b The radial superprofiles in UGC 8833, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

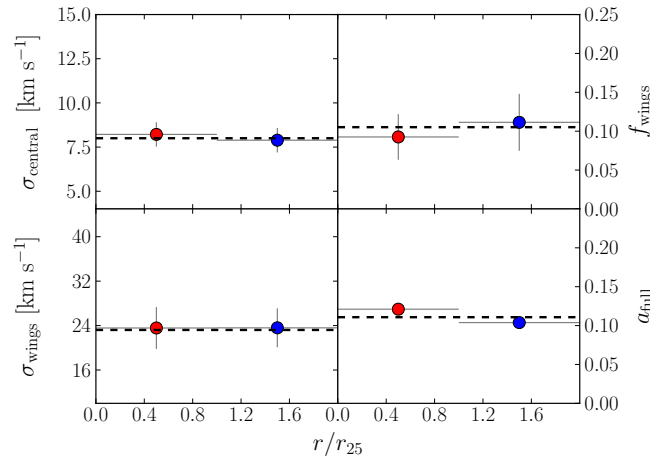


Figure 4.37c Variation of the superprofile parameters as a function of normalized radius for UGC 8833. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

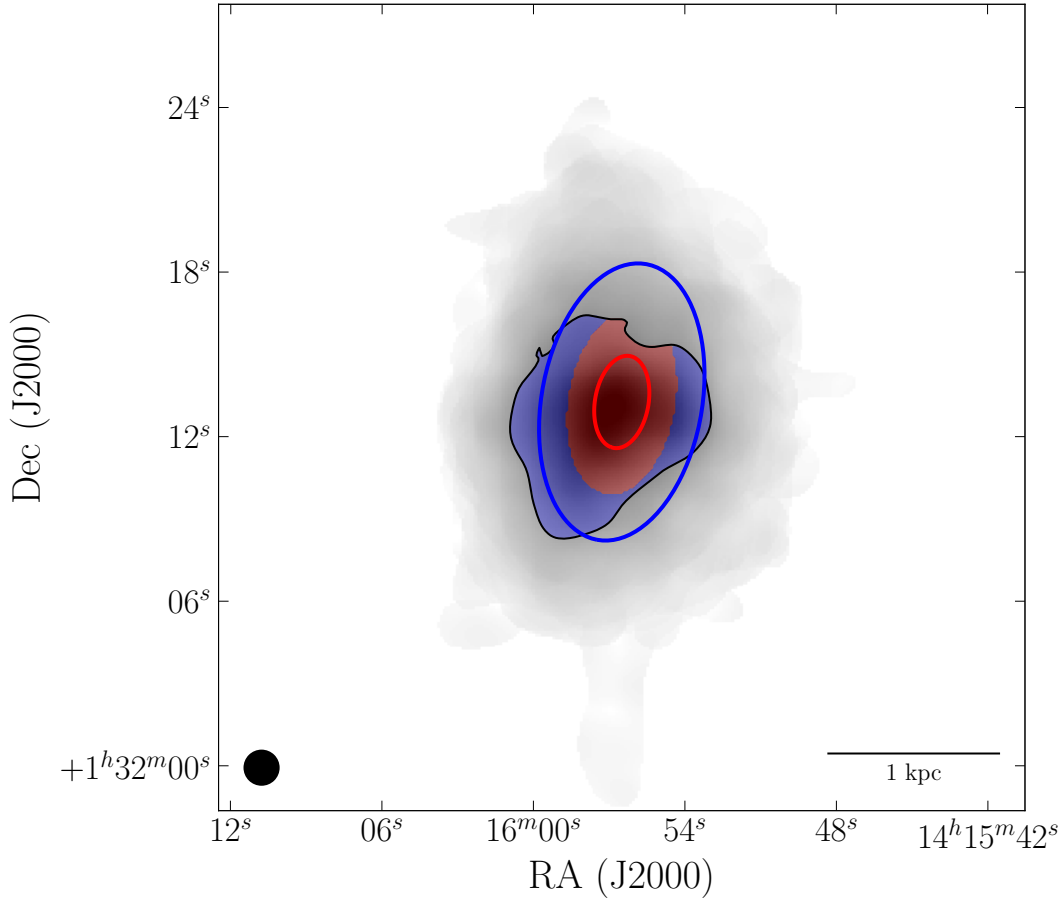


Figure 4.38a Radial annuli in which radial superprofiles are generated for DDO 187. The background greyscale shows Σ_{HI} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored solid lines represent the average radius of each annulus, and the corresponding shaded regions of the same color indicate which pixels have contributed to each radial superprofile.

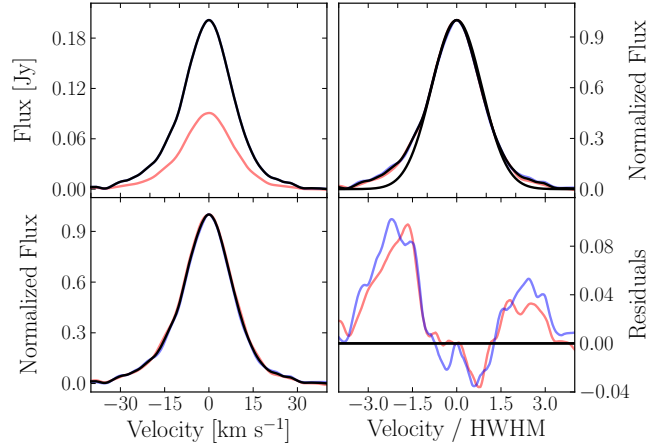


Figure 4.38b The radial superprofiles in DDO 187, where colors indicate the corresponding radial annuli in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

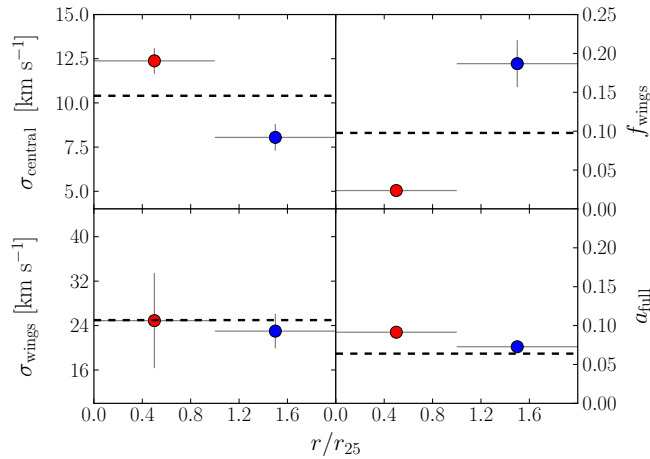


Figure 4.38c Variation of the superprofile parameters as a function of normalized radius for DDO 187. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

4.7.2 Σ_{SFR} *Superprofiles*

In the following pages, we present the superprofiles generated in subregions of constant Σ_{SFR} . For a single galaxy, the figures are the same as Figures 4.6a and 4.6c. Galaxies are shown in order of decreasing $M_{\text{baryon,tot}}$, with the exception of NGC 7993, which was previously shown in the text.

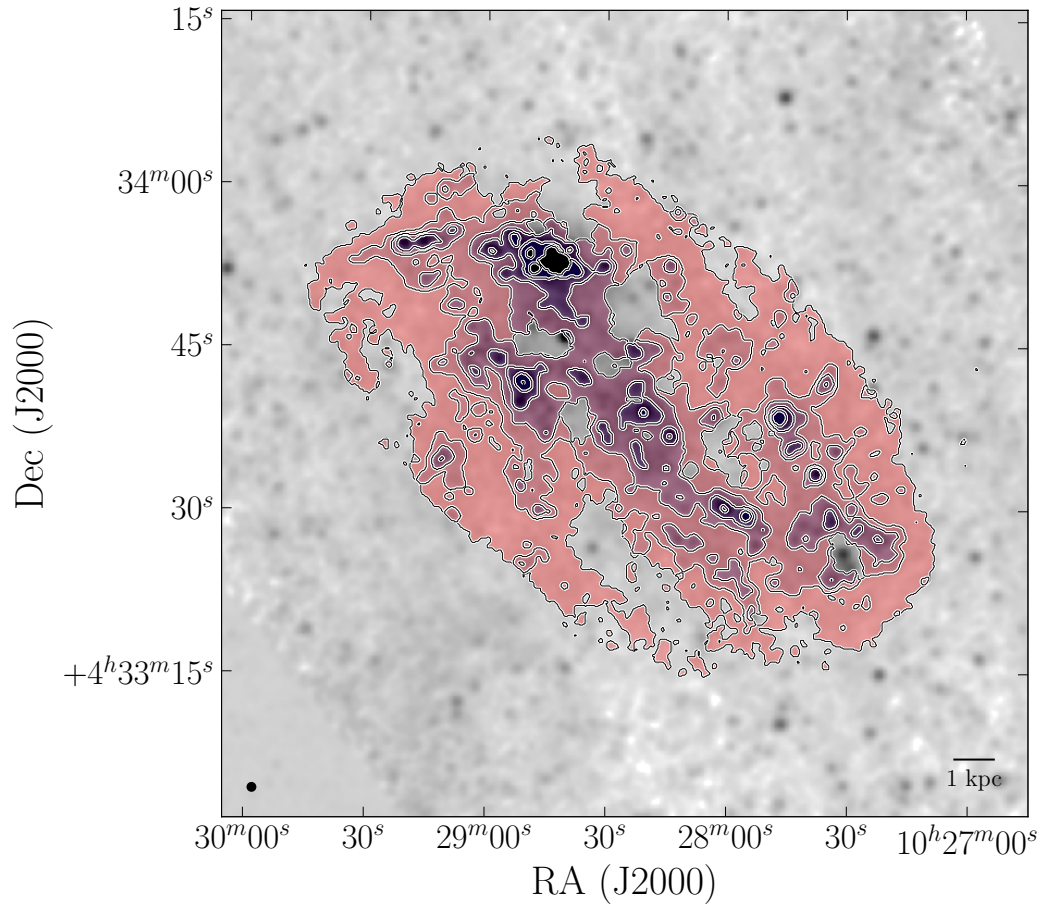


Figure 4.39a Subregions in which Σ_{SFR} superprofiles are generated for IC2574. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

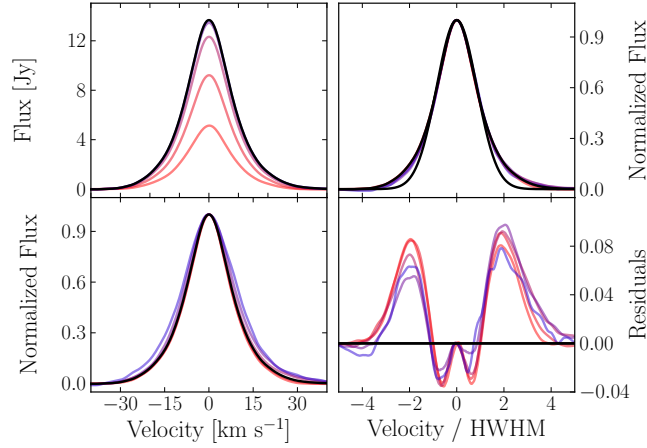


Figure 4.39b The Σ_{SFR} superprofiles in IC 2574, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

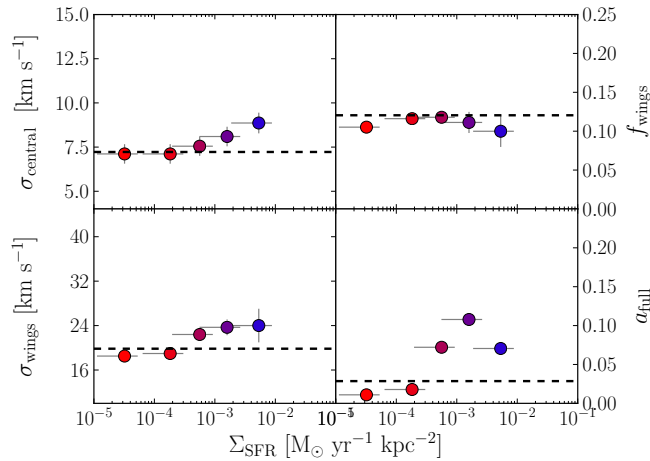


Figure 4.39c Variation of the superprofile parameters as a function of Σ_{SFR} for IC 2574. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{full} (lower).

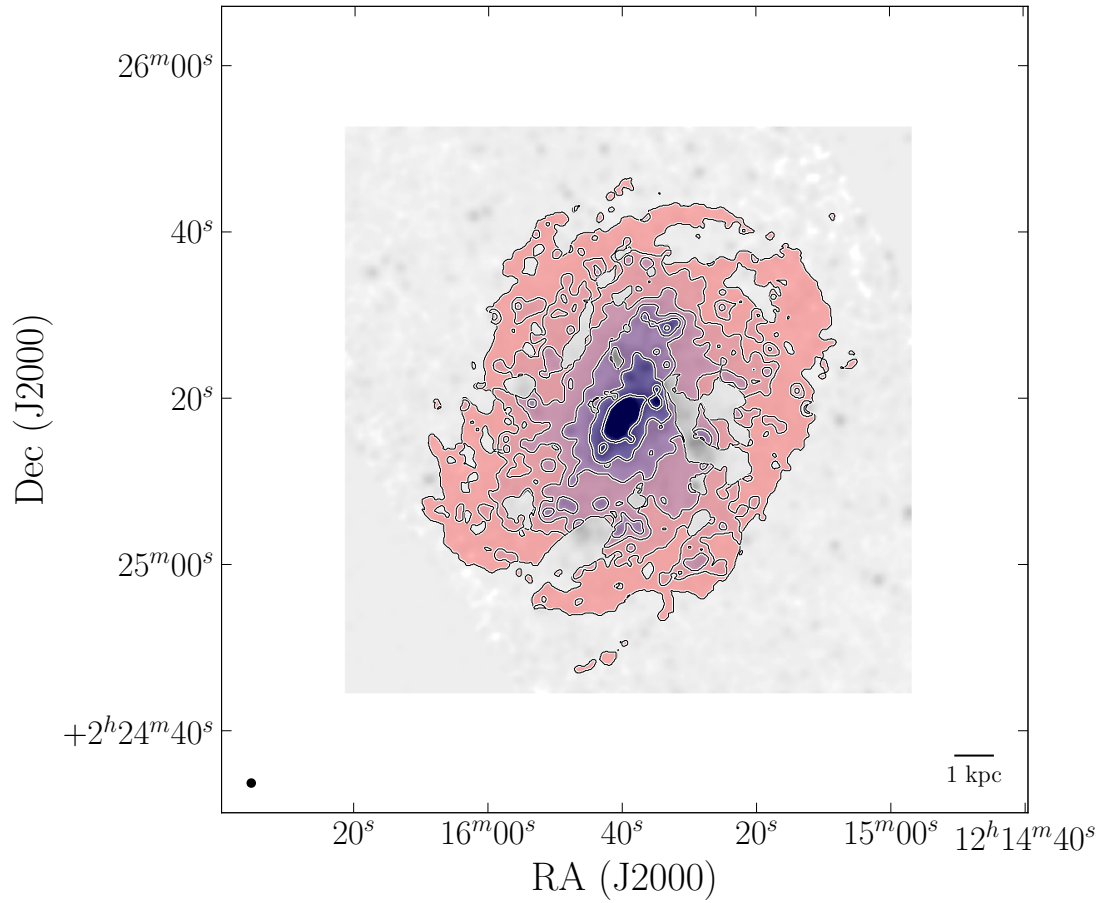


Figure 4.40a Σ_{SFR} regions in which radial superprofiles are generated for NGC 4214. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

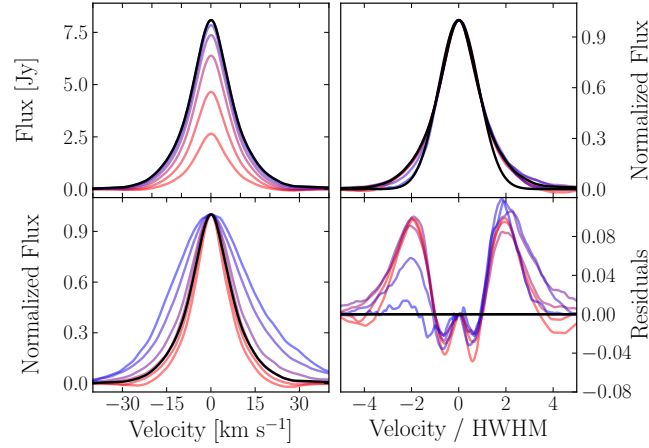


Figure 4.40b The Σ_{SFR} superprofiles in NGC 4214, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

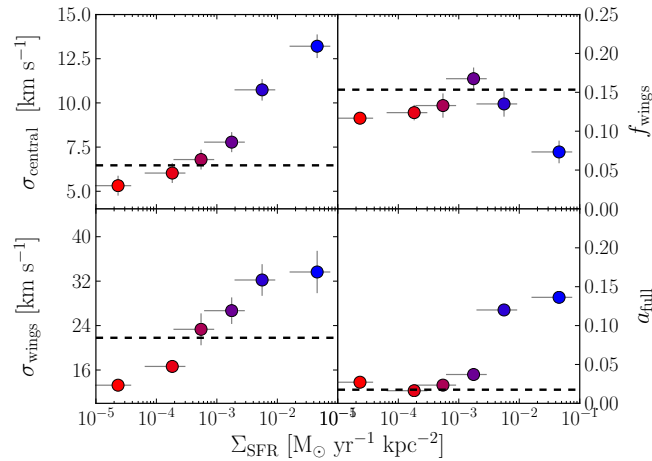


Figure 4.40c Variation of the superprofile parameters as a function of Σ_{SFR} for NGC 4214. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

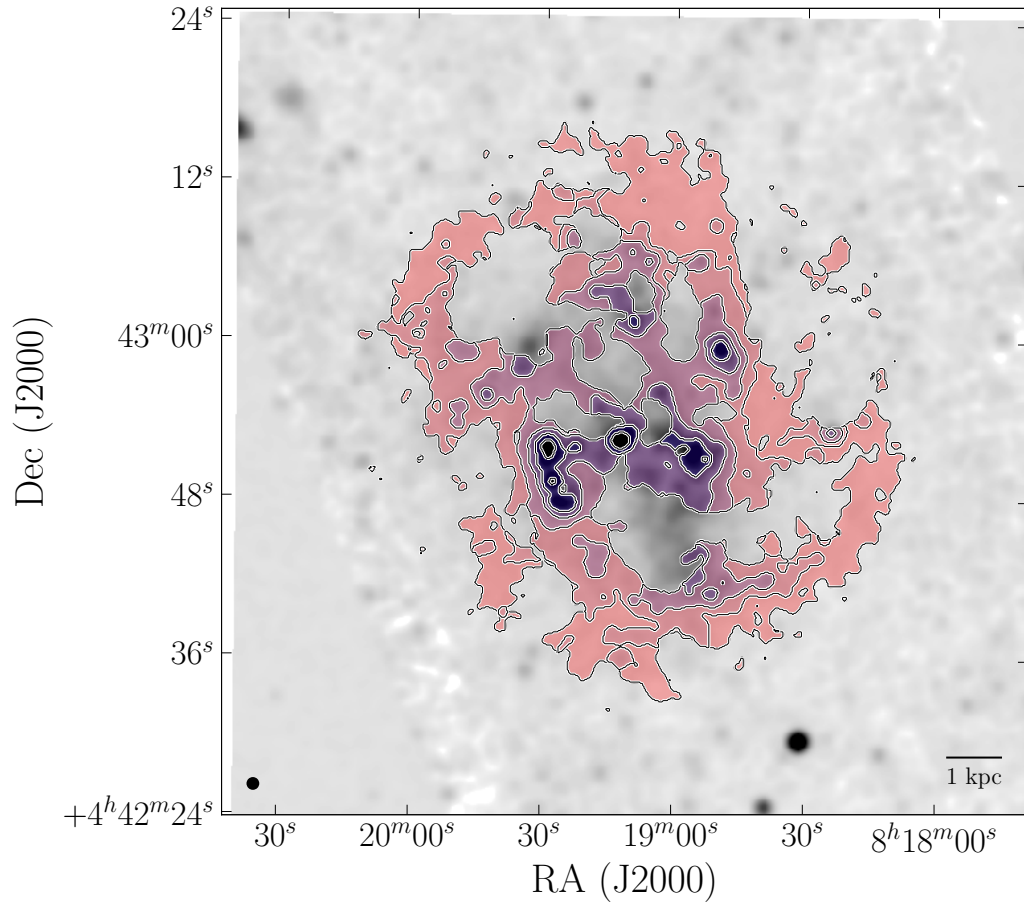


Figure 4.41a Subregions in which Σ_{SFR} superprofiles are generated for Ho II. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

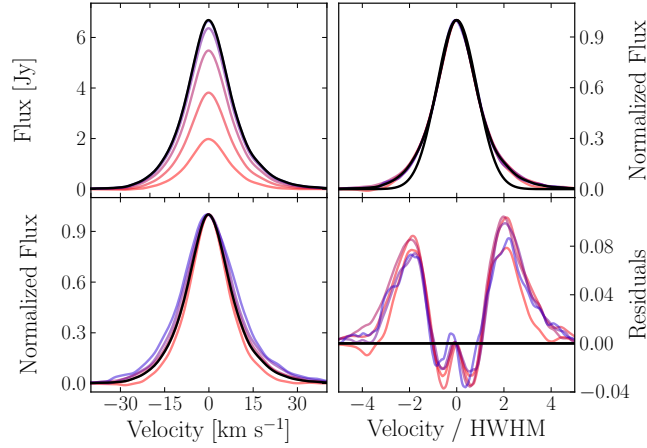


Figure 4.41b The Σ_{SFR} superprofiles in Ho II, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

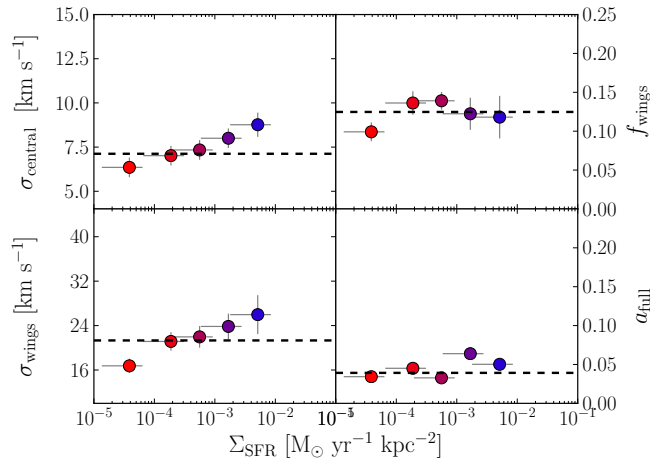


Figure 4.41c Variation of the superprofile parameters as a function of Σ_{SFR} for Ho II. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

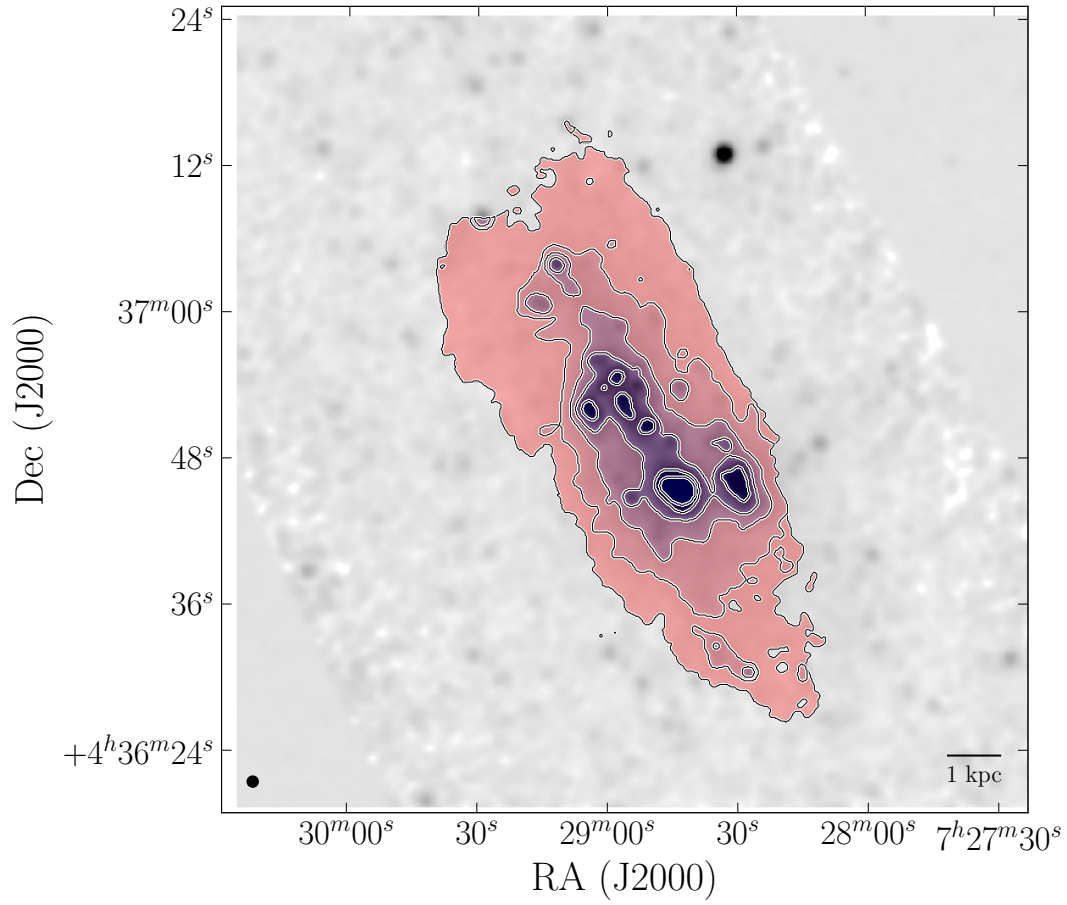


Figure 4.42a Subregions in which Σ_{SFR} superprofiles are generated for NGC 2366. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

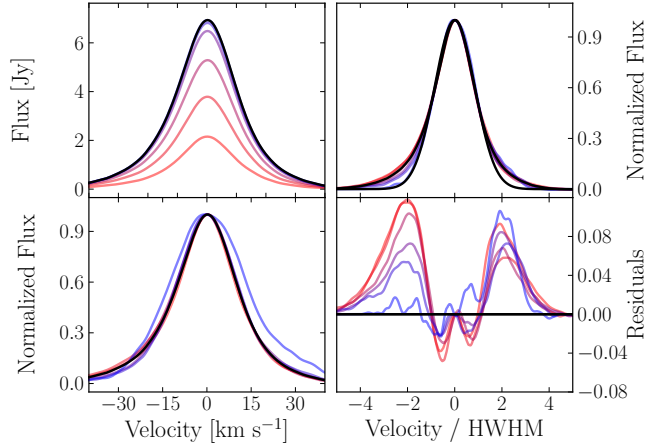


Figure 4.42b The Σ_{SFR} superprofiles in NGC 2366, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

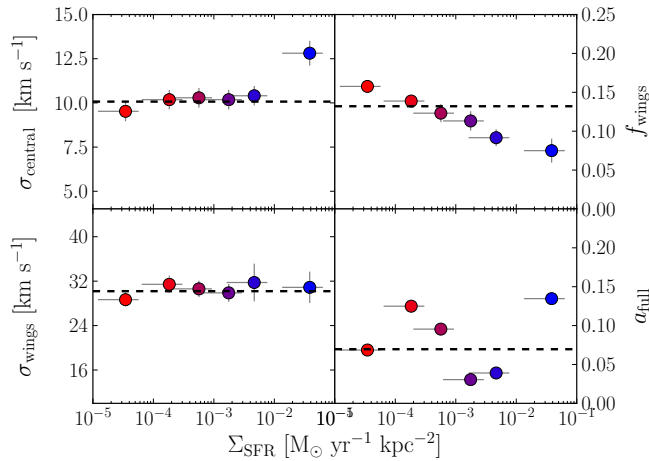


Figure 4.42c Variation of the superprofile parameters as a function of Σ_{SFR} for NGC 2366. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{full} (lower).

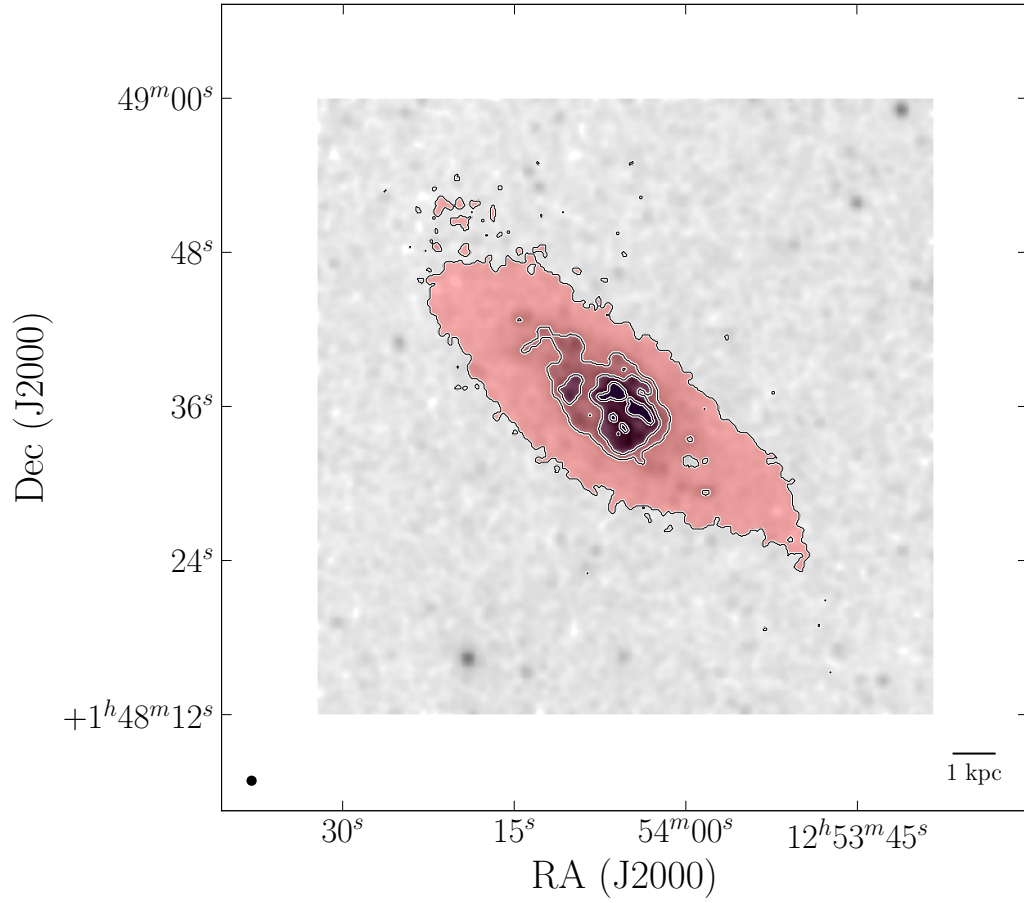


Figure 4.43a Subregions in which Σ_{SFR} superprofiles are generated for DDO 154. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

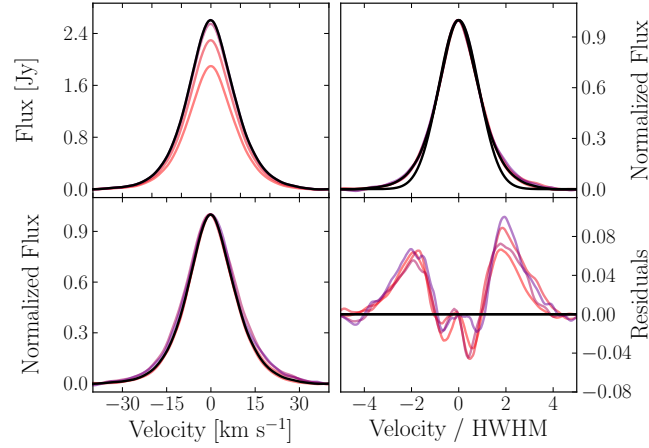


Figure 4.43b The Σ_{SFR} superprofiles in DDO 154, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

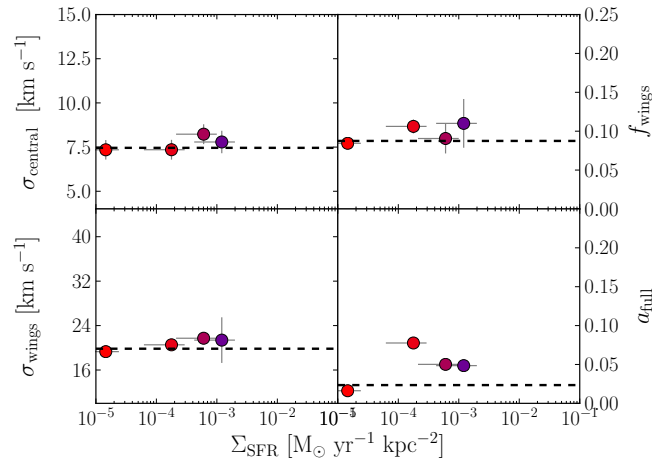


Figure 4.43c Variation of the superprofile parameters as a function of Σ_{SFR} for DDO 154. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

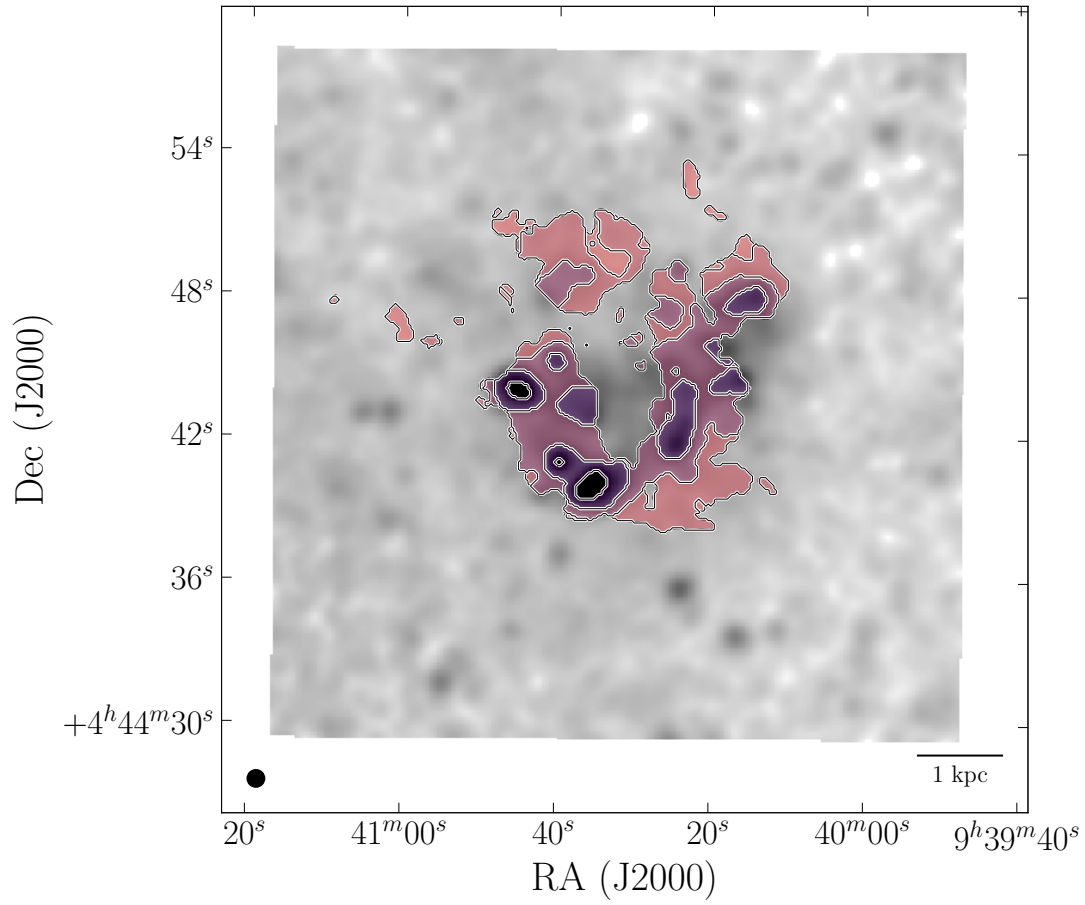


Figure 4.44a Subregions in which Σ_{SFR} superprofiles are generated for Ho I. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

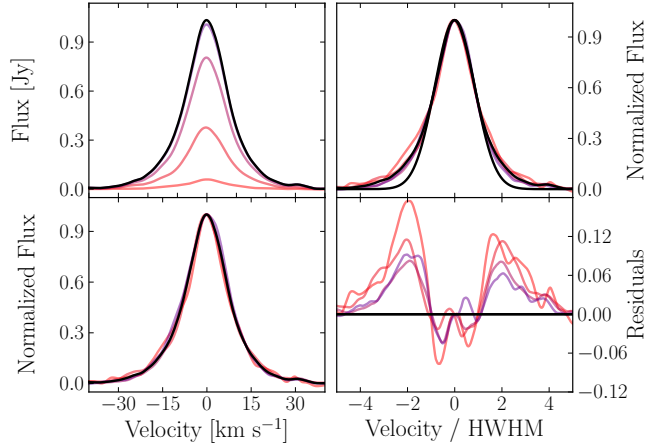


Figure 4.44b The Σ_{SFR} superprofiles in Ho I, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

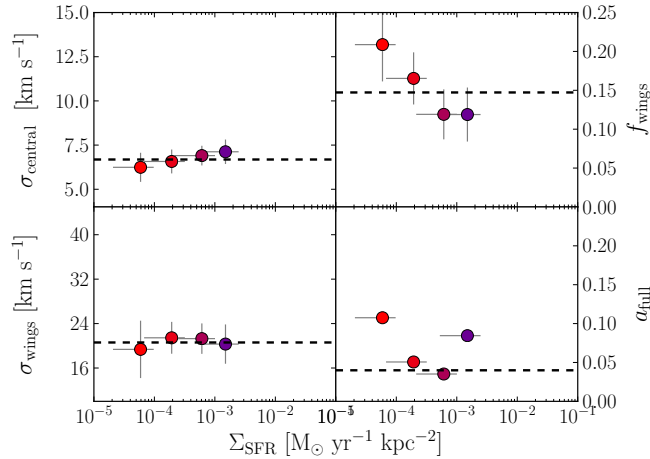


Figure 4.44c Variation of the superprofile parameters as a function of Σ_{SFR} for Ho I. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

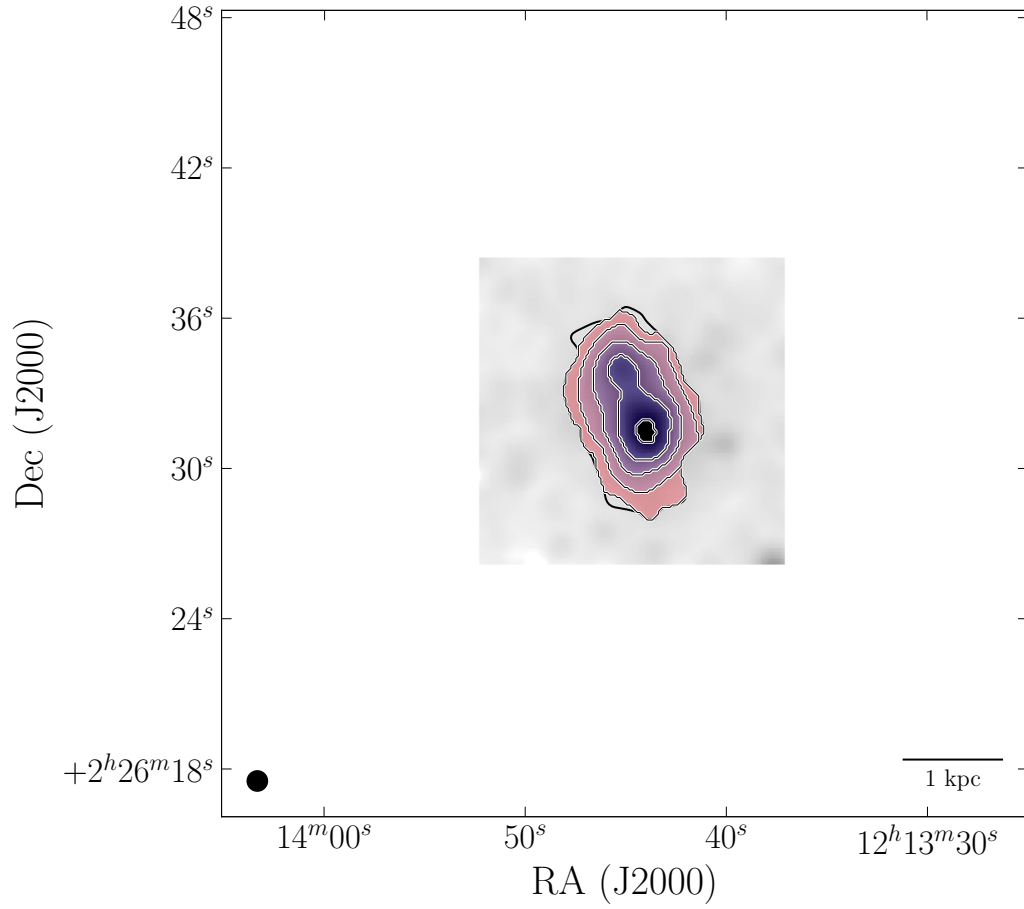


Figure 4.45a Subregions in which Σ_{SFR} superprofiles are generated for NGC 4190. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

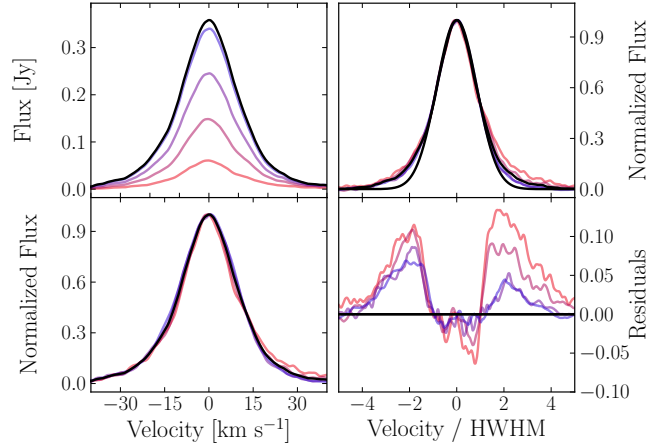


Figure 4.45b The Σ_{SFR} superprofiles in NGC 4190, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

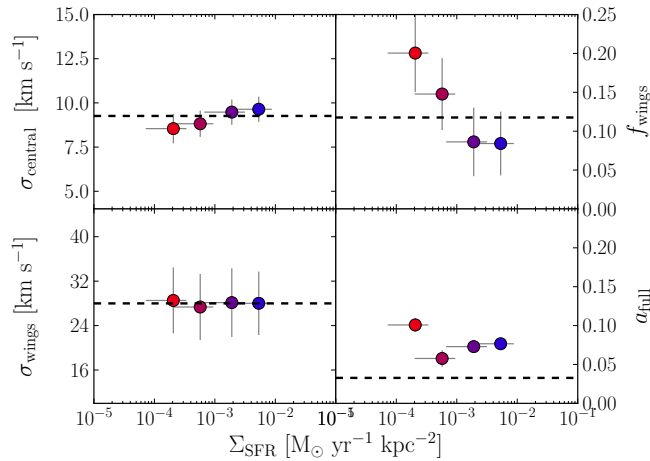


Figure 4.45c Variation of the superprofile parameters as a function of Σ_{SFR} for NGC 4190. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

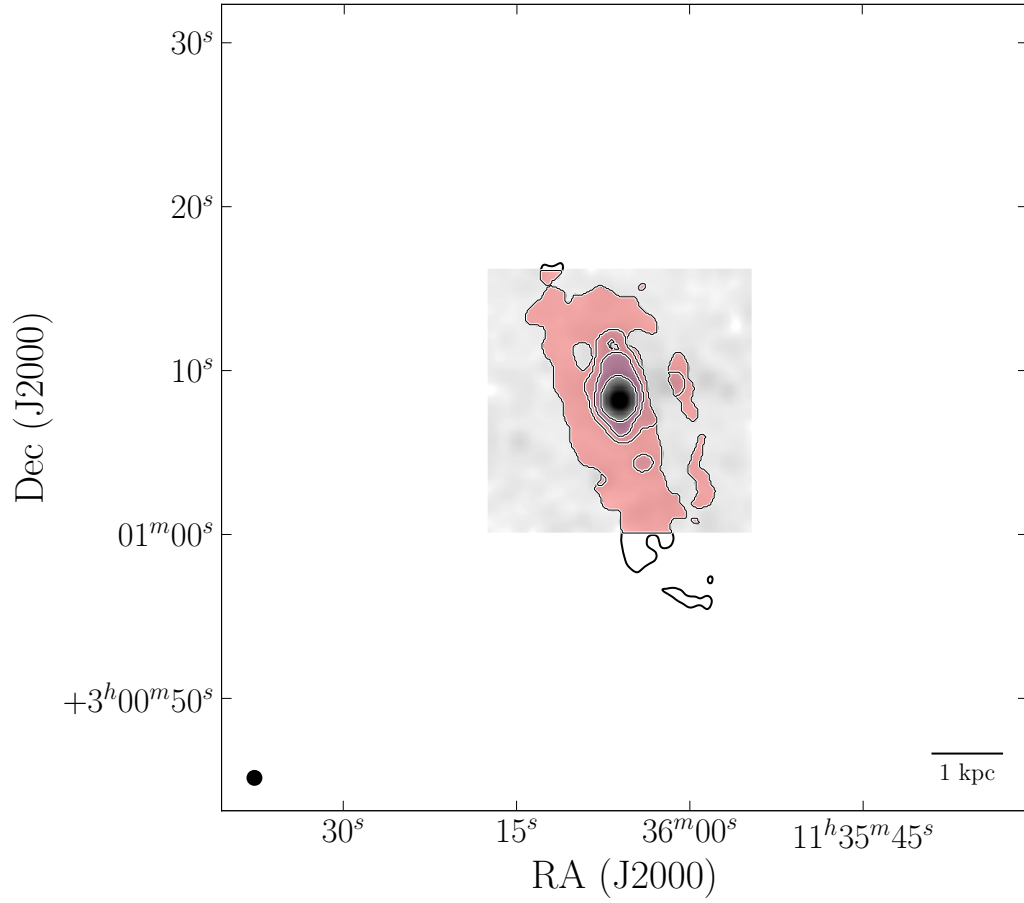


Figure 4.46a Subregions in which Σ_{SFR} superprofiles are generated for NGC 3741. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

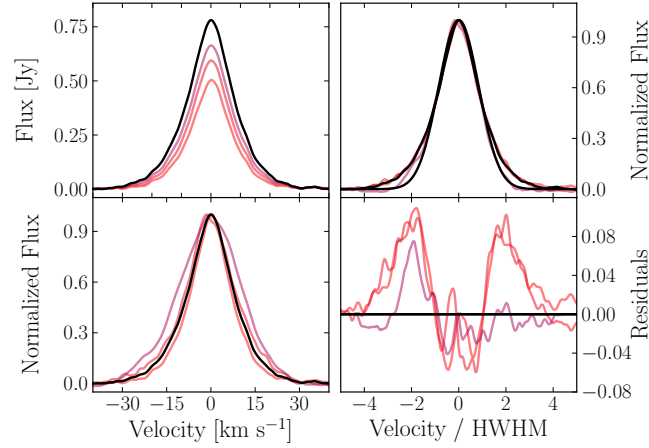


Figure 4.46b The Σ_{SFR} superprofiles in NGC 3741, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

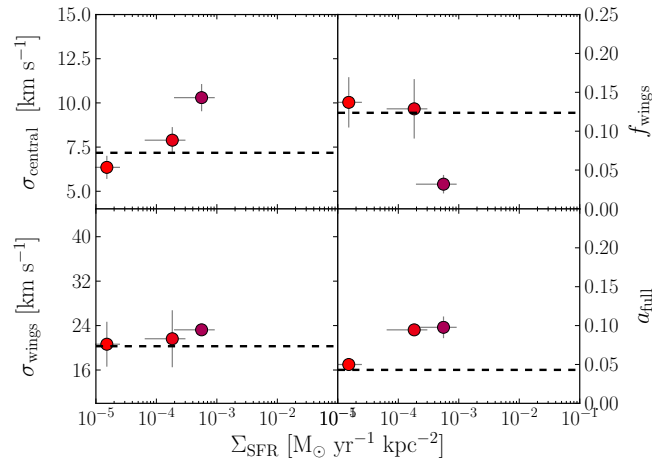


Figure 4.46c Variation of the superprofile parameters as a function of Σ_{SFR} for NGC 3741. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

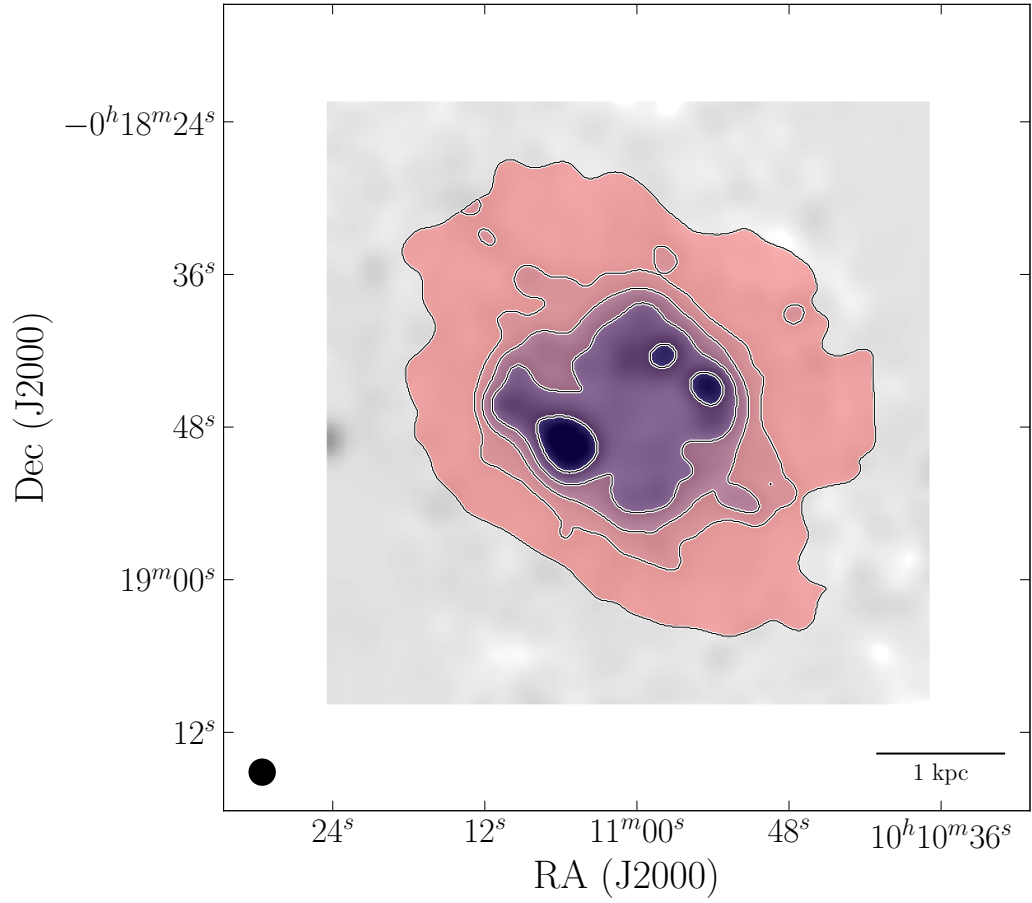


Figure 4.47a Subregions in which Σ_{SFR} superprofiles are generated for Sextans A. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

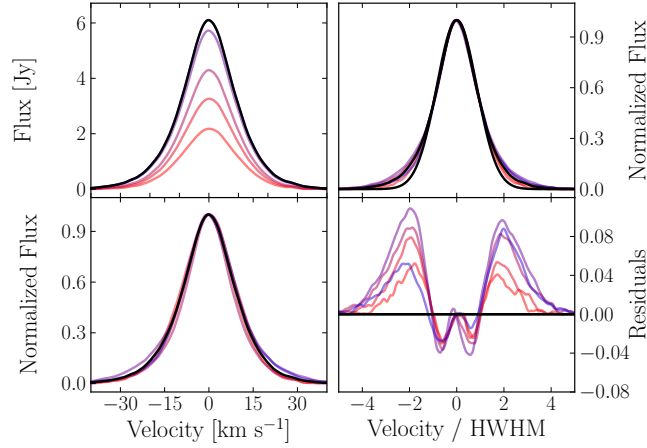


Figure 4.47b The Σ_{SFR} superprofiles in Sextans A, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

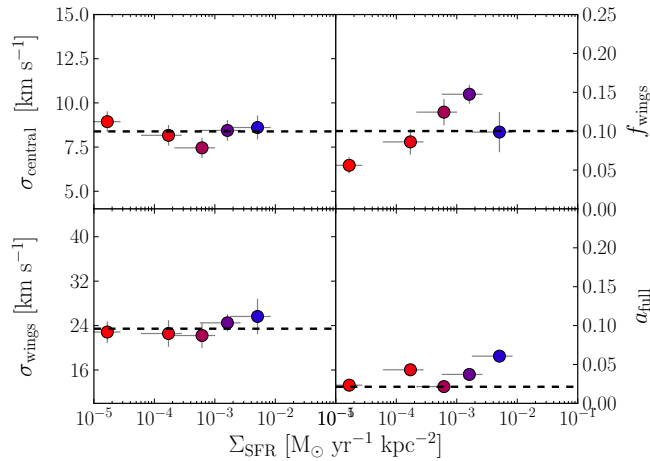


Figure 4.47c Variation of the superprofile parameters as a function of Σ_{SFR} for Sextans A. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

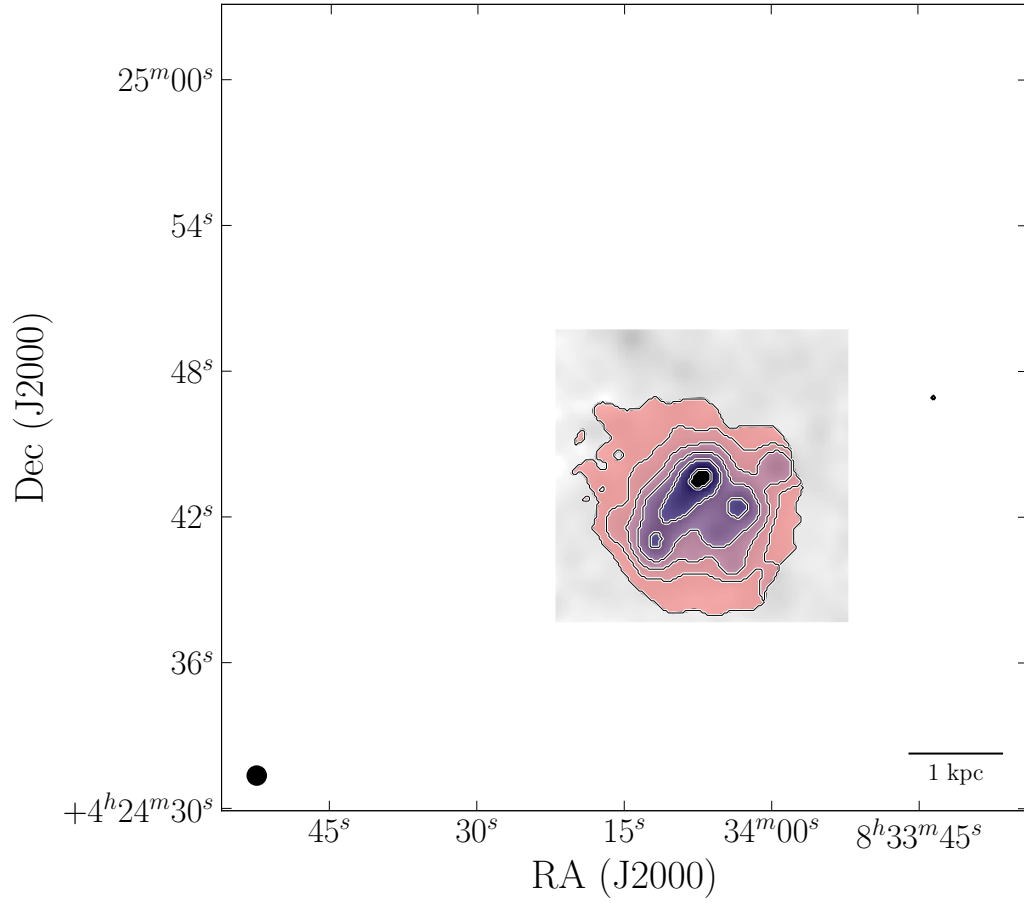


Figure 4.48a Subregions in which Σ_{SFR} superprofiles are generated for DDO 53. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

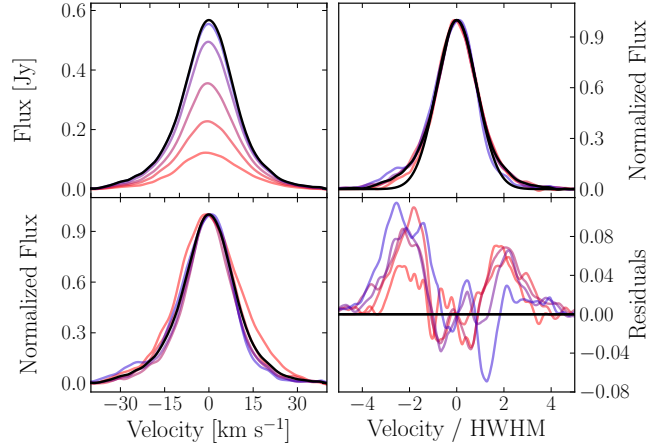


Figure 4.48b The Σ_{SFR} superprofiles in DDO 53, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

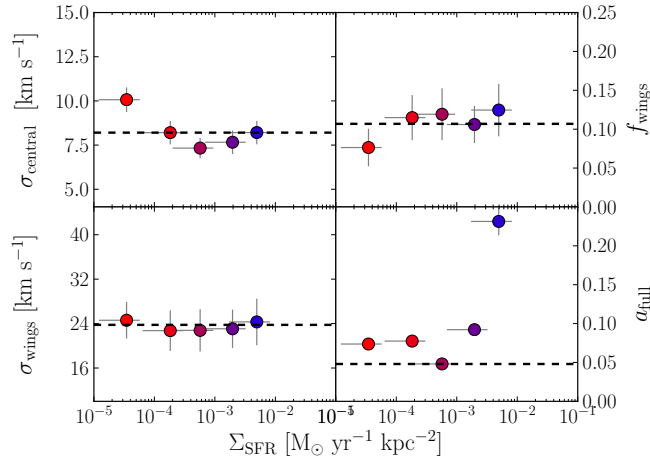


Figure 4.48c Variation of the superprofile parameters as a function of Σ_{SFR} for DDO 53. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{full} (lower).

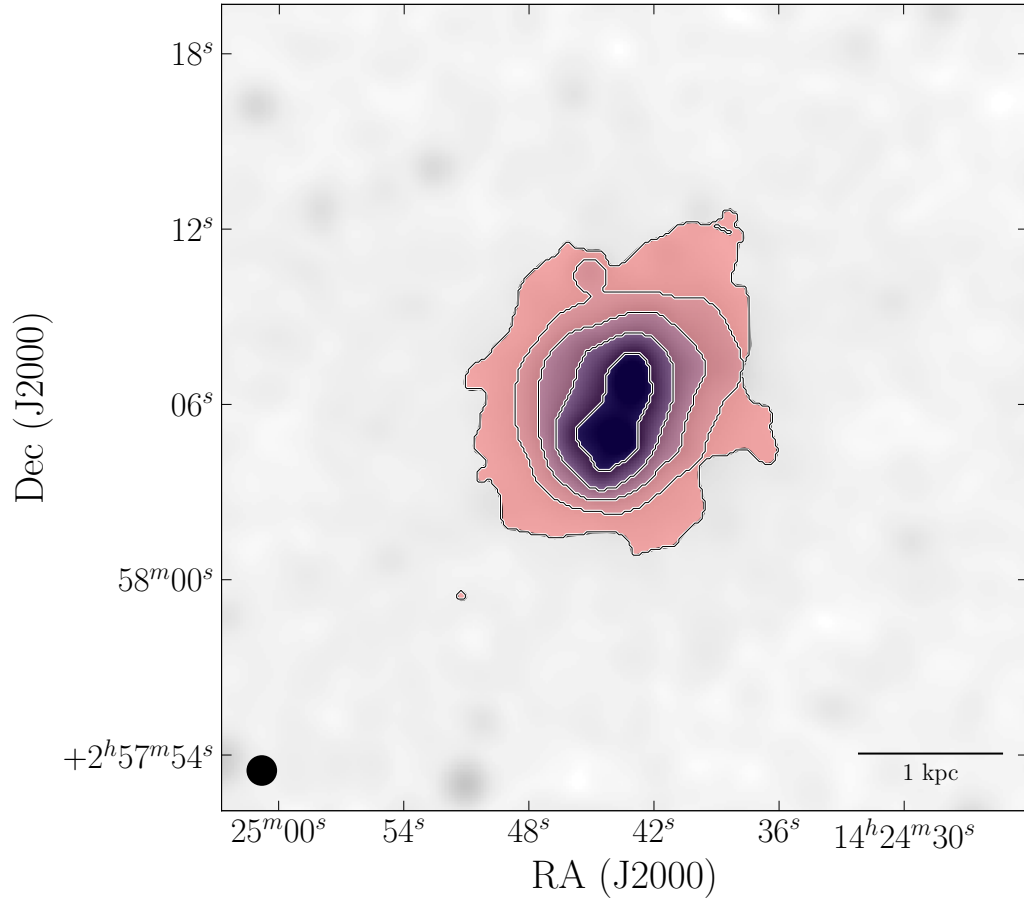


Figure 4.49a Subregions in which Σ_{SFR} superprofiles are generated for DDO 190. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

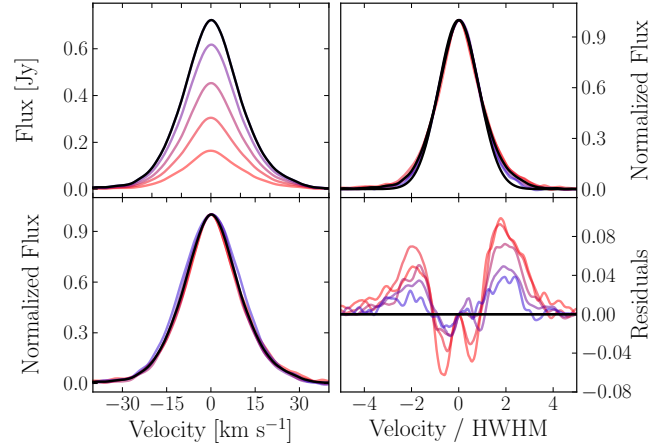


Figure 4.49b The Σ_{SFR} superprofiles in DDO 190, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

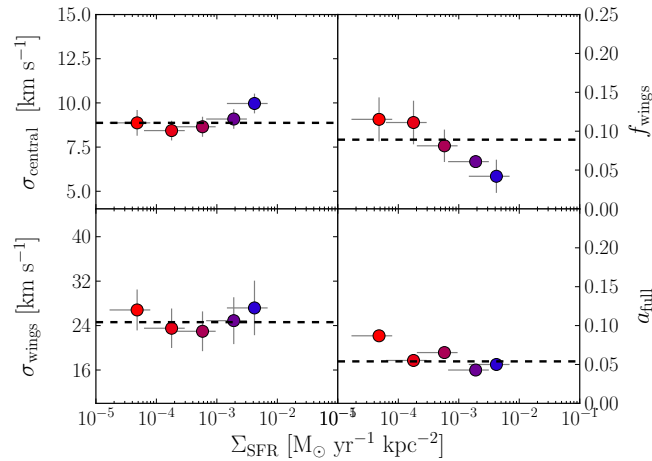


Figure 4.49c Variation of the superprofile parameters as a function of Σ_{SFR} for DDO 190. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

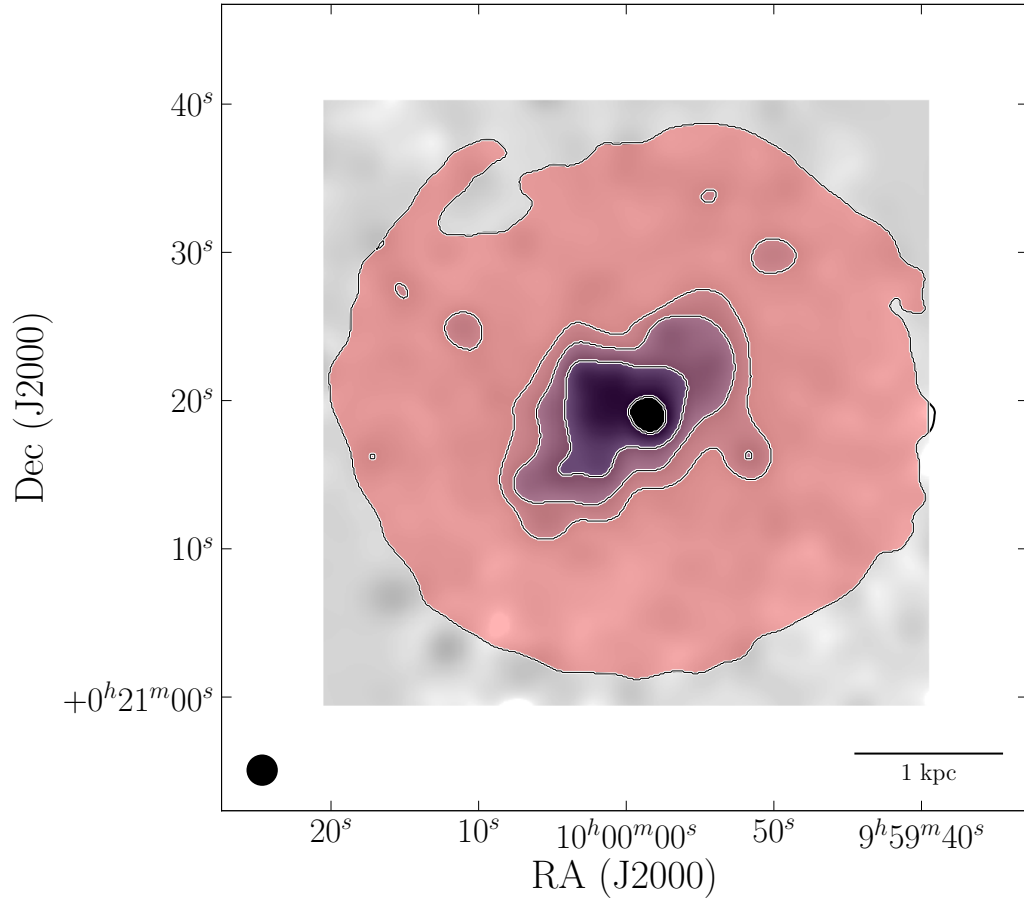


Figure 4.50a Subregions in which Σ_{SFR} superprofiles are generated for Sextans B. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

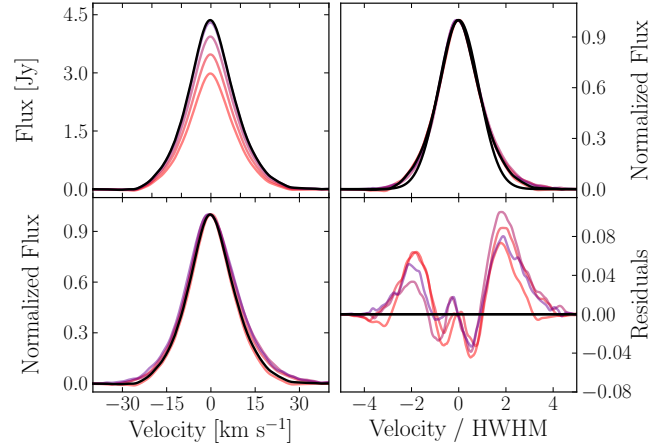


Figure 4.50b The Σ_{SFR} superprofiles in Sextans B, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

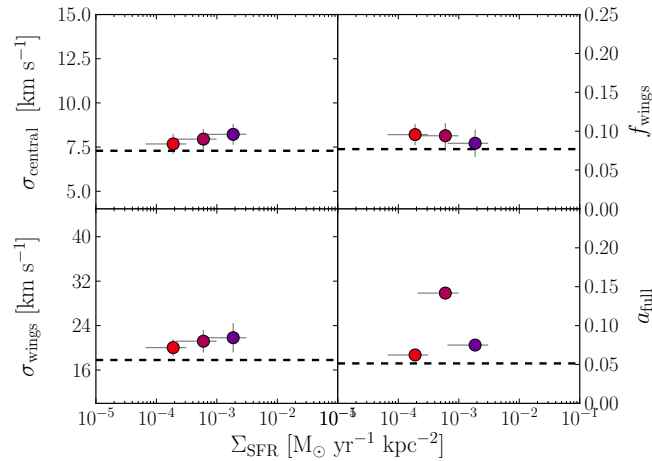


Figure 4.50c Variation of the superprofile parameters as a function of Σ_{SFR} for Sextans B. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

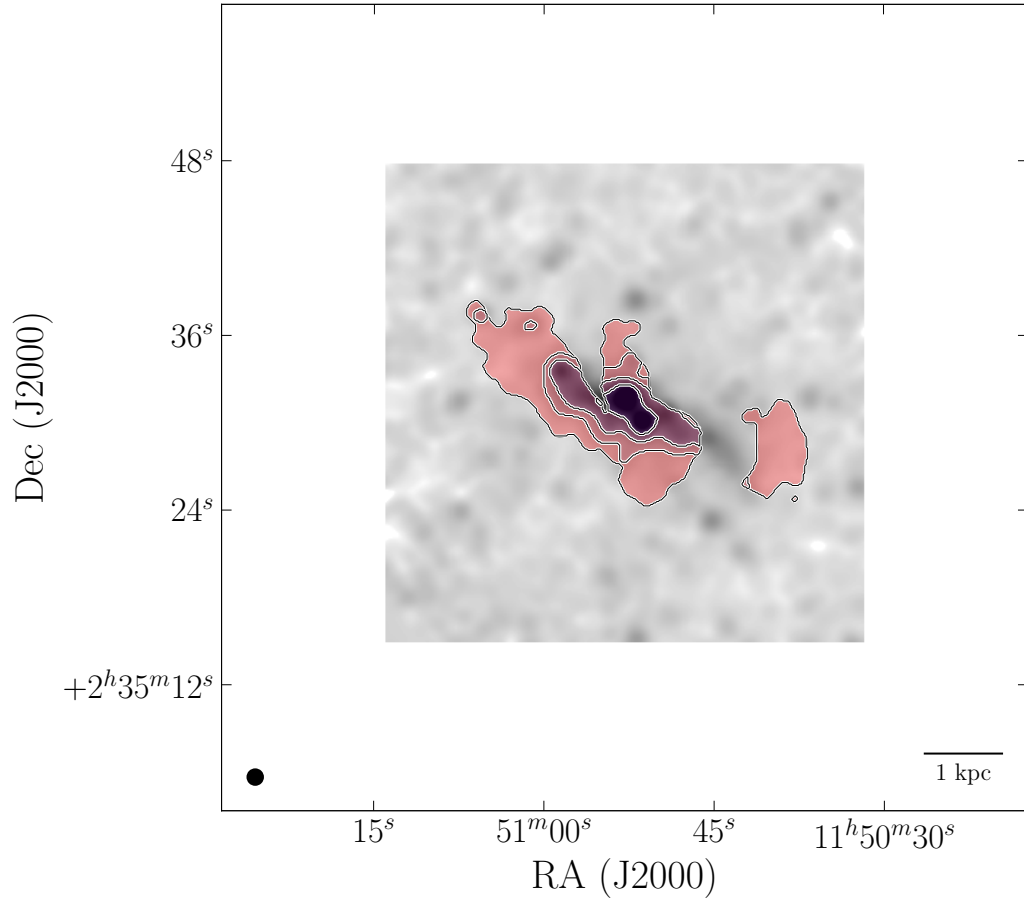


Figure 4.51a Subregions in which Σ_{SFR} superprofiles are generated for DDO 99. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

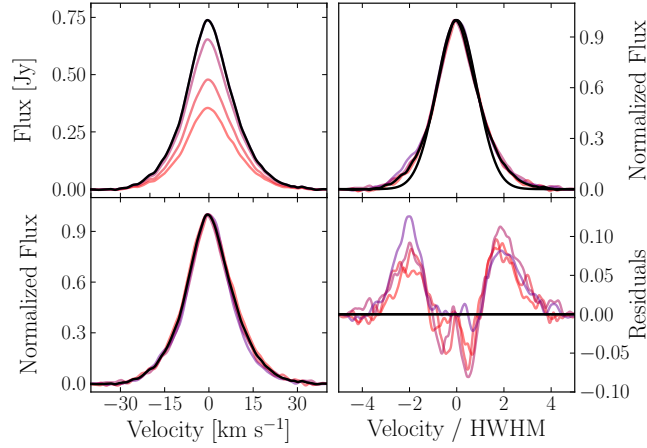


Figure 4.51b The Σ_{SFR} superprofiles in DDO 99, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

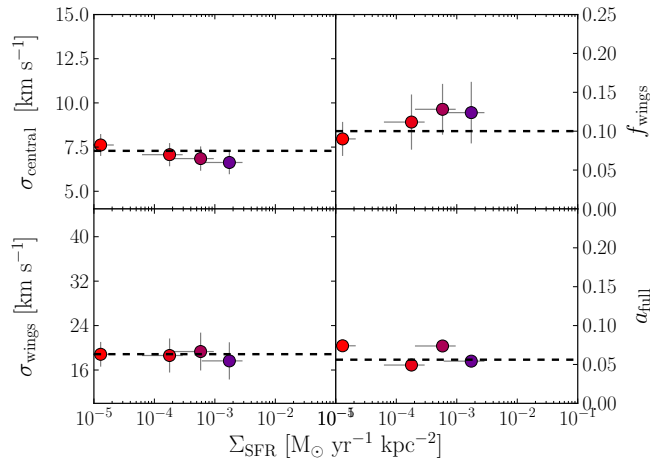


Figure 4.51c Variation of the superprofile parameters as a function of Σ_{SFR} for DDO 99. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{full} (lower).

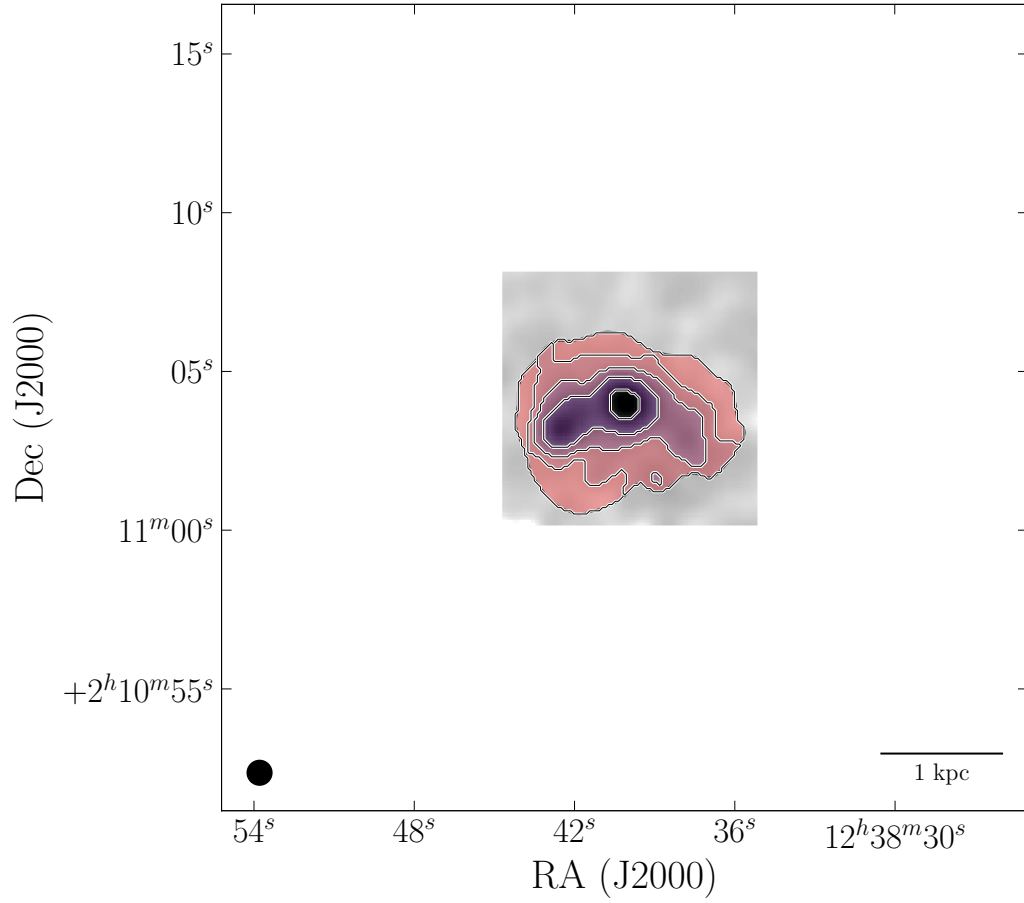


Figure 4.52a Subregions in which Σ_{SFR} superprofiles are generated for UGCA 292. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

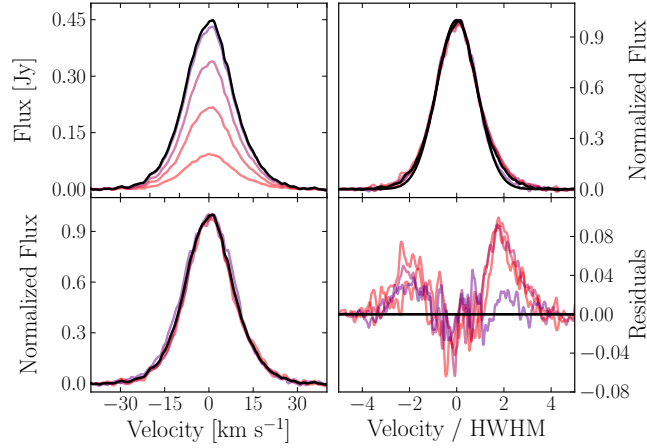


Figure 4.52b The Σ_{SFR} superprofiles in UGCA 292, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

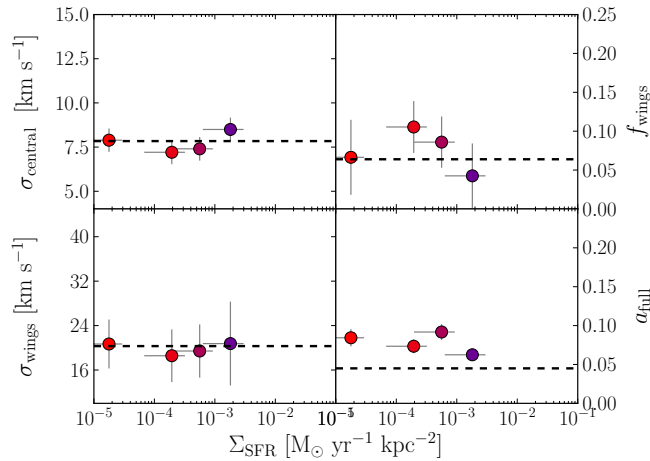


Figure 4.52c Variation of the superprofile parameters as a function of Σ_{SFR} for UGCA 292. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

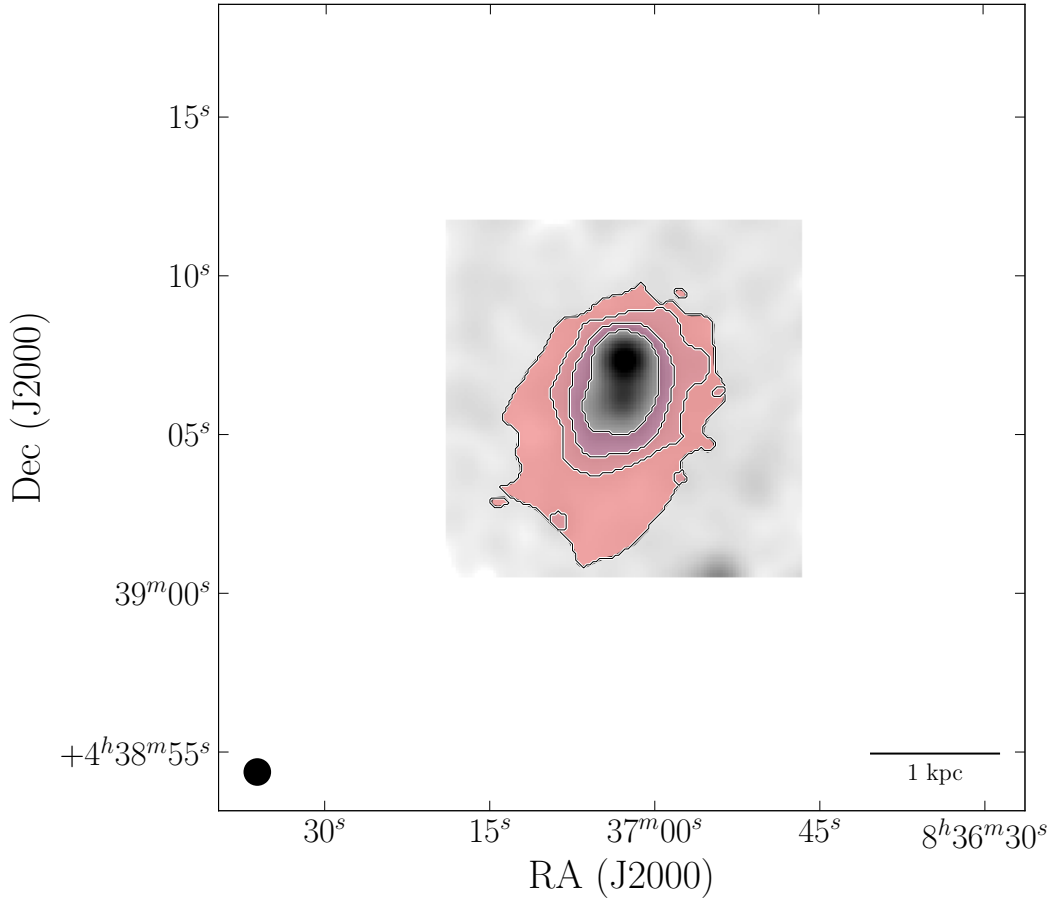


Figure 4.53a Subregions in which Σ_{SFR} superprofiles are generated for UGC 4483. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

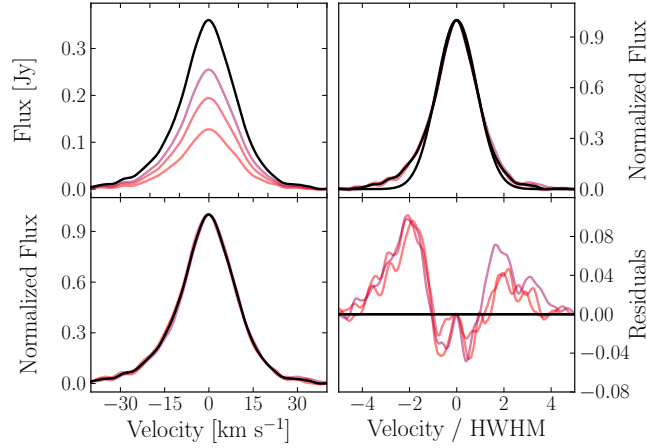


Figure 4.53b The Σ_{SFR} superprofiles in UGC 4483, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

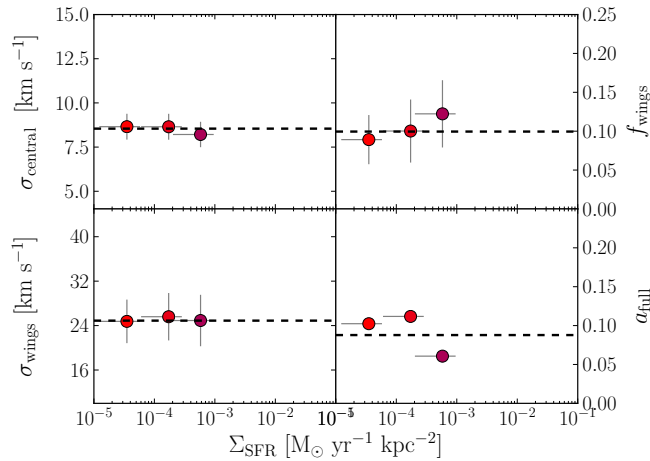


Figure 4.53c Variation of the superprofile parameters as a function of Σ_{SFR} for UGC 4483. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{full} (lower).

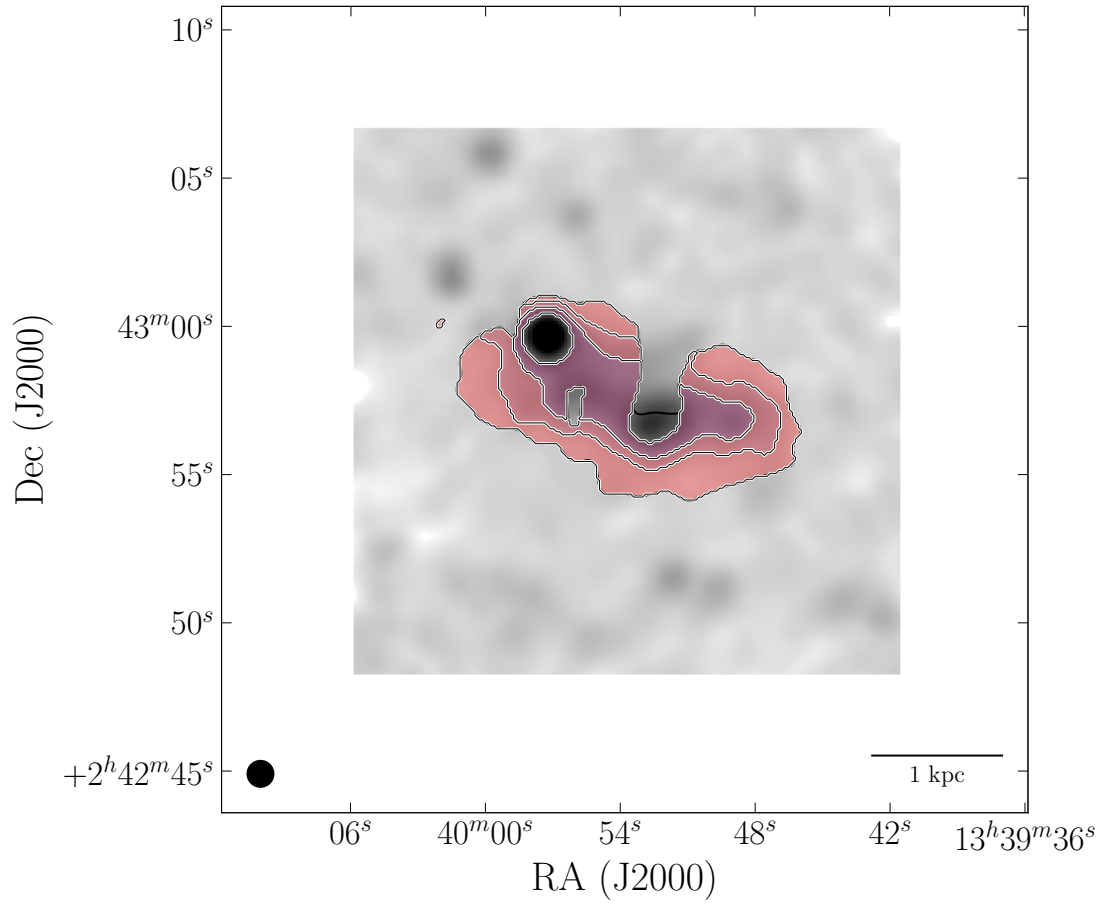


Figure 4.54a Subregions in which Σ_{SFR} superprofiles are generated for DDO 181. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

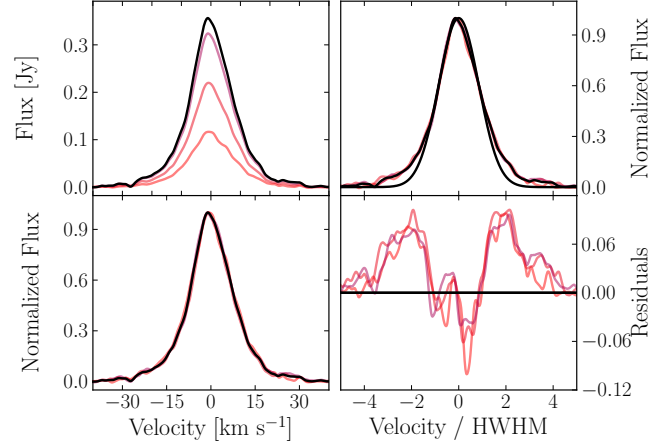


Figure 4.54b The Σ_{SFR} superprofiles in DDO 181, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

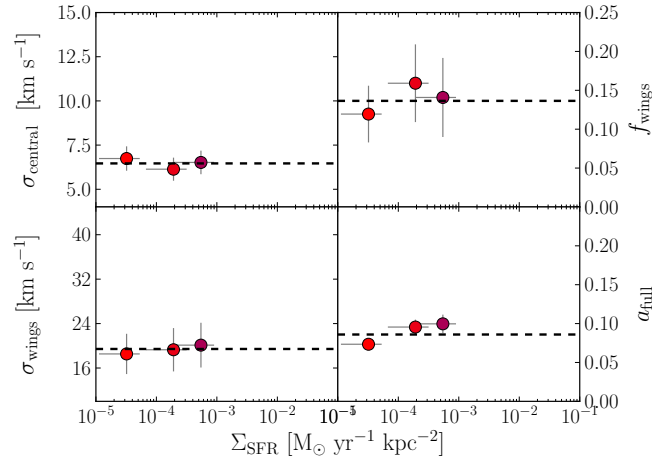


Figure 4.54c Variation of the superprofile parameters as a function of Σ_{SFR} for DDO 181. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{full} (lower).

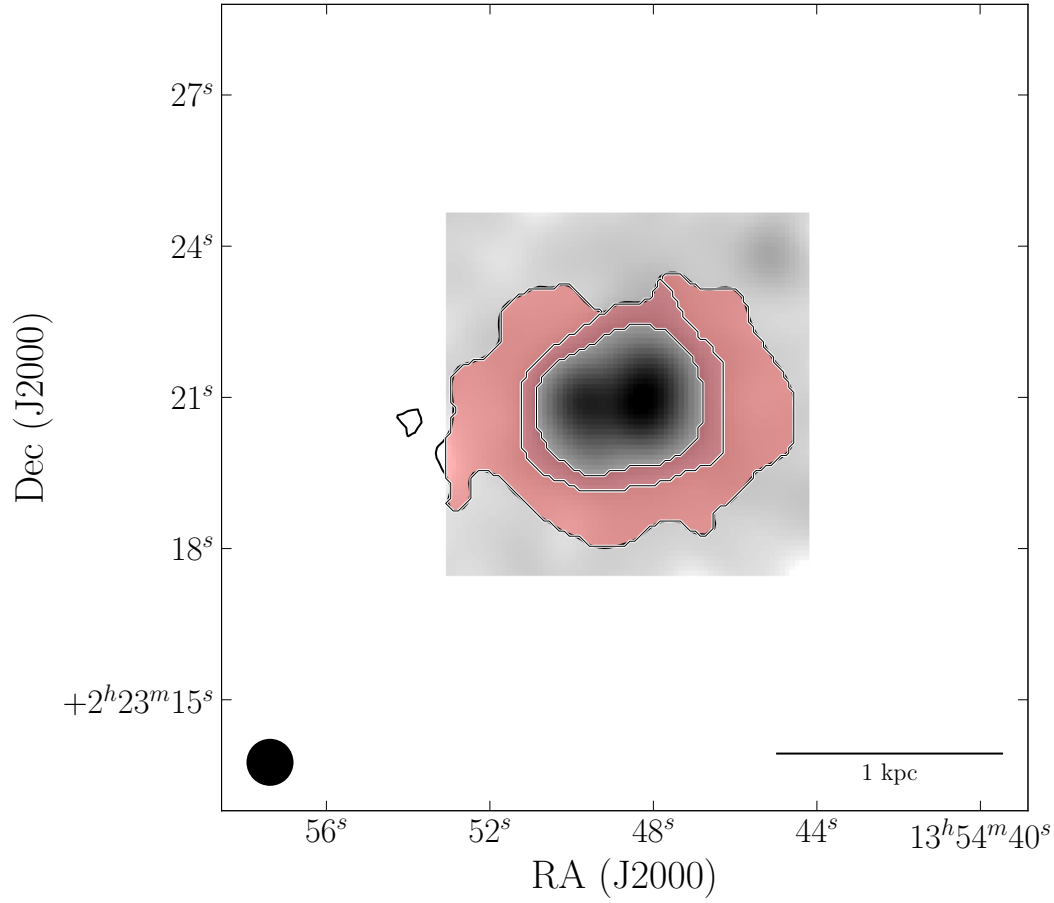


Figure 4.55a Subregions in which Σ_{SFR} superprofiles are generated for UGC 8833. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

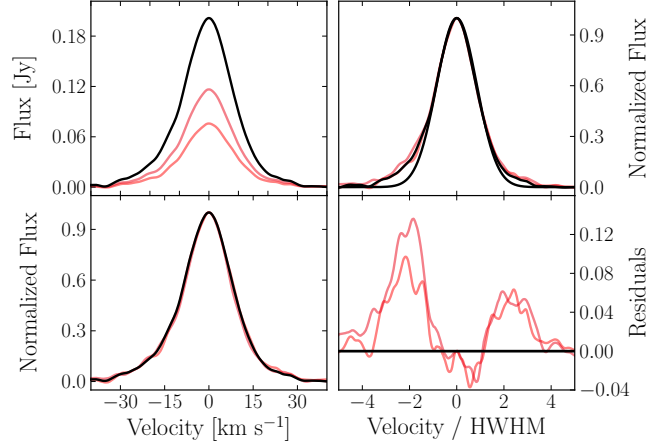


Figure 4.55b The Σ_{SFR} superprofiles in UGC 8833, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

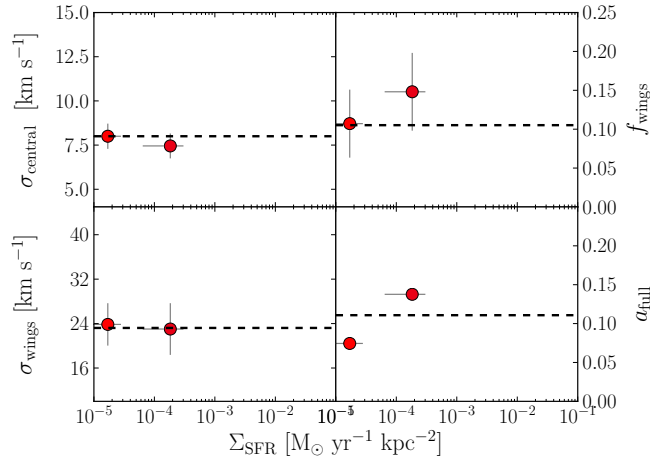


Figure 4.55c Variation of the superprofile parameters as a function of Σ_{SFR} for UGC 8833. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{wings} (lower).

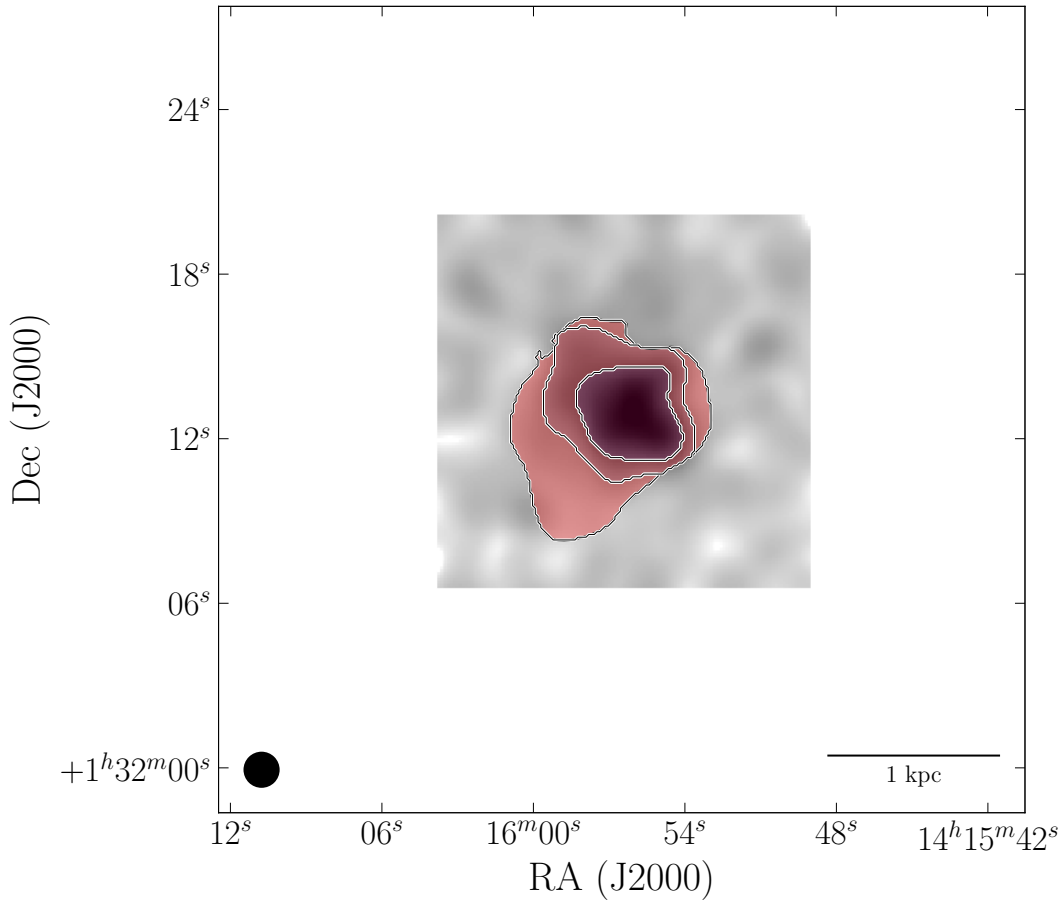


Figure 4.56a Subregions in which Σ_{SFR} superprofiles are generated for DDO 187. The background greyscale shows Σ_{SFR} . The solid black line represents the $S/N > 5$ threshold where we can accurately measure v_{peak} . The colored regions indicate which pixels have contributed to each Σ_{SFR} superprofile.

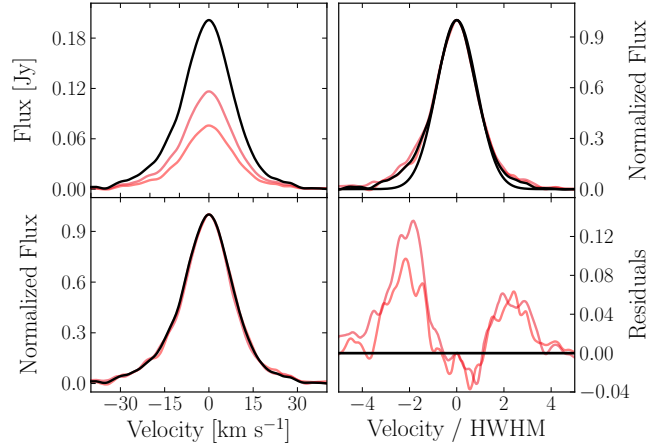


Figure 4.56b The Σ_{SFR} superprofiles in DDO 187, where colors indicate the corresponding Σ_{SFR} regions in the previous figure. The left hand panels show the raw superprofiles (upper left) and the superprofiles normalized to the same peak flux (lower left). The right hand panels show the flux-normalized superprofiles scaled by the HWHM (upper right) and the flux-normalized superprofiles minus the model of the Gaussian core (lower right). The black line represents the global superprofile in the left panels and the HWHM Gaussian model in the right panels.

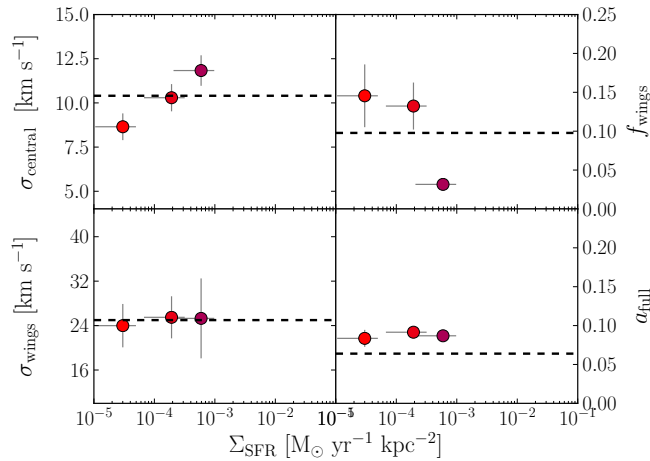


Figure 4.56c Variation of the superprofile parameters as a function of Σ_{SFR} for DDO 187. The solid dashed line shows the parameter value for the global superprofile (Chapter 3). The left panels show σ_{central} (upper) and σ_{wings} (lower), and the right panels show f_{wings} (upper) and a_{full} (lower).

Chapter 5

TIMESCALES ON WHICH SF COUPLES TO THE NEUTRAL ISM

Turbulent neutral hydrogen (H I) line widths are often thought to be driven primarily by SF, but the timescale for converting SF energy to H I kinetic energy is unclear. As a complication, studies on the connection between H I line widths and SF in external galaxies often use broadband tracers for the SF rate, which must implicitly assume that SF histories (SFHs) have been constant over the timescale of the tracer. In this paper, we compare measures of H I energy to time-resolved SFHs in a number of nearby dwarf galaxies. We find that H I energy surface density is strongly correlated only with SF that occurred 30–40 Myr ago. This timescale corresponds to the approximate lifetime of the lowest mass supernova progenitors ($\sim 8 M_{\odot}$). This analysis suggests that the coupling between SF and the neutral ISM is strongest on this timescale, due either to an intrinsic delay between the release of the peak energy from SF or to the coherent effects of many SNe during this interval. At $\Sigma_{\text{SFR}} > 10^{-3} M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, we find a mean coupling efficiency between SF energy and H I energy of $\epsilon = 0.11 \pm 0.04$ using the 30–40 Myr timescale. However, unphysical efficiencies are required in lower Σ_{SFR} systems, implying that SF is not the primary driver of H I kinematics at $\Sigma_{\text{SFR}} < 10^{-3} M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$.

5.1 Introduction

Neutral hydrogen (H I) line widths in galaxies are commonly thought to be due to turbulence driven by SF (SF), which releases energy through ionizing radiation, stellar winds, and supernova explosions (SNe; e.g., Spitzer, 1978; Mac Low & Klessen, 2004). Because turbulence decays rapidly in typical ISM conditions ($\tau \sim 10$ Myr; Mac Low, 1999), any driver must continuously replenish the observed turbulent energy. At high SF rate surface density (Σ_{SFR}), a number of studies have found strong correlations between the amount of SF and H I turbulence, and have used these correlation to constrain possible mechanisms

by which SF couples to the neutral ISM (e.g., Tamburro et al., 2009; Joung et al., 2009). At low Σ_{SFR} , however, there appears to be little connection between SF intensity and H I velocity dispersion as found in dwarf galaxies or the outer disks of spirals (van Zee & Bryant, 1999; Dib et al., 2006; Tamburro et al., 2009). The primary driver of turbulence remains unknown in these low Σ_{SFR} regimes.

In addition to uncertainties in the driving mechanisms of turbulence, the timescale for driving H I turbulence is also unknown. This timescale cannot be calculated from first principles, and is challenging to constrain observationally because the timescale for energy input from SF is also uncertain. Common tracers of the SF rate (SFR) are either H α or far ultraviolet (FUV) emission, occasionally with the inclusion of far-infrared (FIR) fluxes to provide an estimate of dust-obscured SF (e.g., Leroy et al., 2008, 2012; Kennicutt & Evans, 2012). FUV wavelengths trace emission from SF over the past 10 – 100 Myr, while H α typically probes much shorter timescales of 3 – 10 Myr (Kennicutt & Evans, 2012, and references therein). The calibration of these tracers relies on the assumption of a constant SFH over the past $\sim 10 - 100$ Myr, and is not yet well-understood for low-SFR systems with large relative variations.

In contrast, time-variable SFHs in galaxies have been well-established (e.g., Grebel, 1997; Mateo, 1998; Dolphin et al., 2005; Weisz et al., 2008, 2011), which complicates the interpretation of FUV- or H α -based SFR indicators, but time-resolved SFHs are difficult to obtain for many galaxies. Additionally, it has recently been shown that the SFR traced by FUV or H α emission may not be well-matched to the actual time-resolved SFH (e.g., McQuinn et al., 2010; Johnson et al., 2012). These SFR estimates also do not allow for a measurement of the impact of SF over time on the surrounding ISM. Moreover, in dwarf galaxies, there are discrepancies between SFRs as traced by FUV emission and by H α (e.g., Lee et al., 2009; Meurer et al., 2009; Boselli et al., 2009). Potential solutions to this problem are stochastic sampling of both the IMF and the cluster mass function, variable SFRs, a variable IMF, or a combination of these possibilities (e.g., Fumagalli et al., 2011; Lee et al., 2011; Weisz et al., 2012; da Silva et al., 2012). More robust comparisons between time-resolved recent SFHs and ISM properties are necessary to constrain the timescales for energy input from SF and the response of the ISM.

In this paper, we address the issue of timescales for energy input from SF using the combination of two unique data sets. The first is the ACS Nearby Galaxy Survey Treasury program (ANGST; Dalcanton et al., 2009), which observed 69 galaxies within ~ 4 Mpc. These data have been used to produce time-resolved SFHs from galaxies’ resolved stellar populations (e.g., Williams et al., 2009; Gogarten et al., 2010; Weisz et al., 2011; Williams et al., 2011). The second dataset is composed of high resolution H I observations from the follow-up Very Large Array-ANGST project (“VLA-ANGST”; Ott et al., 2012) and The H I Nearby Galaxy Survey (“THINGS”; Walter et al., 2008). Our sample is composed primarily of dwarf galaxies. These systems have both lower gravitational wells compared to spirals, which should enhance the effects of energy deposition from SF, as well as larger scale heights, which should more easily contain the energy released from SF within the disk. With these two datasets, we search for a preferred timescale over which energy input from SF transfers to the surrounding neutral ISM. In § 5.2, we discuss the sample selection and the data used to address this question. In § 5.3, we calculate H I energies and Σ_{SFR} values. In § 5.4 we assess the level of correlation between H I energy and SF on a variety of timescales. In § 5.5, we discuss the implied coupling efficiencies between SF energy and H I energy, as well as the physical causes that drive the observed correlations. Finally, in § 5.6, we summarize our results.

5.2 Sample and Data

We first introduce the general properties of our sample in § 5.2.1. We then briefly describe the data used to derive SFHs and H I properties in § 5.2.2 and 5.2.3.

5.2.1 The Sample

Our sample consists of a subset of ANGST galaxies (Dalcanton et al., 2009) that have high-quality H I observations through either VLA-ANGST or THINGS. In Chapter 3, we presented analysis of H I kinematics on global scales by co-adding individual H I line-of-sight spectra after removal of the rotational velocity. We select the sample for this paper from that in Chapter 3. The original selection criteria are described in detail in Chapter 3, but we briefly review them here:

1. H I instrumental spatial resolution smaller than our working resolution of 200 pc, which is the approximate spatial resolution at the limit of the ANGST survey;
2. Velocity resolution $\Delta v \leq 2.6 \text{ km s}^{-1}$, to accurately determine the peak of each H I line-of-sight spectrum and its corresponding velocity (v_{peak}), as well as the average line width;
3. Inclination $< 70^\circ$, as line-of-sight profiles for galaxies with larger inclinations may be artificially broadened;
4. No noticeable contamination from the Milky Way or a companion, to accurately determine v_{peak} ;
5. More than 10 independent beams across the galaxy disk above the signal-to-noise threshold ($S/N > 5$).

These choices maximize our data quality, as described more fully in Chapter 3.

Applying these criteria leave us with 18 galaxies, primarily with de Vaucouleurs T-type of 10 (i.e., dwarf irregulars), as many of the more massive spirals were eliminated based on the first or second criteria. General properties of the sample are given in Table 5.1. Galaxies are listed in decreasing total baryonic mass ($M_{\text{baryon,tot}}$). We give (1) the galaxy name; (2) the survey for H I data; (3-4) position in J2000 coordinates; (5) distance in Mpc from Dalcanton et al. (2009); (6) inclination from Chapter 3, with the exception of Sextans B where an $i \sim 30^\circ$ better matches the H I morphology compared with the inclination quoted in Chapter 3; (7) $M_{\text{baryon,tot}}$ from Chapter 3; (8) total H I mass M_{HI} from Chapter 3; (9) average SFR in the ANGST aperture over the past 100 Myr derived from ANGST SFHs (see § 5.2.2); (10) de Vaucouleurs T-type.

We show the inclination-corrected H I column density maps of our sample in Figure 5.1a, with the ANGST footprints overlaid. While a few of the galaxies in the sample have disk-like morphologies, the majority are dwarf irregulars. In some cases, the ANGST aperture is fully covered by H I with $S/N > 5$. In others, the $S/N > 5$ region is smaller than the

ANGST aperture, but in these galaxies the majority of the SF is located in the same region as the high S/N H I.

5.2.2 SF Histories

To determine the time-resolved SFHs, we use data from ANGST, which provides multi-color *Hubble Space Telescope* photometry of resolved stars in 69 nearby galaxies. The survey and data processing pipeline are described in more detail in Dalcanton et al. (2009). The calibrated photometric data from ANGST can be translated into color-magnitude diagrams (CMDs), which can then be modeled to estimate the time-resolved SFH of the constituent stars (e.g., Dolphin, 2002). As described in Dolphin (2002), the SFHs are generated by modeling each CMD as the linear combination of simple stellar populations with a variety of ages, assuming a single power law IMF $dN/dm \propto m^{-2.3}$. When calculating the SFHs, other effects such as dust reddening, completeness limits, and photometric errors are taken into account. The uncertainties on the SFHs for each galaxy are estimated for each galaxy by Monte Carlo realizations of the SFH, which account for uncertainty in stochastic sampling of the IMF. Further details on the generation of the SFHs used this paper can be found in Weisz et al. (2011).

The time-resolved cumulative SFHs for the sample are shown in Figure 5.2, in order of decreasing $M_{\text{baryon,tot}}$. Each panel represents a single galaxy. Within one panel, the thick red line shows the best-fit cumulative mass in stars formed between now and some time t in the past ($M_{\star}(< t)$), normalized to the total mass in stars formed within the past 100 Myr (i.e., $M_{\star}(< 100 \text{ Myr})$); the value of $\log M_{\star}(< 100 \text{ Myr})$ for each galaxy is shown beneath the galaxy name. The transparent black lines show the Monte Carlo realizations of the SFH, scaled to $M_{\star}(< 100 \text{ Myr})$ of the best-fit SFH. Galaxies with smaller scatter around the best-fit line are therefore more certain. Some galaxies (e.g., DDO 125 and DDO 190) show relatively constant SFHs, characterized by a straight diagonal line, while others have either more SF at recent times (e.g., Sextans A, GR 8) or little recent SF (e.g., DDO 187, UGC 4483). Figure 1 gives the impression that the variations away from a constant SFR increase in significance with decreasing $M_{\text{baryon,tot}}$.

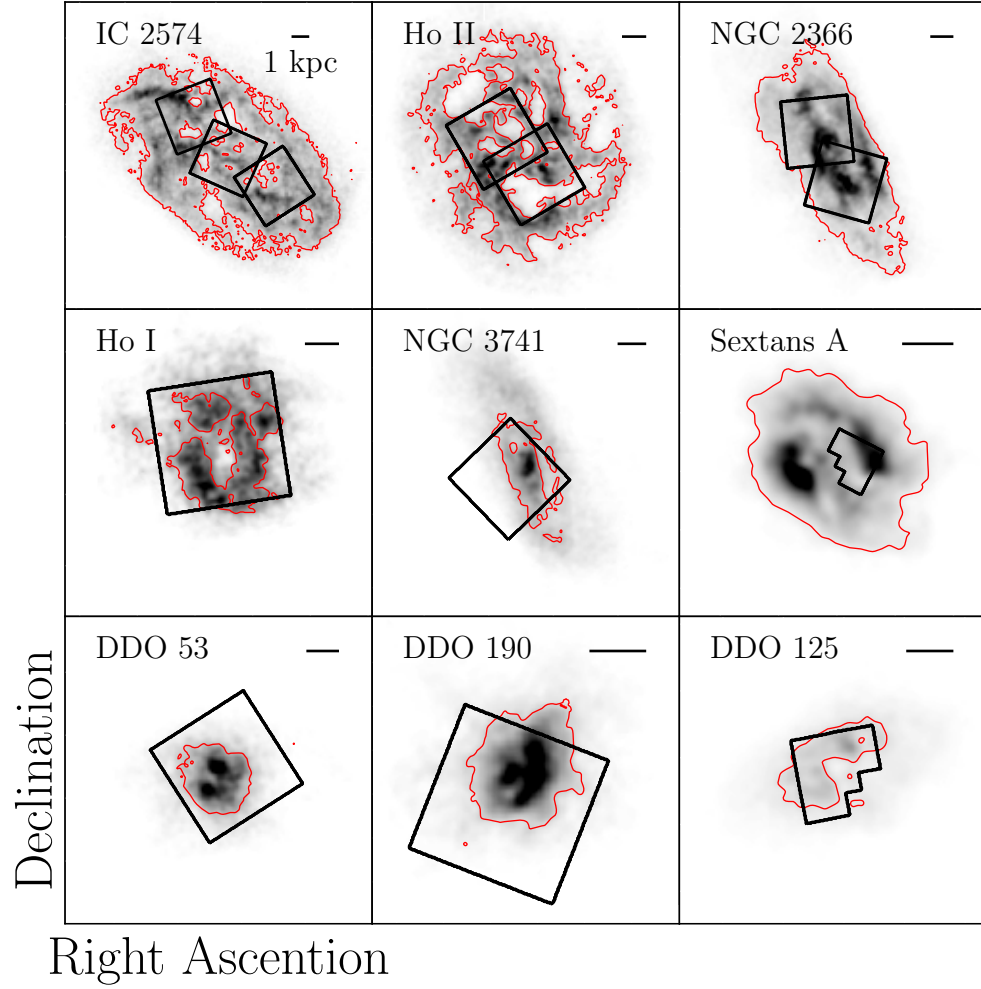


Figure 5.1a H I column density maps for the sample, scaled between 0 and $2 \times 10^{21} \text{ cm}^{-2}$. The ANGST footprints are overlaid as the thick black solid line. We also show the $S/N = 5$ level of the H I spectra as the red contour. Only regions that are both inside the ANGST footprint and with $S/N > 5$ are included in our analysis. The scale bar indicates 1 kpc in all panels, and the physical resolution of all H I data is 200 pc at the distance of each galaxy.

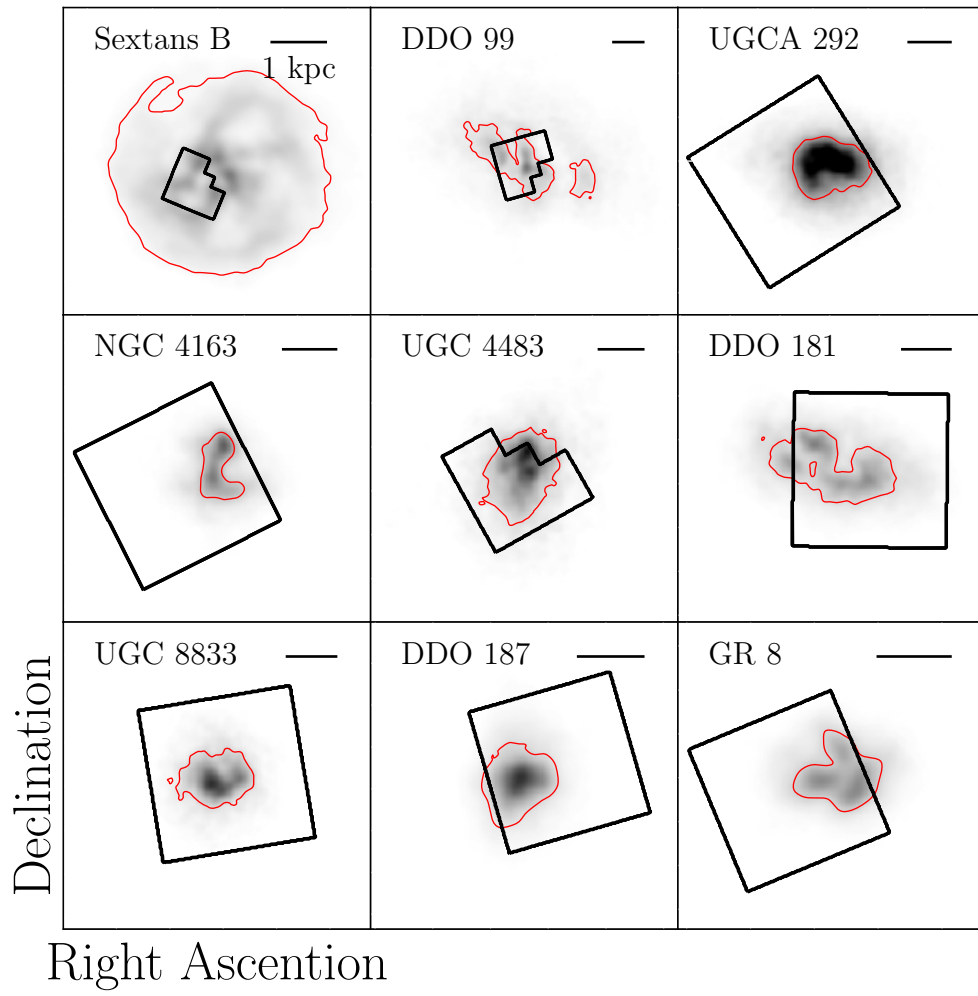


Figure 5.1b continued.

Table 5.1: The sample. Galaxies are listed in order of decreasing $M_{\text{baryon,tot}}$. All references are as given in Chapter 3. (1) Galaxy name; (2) H I survey; (3-4) Position in J2000 coordinates; (5) Distance in Mpc; (6) Inclination; (7) $M_{\text{baryon,tot}}$ in $\log M_{\odot}$; (8) $M_{\text{HI,tot}}$ in $\log M_{\odot}$; (9) ANGST $\text{SFR}_{\star}(< 100 \text{ Myr})$; (10) de Vaucouleurs T-type.

1	2	3	4	5	6	7	8	9	10
Galaxy	Survey	RA (hh:mm:ss)	Dec (dd:mm:ss)	Distance (Mpc)	i ($^{\circ}$)	$M_{\text{baryon,tot}}$ ($\log M_{\odot}$)	$M_{\text{HI,tot}}$ ($\log M_{\odot}$)	$\langle \text{SFR}(< 100 \text{ Myr}) \rangle$ ($10^{-3} M_{\odot} \text{ yr}^{-1}$)	Type
IC 2574	THINGS	10:28:27.7	+68:24:59	3.79	55	9.4	9.1	82.5	9
Ho II	THINGS	08:19:05.0	+70:43:12	3.38	49	9.0	8.8	67.1	10
NGC 2366	THINGS	07:28:53.4	+69:12:51	3.21	63	9.0	8.8	66.7	10
Ho I	THINGS	09:40:32.3	+71:10:56	3.90	13	8.4	8.2	15.9	10
NGC 3741	VLA-ANGST	11:36:06.4	+45:17:07	3.24	64	8.1	7.9	4.5	10
Sextans A	VLA-ANGST	10:11:00.8	-04:41:34	1.38	36	8.0	7.8	4.3	10
DDO 53	THINGS	08:34:07.2	+66:10:54	3.61	27	8.0	7.8	3.4	10
DDO 190	VLA-ANGST	14:24:43.5	+44:31:33	2.79	30	8.0	7.6	7.9	10
DDO 125	VLA-ANGST	12:27:41.8	+43:29:38	2.58	63	7.9	7.5	6.7	10
Sextans B	VLA-ANGST	10:00:00.1	+05:19:56	1.39	30	7.9	7.6	1.8	10
DDO 99	VLA-ANGST	11:50:53.0	+38:52:50	2.59	60	7.9	7.7	5.2	10
UGCA 292	VLA-ANGST	12:38:40.0	+32:46:00	3.62	16	7.8	7.6	3.3	10
NGC 4163	VLA-ANGST	12:12:09.1	+36:10:09	2.86	45	7.7	7.0	2.4	10
UGC 4483	VLA-ANGST	08:37:03.0	+69:46:31	3.41	42	7.7	7.5	3.2	10
DDO 181	VLA-ANGST	13:39:53.8	+40:44:21	3.14	50	7.7	7.4	3.5	10
UGC 8833	VLA-ANGST	13:54:48.7	+35:50:15	3.08	33	7.4	7.1	1.7	10
DDO 187	VLA-ANGST	14:15:56.5	+23:03:19	2.21	55	7.3	7.1	1.3	10
GR 8	VLA-ANGST	12:58:40.4	+14:13:03	2.08	33	7.1	6.8	1.3	10

The SF rates determined by ANGST are often higher than those measured by the FUV + $24\mu\text{m}$ method described in Chapter 3. This discrepancy has been previously noted by Johnson et al. (2012), who found that non-uniform SFHs can introduce a factor of ~ 2 scatter to the SFR as determined by FUV emission, as well as a systematic offset in the spectral synthesis models used to calibrate FUV SFR indicators.

5.2.3 H I

We use H I data cubes from THINGS and VLA-ANGST to estimate the H I kinematics and kinetic energies of the sample. We use the same data processing as described in Chapter 3. To briefly summarize, we produce data cubes smoothed to 200 pc physical resolution using the AIPS task CONVL. We then regenerate masks by blanking noise-only regions and recalculate moment maps using the convolved cubes and associated masks. We note that the moment maps are generated from the flux-rescaled cubes, following Walter et al. (2008) and Ott et al. (2012). We use the 200 pc resolution data cubes and moment maps throughout the remainder of this paper.

5.3 Analysis

In this section, we describe the measurements we use to compare time-resolved SF to the properties of the neutral ISM. We first explain how we quantify both the H I energies in § 5.3.1 and the time-resolved SFH in § 5.3.2.

5.3.1 H I Energies

For all measurements of H I energies, we include only those pixels above a signal-to-noise ratio $S/N > 5$, where S/N is determined as the ratio between the maximum of the Gauss-Hermite polynomial fit to the line-of-sight spectrum of that pixel and the noise in a single channel, σ_{chan} . To generate a matched-aperture measurement, we only include pixels that are also in the aperture of the ANGST observations. The included pixels for each galaxy are those in Figure 5.1a that are within both the black ANGST footprints and the red $S/N > 5$ contours.

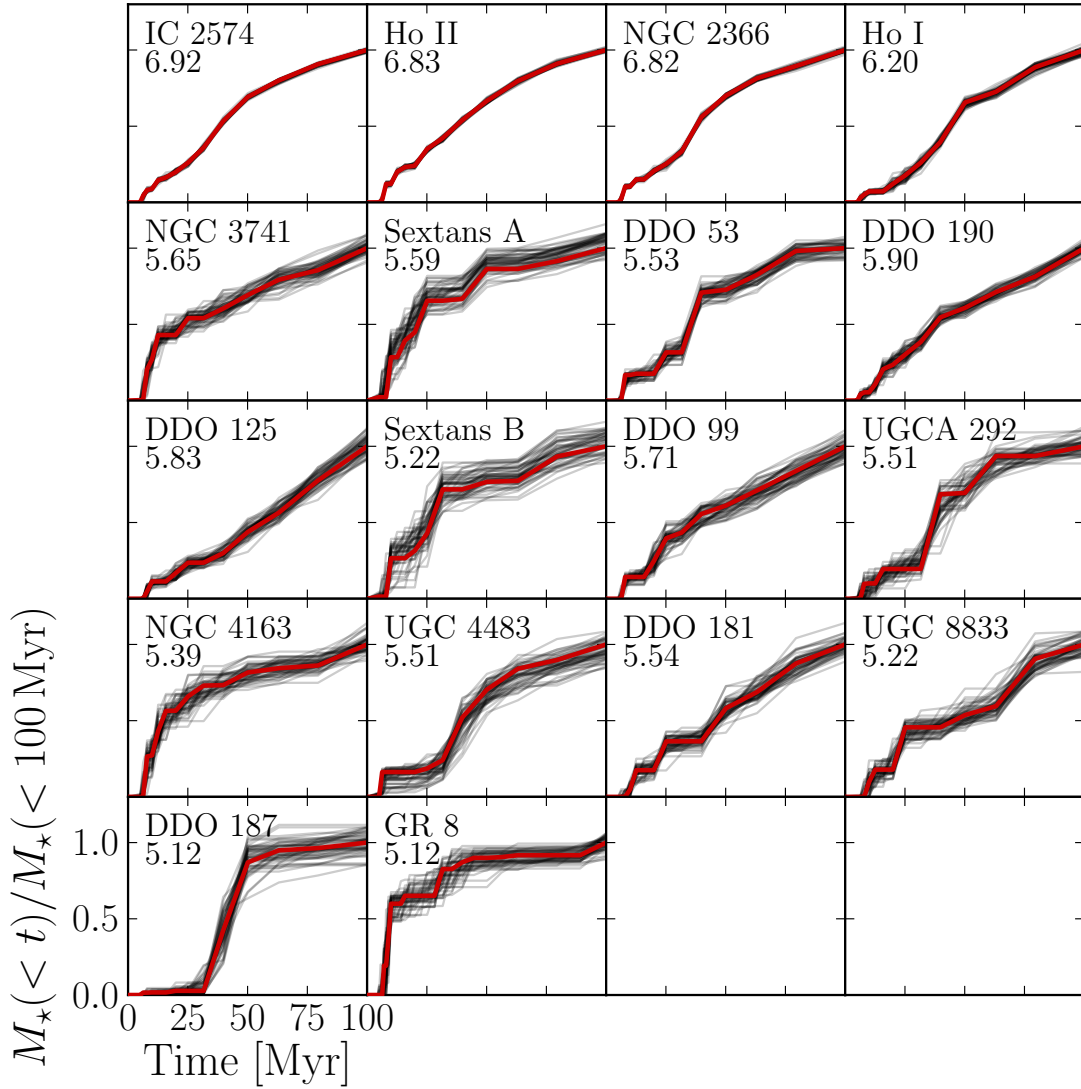


Figure 5.2 The cumulative number of stars formed, $M_*(< t)$, as a function of time for the sample. Each panel shows one galaxy. The best fit SFH to the CMD shown in red. The transparent black lines represent different Monte Carlo realizations of the SFH with appropriate uncertainties. The y-axis is normalized to $M_*(< 100 \text{ Myr})$ for all galaxies, and the MC runs are scaled to $M_*(< 100 \text{ Myr})$ of the best-fit SFH. The value of $\log M_*(< 100 \text{ Myr})$ is shown below the galaxy name, in units of $\log M_\odot$.

Our analysis is based on H I superprofiles using the methodology presented in Chapter 3, where we have removed the relative line-of-sight velocity (largely due to rotation) and co-added the resulting line-of-sight spectra to measure the integrated turbulent velocity structure with high signal-to-noise. To derive the superprofiles, we determine the velocity of the peak (v_{peak}) of the line-of-sight spectrum along each pixel, for all pixels also in the ANGST aperture. We then co-add these line-of-sight spectra after subtracting each pixel's v_{peak} to produce a flux-weighted average H I line profile. An example superprofile for Sextans A is shown in Figure 5.3. The superprofile itself is shown as the thick black line, and the uncertainty is shown as the grey shaded region around the superprofile.

We model the central peak of the superprofile with a Gaussian profile scaled to its half-width half-maximum (HWHM) and amplitude, and adopt the parameterization and physical interpretation presented in Chapter 3. Specifically, the Gaussian width that corresponds to the HWHM model yields σ_{central} and represents the average turbulent velocity of the H I. Gas with velocities above that expected from a Gaussian core is referred to as the “wings.” This anomalous gas is potentially due to expanding or asymmetric H I structures but may also be an inherent property of H I line profiles (e.g., Chapter 3).

We calculate f_{wings} , the fraction of gas moving faster than expected based on the HWHM Gaussian model, as

$$f_{\text{wings}} = \frac{\sum_{|v| > \text{HWHM}} [S(v) - G(v)]}{\sum_{|v| > 0} S(v)}. \quad (5.1)$$

In this equation, v is the velocity offset relative to the peak. $S(v)$ and $G(v)$ are the measured superprofile and HWHM Gaussian model, respectively. We represent the flux contributing to f_{wings} as the transparent shaded red region in Figure 5.3.

We also quantify the *rms* velocity of the excess H I in the wings:

$$\sigma_{\text{wings}}^2 = \frac{\sum_{|v| > \text{HWHM}} [S(v) - G(v)] v^2}{\sum_{|v| > \text{HWHM}} [S(v) - G(v)]}. \quad (5.2)$$

This parameter is proportional to the energy per unit mass in the wings of the superprofile.

In Figure 5.3, we show σ_{wings} as a solid vertical red line at $\pm\sigma_{\text{wings}}$.

For each galaxy, we also characterize the average line width of the H I width the average of the second moment value of the velocity, σ , which provides an estimate that is independent of the superprofile parameterization chosen above and that is widely used in the literature. This quantity makes no assumption about the underlying structure of H I emission (e.g., Tamburro et al., 2009). We use the second moment values of all included pixels to calculate a flux-weighted average second moment:

$$\langle\sigma_{\text{m2}}\rangle = \frac{\sum_i \sigma_i N_{\text{HI},i}}{\sum_i N_{\text{HI},i}}, \quad (5.3)$$

where $N_{\text{HI},i}$ is the column density of each pixel included in the average and σ_i is the second velocity moment of each line-of-sight spectrum. The flux weighting in this equation accounts for the fact that regions of high H I column density require more energy input compared to regions of low H I column density to produce the same line width.

We list the three H I velocities for the sample in Table 5.2, in order of decreasing $M_{\text{baryon,tot}}$. The columns are (1) galaxy name; (2) velocity resolution, Δv , (3) the number of independent resolution elements contributing to the superprofile, N_{beams} ; (4) the average H I surface density associated with the superprofile, $M_{\text{SP}}/A_{\text{HI}}$; (5) $\langle\sigma_{\text{m2}}\rangle$; (6) σ_{central} ; (7) σ_{wings} ; (8) f_{wings} .

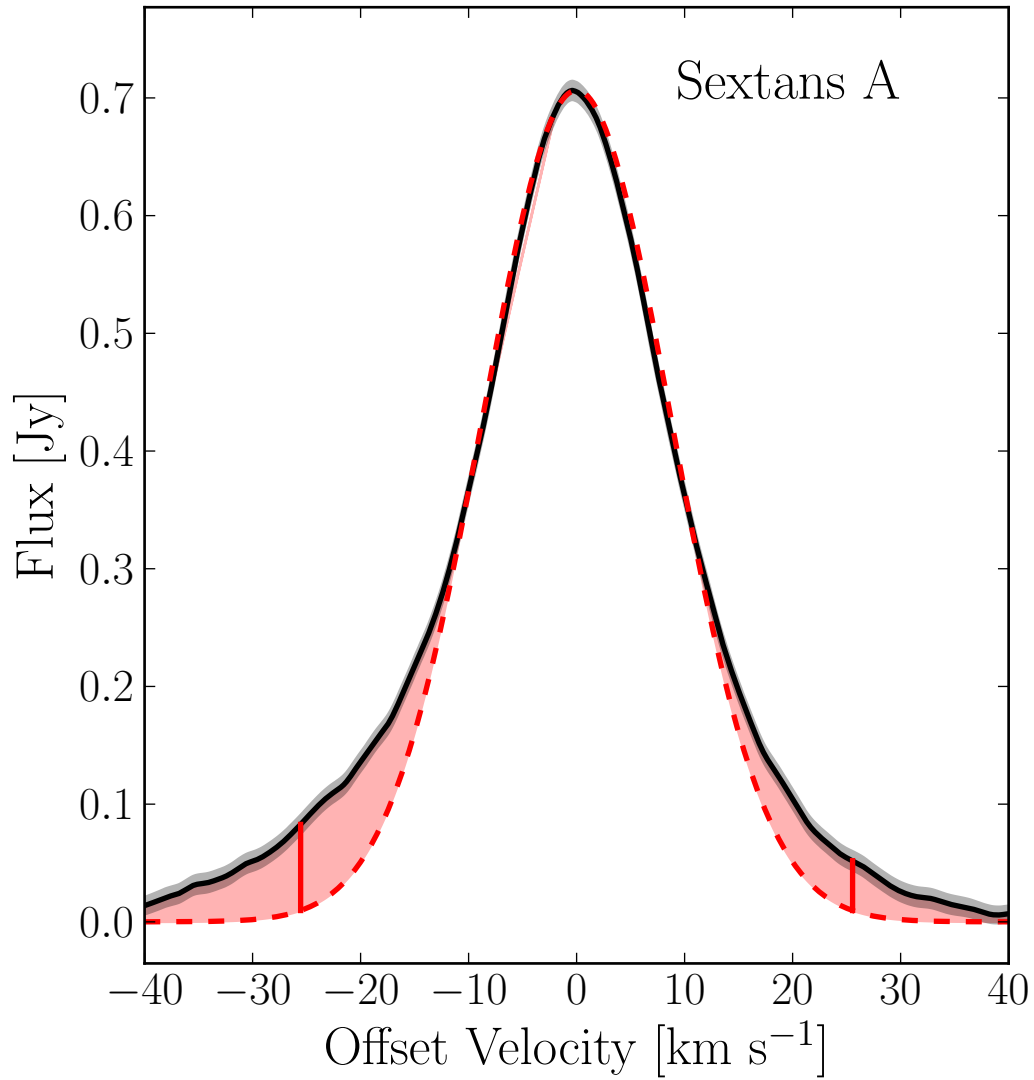


Figure 5.3 The superprofile for Sextans A in the ANGST FOV. The thick black line is the superprofile itself, with noise shown as the shaded grey region surrounding the superprofile. The thick dashed red line is the HWHM-scaled Gaussian model. The pink shaded region between the model and the superprofile represents f_{wings} , and the solid red vertical lines show $\pm \sigma_{\text{wings}}$.

Table 5.2: Sample parameters. Galaxies are listed in order of decreasing $M_{\text{baryon,tot}}$. (1) Galaxy name. (2) Velocity resolution. (3) N_{beams} of the superprofiles. (4) Average H I surface density of the superprofiles. (5) $\langle\sigma_{\text{m2}}\rangle$. (6) σ_{central} . (7) σ_{wings} . (8) f_{wings} .

1	2	3	4	5	6	7	8
Galaxy	Δv	N_{beams}	$\langle M_{\text{HI}}/A_{\text{HI}} \rangle$	$\langle\sigma_{\text{m2}}\rangle$	σ_{central}	σ_{wings}	f_{wings}
	(km s ⁻¹)		(M _⊙ pc ⁻²)	(km s ⁻¹)	(km s ⁻¹)	(km s ⁻¹)	
IC 2574	2.6	810	5.9	9.9 ± 1.7	7.6 ± 0.5	21.9 ± 0.7	0.12 ± 0.01
Ho II	2.6	281	7.3	10.4 ± 1.7	7.8 ± 0.6	23.7 ± 1.5	0.14 ± 0.01
NGC 2366	2.6	433	7.6	13.8 ± 2.0	10.3 ± 0.5	31.2 ± 0.9	0.13 ± 0.01
Ho I	2.6	152	9.6	8.8 ± 1.2	6.9 ± 0.6	21.3 ± 2.1	0.13 ± 0.02
NGC 3741	1.3	85	3.7	9.3 ± 1.6	7.4 ± 0.6	20.0 ± 2.4	0.12 ± 0.02
Sextans A	1.3	17	7.7	10.9 ± 2.3	8.7 ± 0.6	25.6 ± 1.9	0.14 ± 0.02
DDO 53	2.6	92	8.4	10.0 ± 1.3	8.2 ± 0.6	23.8 ± 1.6	0.11 ± 0.02
DDO 190	2.6	64	8.7	10.6 ± 1.2	9.1 ± 0.7	25.3 ± 2.6	0.07 ± 0.01
DDO 125	0.6	39	2.9	7.3 ± 0.7	6.1 ± 0.6	17.0 ± 2.7	0.15 ± 0.03
Sextans B	1.3	18	5.9	9.0 ± 1.0	7.8 ± 0.6	21.2 ± 1.9	0.10 ± 0.01
DDO 99	1.3	37	3.5	8.5 ± 1.4	7.1 ± 0.6	19.1 ± 2.0	0.11 ± 0.02
UGCA 292	0.6	45	13.3	8.6 ± 0.7	7.8 ± 0.6	20.3 ± 3.5	0.06 ± 0.02
NGC 4163	0.6	14	5.5	8.4 ± 0.6	7.7 ± 0.7	22.1 ± 3.0	0.09 ± 0.04
UGC 4483	2.6	43	7.0	10.1 ± 1.1	8.3 ± 0.6	23.8 ± 2.6	0.10 ± 0.02
DDO 181	1.3	46	4.0	8.1 ± 0.7	6.6 ± 0.6	19.9 ± 2.7	0.13 ± 0.03
UGC 8833	2.6	30	6.1	9.8 ± 1.1	8.0 ± 0.7	23.2 ± 2.8	0.11 ± 0.02
DDO 187	1.3	20	5.3	11.6 ± 1.5	10.6 ± 0.7	25.2 ± 3.2	0.09 ± 0.02
GR 8	0.6	15	4.7	8.0 ± 0.5	7.5 ± 0.6	20.0 ± 2.4	0.12 ± 0.03

We use three H I energy estimates for our analysis: one based on the central peak of the superprofiles (corresponding to σ_{central}), one based on the wings of the superprofiles (corresponding to σ_{wings}), and one based on the average second moment value for each galaxy (corresponding to $\langle\sigma_{\text{m2}}\rangle$). However, these velocities alone do not provide an ideal comparison

with energy input from SF, because regions with the same H I energy but different H I masses will also have different line widths. We therefore use the average energy in the superprofile peak, the superprofile wings, and the entire line profiles when comparing to SF.

We estimate the energy surface density in the central peak of the superprofile as:

$$\Sigma_{\text{E,central}} = \frac{3}{2} \frac{M_{\text{SP}}}{A_{\text{HI}}} (1 - f_{\text{wings}})(1 - f_{\text{cold}}) \sigma_{\text{central}}^2, \quad (5.4)$$

where $M_{\text{SP}}(1 - f_{\text{wings}})$ is the total H I mass contained in the central peak, and A_{HI} is the area covered by the H I. The $(1 - f_{\text{cold}})$ correction accounts for the mass of dynamically cold H I ($\sigma < 6 \text{ km s}^{-1}$), which has kinematics that are not well-described by σ_{central} . While the fraction of cold H I is very uncertain in dwarfs, we choose $f_{\text{cold}} = 0.15$, a value in line with previous estimates of f_{cold} in dwarf galaxies (between 1 – 20%; Young et al., 2003; Bolatto et al., 2011; Warren et al., 2012). The contribution of cold H I gas to the superprofile may account for the fact that the central peaks are narrower than the HWHM Gaussian model. The 3/2 factor accounts for motion in all three directions, assuming an isotropic velocity dispersion.

Second, we estimate the energy surface density in the wings of the superprofile as:

$$\Sigma_{\text{E,wings}} = \frac{3}{2} \frac{M_{\text{SP}}}{A_{\text{HI}}} f_{\text{wings}} \sigma_{\text{wings}}^2. \quad (5.5)$$

Here, $(M_{\text{SP}}/A_{\text{HI}}) \times f_{\text{wings}}$ represents the total H I surface density associated with the wings of the superprofile.

Finally, we estimate the average energy surface density of the entire line-of-sight profiles as:

$$\Sigma_{\text{E,m2}} = \frac{3}{2} \frac{M_{\text{SP}}}{A_{\text{HI}}} \sigma_{\text{m2}}^2, \quad (5.6)$$

where $M_{\text{SP}}/A_{\text{HI}}$ is the average H I surface density of the superprofile. This estimate accounts for the energy in the full line profile and is independent of parameterization, and essentially combines the energies in Equations 5.4 and 5.5.

5.3.2 SFH Measurements

Next, we measure the time-resolved SF rates. We use the ANGST SFHs to calculate the average SF rate between times t_i and t_f :

$$\text{SFR}(t_i \rightarrow t_f) = \frac{M_\star(< t_f) - M_\star(< t_i)}{t_f - t_i}, \quad (5.7)$$

where $M_\star(< t)$ is the total stellar mass formed between now and a time t in the past, within the ANGST aperture. Note that t_i and t_f are the initial and final times in an integration going back in time, where the present is defined as $t = 0$ and *not* the initial and final times of a SF event. When calculating $\text{SFR}(t_i \rightarrow t_f)$ for time ranges that fall in between bins, we linearly interpolate across the bins. This interpolation has a larger effect at times further in the past because the input time bins are uniformly spaced in logarithmic time with $\Delta \log_{10}(t/\text{Myr}) = 0.1$. We adopt a time step of 10 Myr, a value that is well-matched to the theoretically dissipation timescale of turbulence in the ISM (Mac Low, 1999). However, our results do not change if we instead use the intrinsic logarithmic time bins instead of the 10 Myr linear bins.

From $\text{SFR}(t_i \rightarrow t_f)$, we can calculate the SF rate surface density over that time range, $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$. For this measurement, we divide $\text{SFR}(t_i \rightarrow t_f)$ by A_{HI} , corrected for galaxy inclination. Some of the dwarf galaxies are smaller than the ANGST aperture, but in these cases the SF is primarily contained in the same regions as the H I.

5.4 Comparing H I Energy to Time-Resolved SF

In this section, we compare the H I energies to the time-resolved Σ_{SFR} values. If the H I turbulent energy is supplied by SF, then we would expect to see a correlation between Σ_{SFR} and at least one measure of H I kinetic energy. However, the correlation may depend on the time interval being considered. We can only measure the H I kinematics at the present time, but the relevant SF energy driving the turbulence is not necessarily from the most recent SF. Instead, the timescale for energy input may reflect the variations in the SFR with time, the numbers and masses of evolving stars at each time, and the timescale for SNe and stellar winds to couple to the neutral ISM. A strong correlation between H I energy and SF

at a specific timescale would support the idea that SF and H I kinematics are coupled on that timescale.

In § 5.4.1 we discuss our method for measuring correlations and deriving the associated uncertainties. In § 5.4.2, we examine correlations in the mean Σ_{SFR} measured between now (i.e., $t_i = 0$) and several t_f values. In § 5.4.3, we search for correlations between all possible pairs of t_i and t_f between now and 100 Myr in the past.

5.4.1 The Spearman Correlation Coefficient r_s and Associated Uncertainties

We measure the degree of correlation between H I kinetic energy and SFR on a given timescale using the Spearman rank correlation coefficient, r_s . This statistic tests only for a monotonic relationship between the two input data sets. The statistic yields $r_s > 0$ for a positive correlation, $r_s = 0$ for completely uncorrelated data, and $r_s < 0$ for an anticorrelation. The probability of finding an r_s value equal to or more extreme than measured from a random data set is given by p_s .

To interpret the significance of r_s , we must have a reliable estimate of the associated uncertainties. There are two sources of uncertainty on the measured r_s values. First, uncertainties in the data themselves can propagate to uncertainties in r_s . Second, the small number of galaxies in this study may not adequately sample the parameter space, potentially skewing r_s values. In this section, we assess the uncertainty due to each of these factors.

We first estimate the uncertainties on r_s due to uncertainties in the data themselves. For the H I $\langle\sigma_{\text{m}2}\rangle$ value, we adopt as the uncertainty the flux-weighted standard deviation of the moment 2 values for the included pixels. For the H I kinematic measurements, we approximate the uncertainties on the measured superprofile parameters based on the noise on each point, given by:

$$\sigma_{\text{SP}} = \sigma_{\text{chan}} \times \sqrt{N_{\text{pix}}/N_{\text{pix/beam}}} \times \frac{F_{\text{rescaled}}}{F_{\text{standard}}}, \quad (5.8)$$

where σ_{chan} is the *rms* noise in a single channel; N_{pix} is the number of channels contributing to a superprofile point, and $N_{\text{pix/beam}}$ is the number of pixels per resolution element; and $F_{\text{rescaled}}/F_{\text{standard}}$ the flux ratio between the total measured flux in the superprofile generated from the flux-rescaled cube to that from the standard cube. These uncertainties are

explained in more detail in Chapter 3. We assume that the observed superprofile is correct, and add Gaussian noise to each point based on Equation 5.8. We then calculate “noisy” parameters for this measurement. After repeating this process 1,000 times, we have determined the allowed distribution of superprofile parameters due to noise. We fit a Gaussian to each parameter’s distribution of noisy values and adopt its 1σ width as the uncertainty on that parameter. We also include systematic uncertainties on the parameters based on finite velocity resolution, as described in detail in Chapter 3. The uncertainties on the H I parameters are given in Table 5.2.

Uncertainties in the SFHs are more complicated, as neighboring time bins are correlated. A burst of SF in one bin could actually have occurred in an adjacent time bin. These uncertainties are accounted for in the Monte Carlo realizations shown in Figure 5.2.

We determine the uncertainties on r_s due to parameter uncertainties with a series of 1,000 realizations of our sample. For each realization, we add an offset to each H I kinematic parameter drawn from a Gaussian distribution with that parameter’s uncertainty as the Gaussian standard deviation. For each galaxy, we calculate $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ from a randomly-chosen Monte Carlo instance of the SFH (black lines in Figure 5.2; see § 5.2.2), instead of the best-fit SFH. We then calculate the r_s value using the “noisy” H I kinematic parameters and $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ from the random Monte Carlo SFH. We then adopt the inner 68% of all allowed r_s values as the uncertainty in r_s due to parameter uncertainties.

Second, the small number of points can affect r_s values if they are not adequately sampling the underlying distribution. We account for this uncertainty using bootstrapping. We randomly draw a new sample of the same size as our original sample, allowing repeats, and calculate r_s for the best-fit SFHs and parameters of the resample. Repeating this procedure gives us a range of r_s values that are statistically allowed by the sample size. As above, we adopt the inner 68% of this range as the uncertainty in the r_s values.

The bootstrapped uncertainties in r_s due to the small sample size are typically larger than those due to uncertainties in the data. For the rest of the paper, we assess the significance of measured r_s values using both uncertainty estimates individually.

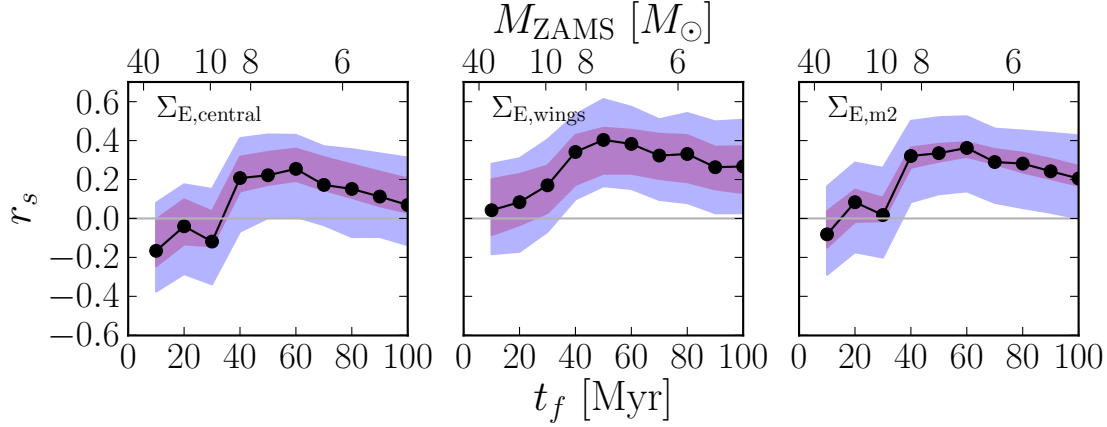


Figure 5.4 Correlation coefficients (r_s) between H I energy and $\Sigma_{\text{SFR}}(0 \rightarrow t_f)$ for the entire sample. We consider H I energy in the central peak of the superprofiles (left panel), in the wings (right panel), and in the full line profiles (right panel). The black points show the observed correlations data between the superprofiles and the best-fit SFHs averaged on timescales between $0 - t_f$. The shaded red and blue regions indicate the allowed range in r_s from data uncertainties and bootstrapping. We do not see positive correlations between Σ_{SFR} and H I energy until we include SF ~ 40 Myr in the past.

5.4.2 Correlations between H I Energy and Mean SFR

We start by comparing H I energetics to SF surface density between now and some time t_f in the past, $\Sigma_{\text{SFR}}(0 \rightarrow t_f)$, for t between $10 - 100$ Myr in 10 Myr steps. For each t_f step, we calculate r_s between $\Sigma_{\text{SFR}}(0 \rightarrow t)$ and each H I energy parameter. We then compare these correlation coefficients as a function of t_f to identify the timescales for which the current energetics of the H I gas are most coupled to SF. We also calculate the uncertainties on r_s for each t_f step based on the procedures described in § 5.4.1.

In Figure 5.4, we show the correlation coefficients between the three H I energy parameters ($\Sigma_{\text{E,central}}$, $\Sigma_{\text{E,wings}}$, and $\Sigma_{\text{E,m2}}$) and the integrated $\Sigma_{\text{SFR}}(0 \rightarrow t_f)$ from the present to a lookback time t_f . The black points represent correlations with the best-fit SFH, and the red and blue shaded regions indicate the allowed ranges in r_s due to the data uncertainties and bootstrapping, respectively.

We find that the H I energies do not show significant correlations with the recent SFR ($t \leq 30$ Myr). Even at $t_f \sim 40$ Myr, the correlation coefficients for the sample size are low

($r_s \lesssim 0.3$), implying that there is a $\sim 20\%$ chance of drawing this sample from a random sample (i.e., $p_s \sim 0.2$).

5.4.3 Correlations between H I Energy and SF on Arbitrary Timescales

The method used in § 5.4.2 assumes that all SF between t_f and the present time affects the ISM. However, the energy input from a SF burst is not necessarily constant or instantaneous. Instead, the majority of energy is released some time after the SF burst actually occurs (e.g., Leitherer et al., 1999), when massive stars end their lives in SNe. Furthermore, the neutral ISM may not show effects from SF until some time after the burst, due not only to this lag but also to a potential delay in converting the localized mechanical SF energy to global turbulent energy in the neutral ISM.. To address this issue, we compare the H I energies with $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ for a range of t_i and t_f values, and generate an r_s value and associated uncertainties for each combination.

In Figure 5.5, we first show the variation in $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ for different values of t_i and t_f for two sample galaxies. The upper panels show the total SFR in the ANGST aperture, binned in 10 Myr intervals. The lower panels show $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$, where the y -axis shows the initial time t_i , the x -axis shows the final time t_f , and the greyscale in each panel indicates the SF surface density of the given time interval associated with that pixel. Along the top and right axes, we have also shown the zero-age main sequence mass of the star whose lifetime corresponds to t_i and t_f (M_{ZAMS}), using models from Marigo et al. (2008); Girardi et al. (2010). Thus, above the one-to-one line is forbidden, and the boxes along the one-to-one line represents the shortest time interval. The color of each box represents $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ for the t_i and t_f corresponding to that box's position, for t_i and t_f between 0 and 100 Myr in 10 Myr steps. It is clear that short bursts of SF can be smoothed out in larger $t_i \rightarrow t_f$ ranges, and in some cases, the average SFR can change by a factor of 10 based on the timescale considered.

We now consider the correlations in the entire sample between H I kinetic energies and Σ_{SFR} , averaged over the $t_i \rightarrow t_f$ ranges shown in Figure 5.5. For each $t_i \rightarrow t_f$ range, we calculate $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ for each galaxy, and calculate the r_s value between $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$

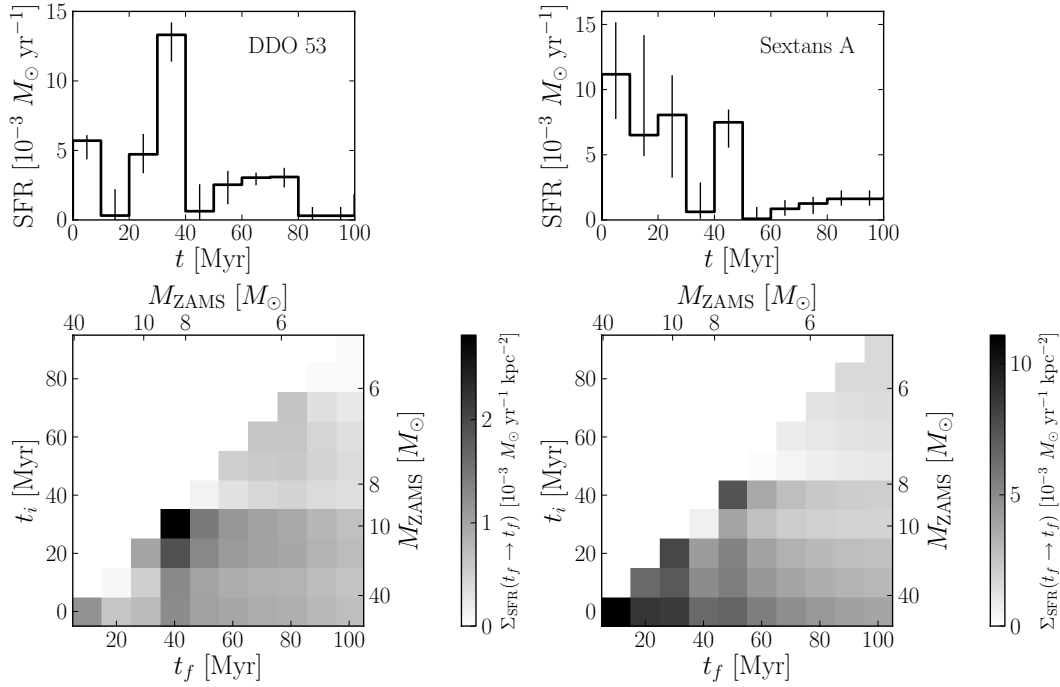


Figure 5.5 Mean $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ averaged over various t_i and t_f for two sample galaxies (DDO 53, left panels; Sextans A, right panels). The upper panels show the total SFR measured in the ANGST aperture, averaged in 10 Myr time bins, with error bars derived from the MC realizations of the SFH. The lower panels show the effects of averaging the measured Σ_{SFR} from ANGST in different time ranges between t_i and t_f . The y -axis shows t_i , and the x -axis shows t_f . The color of each box at a given t_i and t_f value represents $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$. The boxes along the diagonal line are an alternative representation of the SFRs shown in the upper panels, after normalization by area (i.e., Σ_{SFR} instead of SFR). Large, short bursts of SF are smeared out as the $t_i \rightarrow t_f$ becomes larger.

and the H I energy surface densities for the entire sample.

In the upper row of Figure 5.6, we present the correlation coefficients between $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ and $\Sigma_{\text{E,central}}$ (right panels), $\Sigma_{\text{E,wings}}$ (middle panels), and $\Sigma_{\text{E,m2}}$ (left panels). As for Figure 5, each bin represents a specific time interval defined by t_i and t_f , and the color coding indicates the sign and strength of the correlation. The lower two rows of Figure 5.6 show the significance of the correlation coefficients in the upper row, based on bootstrapping and data uncertainties. In general, the bootstrap uncertainties provide more stringent limits on the significance of measured r_s values.

We find significant correlations between H I energy surface density and Σ_{SFR} over time-scales that include SF between 30 – 60 Myr. The H I energy in the central peak is most strongly correlated with Σ_{SFR} at $t \sim 30 - 40$ Myr, while the energy in the wings is most correlated at slightly later times ($t \sim 30 - 60$ Myr). As expected, the correlation coefficients between $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ and $\Sigma_{\text{E,m2}}$ are a combination of those with $\Sigma_{\text{E,central}}$ and $\Sigma_{\text{E,wings}}$. We also note that there are no significant correlations when only SF older than 40 Myr is included.

We also find correlations with time ranges that include the 30 – 40 Myr time bin but cover a longer time range (i.e., the bins to the lower right of the 30 – 40 Myr bins). It is likely that these correlations are primarily due to a correlation with the 30 – 40 Myr bin alone. To test this idea, we generate random SFHs for each galaxy with the same median SFR as measured within the past 100 Myr and with Gaussian fluctuations based on the standard deviation of the SFR for each galaxy. We then set the SFR between 30 – 40 Myr to its actual value for each galaxy, which allows us to test whether the underlying correlation at 30 – 40 Myr is responsible for the observed correlations with time ranges that include the 30 – 40 Myr interval. We then calculate the correlation coefficients as for the real data.

In Figure 5.7, we plot the average r_s values between H I energy surface density and $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ for 20 randomly-generated SFHs with the imposed correlation at 30 – 40 Myr. The correlation coefficients for bins that include the 30 – 40 Myr bin still appear correlated due to the imposed correlation at 30 – 40 Myr even though the SFRs in other time ranges were randomly-generated, while time bins that do not include the 30 – 40 Myr period are completely uncorrelated. The sharp edges in Figure 5.6 are most likely due to

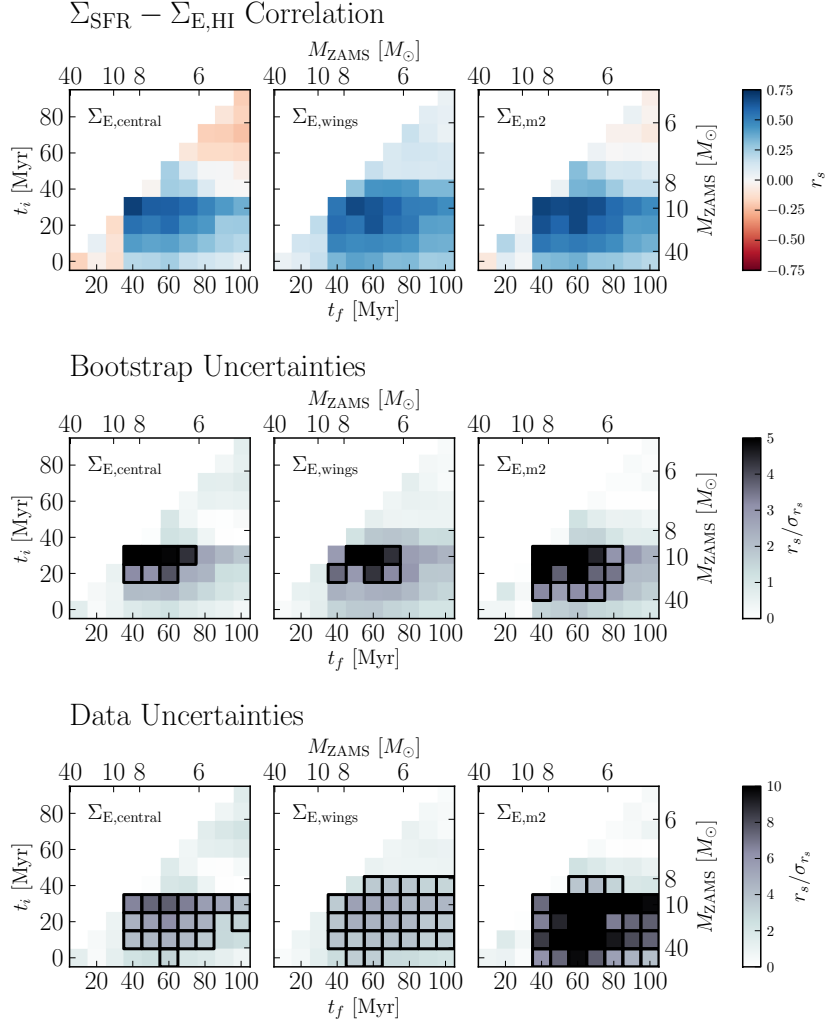


Figure 5.6 Correlation coefficients r_s and associated uncertainties between $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ and H I energy surface densities for $\Sigma_{\text{E,central}}$, $\Sigma_{\text{E,wings}}$, and $\Sigma_{\text{E,m2}}$ for the entire sample. The upper panel shows the r_s values themselves, with the x -axis representing t_i values and the y -axis representing t_f values. We have shown the masses of stars whose ages correspond to the t_i and t_f values (M_{ZAMS}) on the upper and right axes. The color of a single box represents the r_s value between that H I energy surface density and $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ for the entire sample. Blue indicates a positive correlation ($r_s > 0$), red indicates a negative correlation ($r_s < 0$), and white indicates no correlation ($r_s = 0$). The lower two rows show the significance (r_s/σ_{r_s}) of the correlation coefficients in the upper panel due to bootstrapping and data uncertainties, with darker colors indicating more significant correlations. We have outlined boxes with $r_s/\sigma_{r_s} > 3$ in black. We find significant correlations between H I energy surface density and $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ on timescales of $\sim 30 - 60$ Myr.

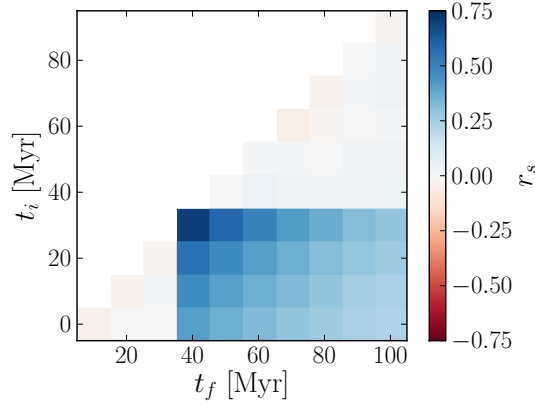


Figure 5.7 Mean Spearman correlation coefficients between the observed $\Sigma_{\text{E,central}}$ and SFHs generated randomly except between 30–40 Myr, where we have set the SFR to the observed SFR. The sharp edges seen at $t_i < 30$ Myr and $t_f > 40$ Myr are solely an artifact of the correlation with SF between 30 – 40 Myr.

this effect. The correlations for $\Sigma_{\text{E,wings}}$ do not show as sharp edges, suggesting that a wider range of time bins contributing to driving the kinematics of the wings.

To test if there are any correlations that remain when SF between 30 – 40 Myr ago is excluded, we artificially set the SFR between 30–40 Myr to 0 and re-calculate the correlation coefficients. The results of this test are shown in Figure 5.8. The positive correlations with other time ranges that include the 30 – 40 Myr range no longer exist, indicating that the SF between 30 – 40 Myr is the main correlation. For $\Sigma_{\text{E,central}}$, the correlations are gone entirely. For $\Sigma_{\text{E,wings}}$, there are still hints of correlations, also suggesting that the wing kinematics also include input from SF 40 – 60 Myr ago.

To illustrate the improvement that time-resolved SFHs provide, we plot $\Sigma_{\text{E,central}}$ versus both $\Sigma_{\text{SFR}}(30 \rightarrow 40 \text{ Myr})$, measured with using ANGST SFHs, and Σ_{SFR} , measured with FUV+24 μm emission in the ANGST aperture in Figure 5.9. We show Σ_{SFR} derived from ANGST SFHs as the filled black circles, and that derived from FUV+24 μm emission as open black circles. We have followed the procedure outlined in Chapter 3 to calculate FUV+24 μm SFRs; as with the other measurements, we include only pixels in the ANGST aperture for this calculation. The r_s value for Σ_{SFR} derived from ANGST SFHs is $r_s = 0.71$ ($p_s = 0.001$), but drops to 0.30 ($p_s = 0.233$) for Σ_{SFR} derived from FUV+24 μm emission.

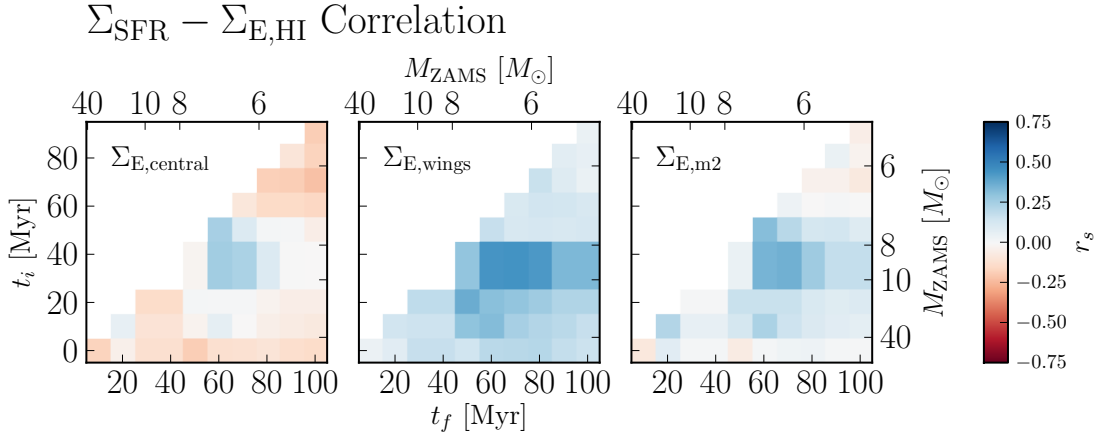


Figure 5.8 The correlation coefficients when SF between 30–40 Myr ago is ignored. The layout of the figure is the same as the upper panel of Figure 5.6. The strong correlations with longer time ranges that include the 30 – 40 Myr time range no longer exist.

The underlying correlation with $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$ using the ANGST SFHs is when Σ_{SFR} is measured with FUV+24 μm .

5.5 Discussion

Now that we have assessed the timescales over which HI energy surface density is most strongly correlated with $\Sigma_{\text{SFR}}(t_i \rightarrow t_f)$, we can discuss the physical causes behind the correlations. In § 5.4, we found that the average turbulent HI energy surface density, traced by $\Sigma_{\text{E,central}}$, shows a strong correlation with Σ_{SFR} at $t \sim 30 - 40$ Myr, suggesting that the neutral ISM is most affected by SF that occurred approximately 30 – 40 Myr in the past. The lack of any correlation with SF younger than 30 Myr or older than 40 Myr likewise suggests that younger or older SF has no significant coupling to the ISM. The energy in the wings is more strongly correlated with SF $\sim 30 - 60$ Myr in the past. This may suggest a longer coupling timescale for kinematic motions in the wings compared to the central peak, but the difference in correlation coefficients compared to the 30 – 40 Myr timescale is not large.

We focus primarily on the correlation between the Σ_{SFR} and the HI energy surface density of the central peak for the remainder of this section. In § 5.5.2, we explore what

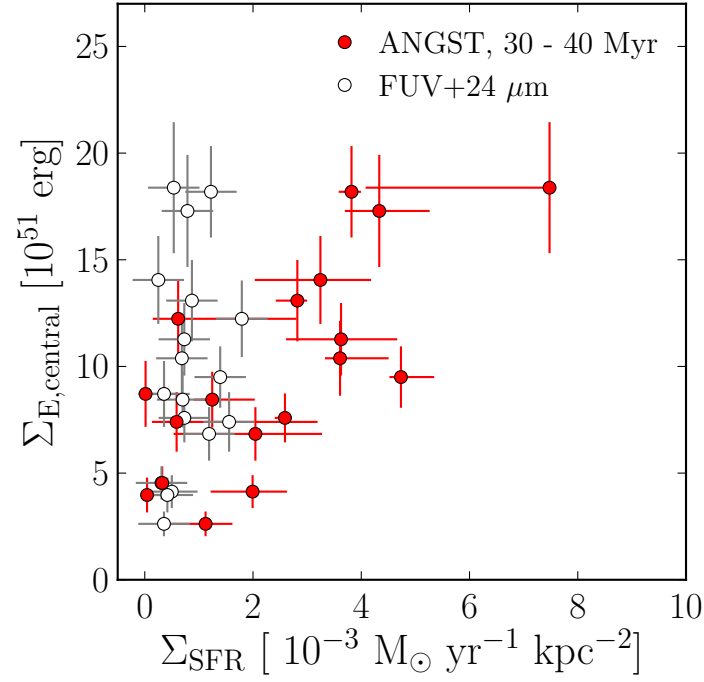


Figure 5.9 The correlation between $\Sigma_{E,central}$ and both $\Sigma_{SFR}(30 \rightarrow 40 \text{ Myr})$, measured with ANGST SFHs, and Σ_{SFR} , measured with FUV+24 μm . The correlation is robust when SF is measured with ANGST SFHs, but disappears when FUV+24 μm emission is used as a SFR tracer.

physical processes could be responsible for this timescale. In § 5.5.1, we investigate the implied efficiencies of coupling SF energy to H I energy in light of the observed correlation.

5.5.1 SF Processes on the 30-40 Myr Timescale

The 30–40 Myr timescale is similar to the lifetime of an $8 M_{\odot}$ star (e.g., Girardi et al., 1996, 2000; Prialnik, 2009), which is approximately the observationally-determined minimum mass of Type II SNe progenitors (Smartt, 2009; Jennings et al., 2012). Due to the steepness of the initial mass function (IMF), the majority of SNe progenitors are $\sim 8 M_{\odot}$. These SNe, from lower-mass progenitors, are traditionally thought to release approximately the same amount of mechanical energy into the ISM as their higher mass counterparts. We therefore might expect that the energy input rate increases with the age of SF burst, as more populous lower-mass progenitors from older SF undergo SNe, up until the time when the stars that can contribute to turbulent energy are too low mass to undergo SNe. However, this naive assumption is complicated by the fact that the relationship between progenitor mass and lifetime is not linear, such that a wider mass range contributes to a given time bin for high mass stars at recent times.

We can compare these two effects as follows. We estimate the rate at which energy is input into the ISM due to an instantaneous burst of SF by comparing the IMF to the lifetime of massive stars, following Shull & Saken (1995). If each SNe emits $E_{51} \equiv 10^{51}$ ergs, the energy input rate due to SNe is given by:

$$\frac{dE_{\text{SN}}}{dt} = E_{51} \frac{d}{dt} N_{\text{SN}}(t), \quad (5.9)$$

where $N_{\text{SN}}(t)$ is number of supernova as a function of time. We can represent dN_{SN}/dt as $[dN/dm][dm/dt]$. The (dN/dm) factor is simply the IMF, which can be written as $(dN/dm) \propto m^{-\alpha}$. To first order, we can also assume that the lifetime of a star, (dm/dt) , is also given by a power law, where $t \propto m^{-\tau}$. Equation 5.9 can therefore be written as:

$$\frac{dE_{\text{SN}}}{dt} \propto \frac{d}{dt} t^{(\alpha-1)/\tau} \propto t^{[(\alpha-1)/\tau]-1}. \quad (5.10)$$

If we adopt $\alpha = 2.3$ for the upper end of the IMF (e.g., Kroupa, 2001) and $\tau = 2.6$ for the mass-lifetime relationship of massive stars (e.g., Prialnik, 2009), we find that $dE/dt \propto t^{-0.5}$,

a scaling similar to that found in STARBURST99 (where $dE/dt \propto t^{-0.45}$; Leitherer et al., 1999). The inverse scaling between dE/dt and t implies that the majority of the energy is released shortly after the burst, contrary to what we might have expected based on only the IMF. Even though the most massive stars are the least populous, the spread in their ages is very small compared to the lower mass SNe progenitors. To produce an energy input rate that increases with time, we would need to either increase the slope of the IMF (α) or decrease the slope of the mass-lifetime relationship for massive stars (τ), such that $(\alpha - 1)/\tau - 1 > 0$. Literature estimates of α range from $\sim 1.5 - 4$, but many of the measurements also have large uncertainties (Weisz et al., 2013, and references therein). For τ to remain the same and still produce dE/dt that increases with time, α must increase to > 3.6 , a value well outside the weighted mean of $\langle\alpha\rangle = 2.46 \pm 0.35$ for the literature values quoted in Weisz et al. (2013). On the other hand, recent results from Jennings et al. (2012) for SN progenitors find that their data are inconsistent with α values outside the range $2.7 - 4.4$. The Jennings et al. (2012) study also finds fewer massive progenitors than expected, which may could help mitigate this mismatch but is unlikely to fully solve it. Second, if α were fixed to 2.3, τ must decrease to < 1.3 , which defies all that is known about stellar evolution. It is unlikely that we could find α and τ values that conspire to produce a dE/dt relationship that increases back to 30 – 40 Myr ago.

If we do not assume that the energy of an individual supernova is fixed, and instead is related mass as $E \propto m^{-\xi}$, we derive a scaling relation given by:

$$\frac{dE_{\text{SN}}}{dt} \propto t^{[(\alpha+\xi-1)/\tau]-1}. \quad (5.11)$$

For the total SNe energy input rate to increase with time, given the above values of $\tau = 2.6$ and $\alpha = 2.3$, we find that $\xi > 2.3$, or $E_{\text{SN}} \propto m^{-2.3}$, which implies a rather unrealistic scaling. Recent research indicates that the supernova energy may increase with increasing mass (Janka, 2012), which is the opposite behavior required to produce a peak energy release rate at later times.

The scaling relation in Equation 5.10 implicitly assumes that the IMF is well-sampled, which only occurs when a large number of stars are formed. In the low-mass, low-SFR regime of our sample, however, the high-mass end of the IMF is sampled stochastically,

so the statistical approach presented by Equation 5.10 does not necessarily apply to our sample. Many of the traditional methods for estimating luminosity, spectra, and energy input from SF assume a well-sampled IMF and therefore do not account for stochasticity (e.g., STARBURST99, Leitherer et al. (1999); GALEV, Kotulla et al. (2009)). Recently, studies have begun to characterize the effects of stochastically sampling the IMF, especially at the low SFRs representative of our sample (e.g., Lee et al., 2009; Weisz et al., 2012; da Silva et al., 2012). The effects of stochasticity on the output SF energy are complicated, especially when considering time-resolved SFHs, and can only be ignored for $\text{SFR} \gg 10^{-2} \text{ M}_{\odot} \text{ yr}^{-1}$ (da Silva et al., 2012), but we can estimate its effects to first order by considering the median lifetime of SNe progenitors in stellar clusters of a given total mass. For each cluster, we draw N stars from an IMF with $\alpha = 2.3$ such that the total mass of the cluster is within 10% of the desired mass, assuming an instantaneous burst. We then calculate the median time after the burst that SNe exploded, using the mass-lifetime relationship above (i.e., $t \propto m^{-2.6}$), and then find the median time after the burst for all the SNe in the cluster.

In Figure 5.10, we plot the histograms of the median age of SNe for 100 multiple realizations of clusters of a given mass. The dashed vertical line in each panel represents the expected median SN progenitor lifetime for a well-sampled IMF. For clusters of $M_{\text{cluster}} = 10^5 \text{ M}_{\odot}$, the lifetime of the median SN progenitor approaches the expected value for a well-sampled IMF. At lower total masses (i.e., $M_{\text{cluster}} = 10^2 - 10^3 \text{ M}_{\odot}$), the median SN progenitor lifetime is not well-defined and depends on random sampling of the IMF. We note that this is a simplistic model for stochasticity in these galaxies, but it provides a back-of-the-envelope estimation of whether stochasticity is important for the sample.

We can compare these masses to the average mass in stars formed by the sample galaxies over a 10 Myr time period. The lowest-mass galaxies have an average SFR over the past 100 Myr of $\sim 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1}$, implying that they form on average $\sim 10^4 \text{ M}_{\odot}$ over 10 Myr. If all the SF over the 10 Myr interval were concentrated in one burst, Figure 5.10 indicates that stochasticity is not important even for the lowest-mass dwarfs. However, it is more likely that SF has been occurred in individual clusters, each with a lower mass. When the cluster mass function is also taken into account, da Silva et al. (2012) estimate that stochastic effects are negligible only for $\text{SFR} \gg 10^{-2} \text{ M}_{\odot} \text{ yr}^{-1}$, a condition that is not met

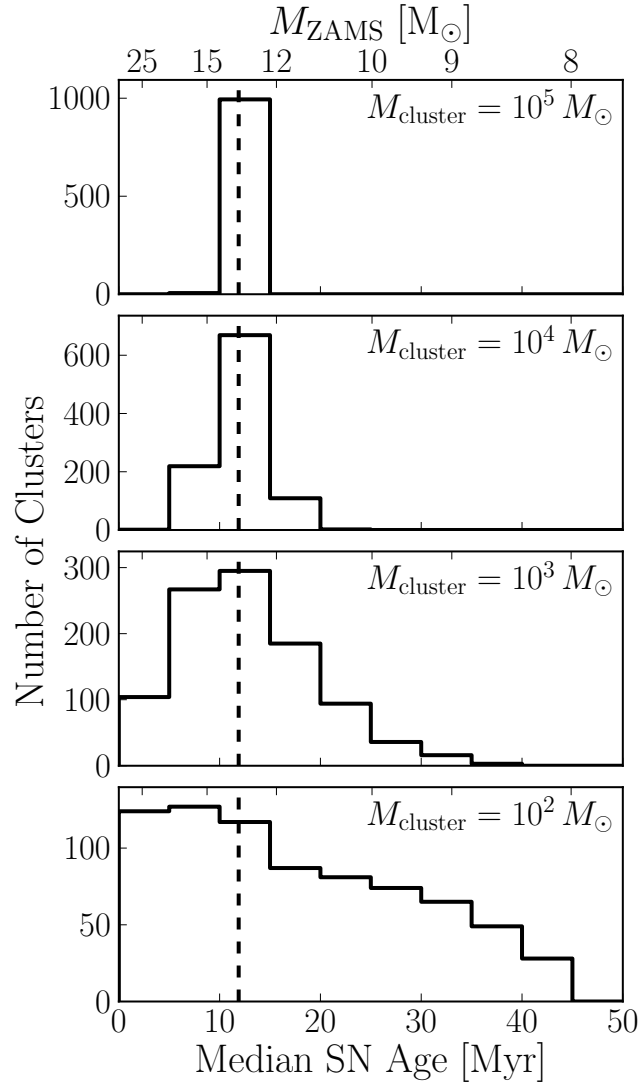


Figure 5.10 Effects of stochasticity on the median lifetime of SN progenitors in clusters of different masses. Each panel shows the histogram of median SN progenitor lifetimes for clusters of the same mass, with mass decreasing in lower panels. The dashed vertical line represents the expected median SN progenitor lifetime for a well-sampled IMF. Clusters of $M_{\text{cluster}} = 10^5 M_{\odot}$ typically approach the expected median age, but stochasticity becomes increasingly important for clusters of $M_{\text{cluster}} \sim 10^2 - 10^3 M_{\odot}$. We have overlaid the approximate M_{ZAMS} corresponding to the median SN progenitor lifetime, assuming that $t \propto m^{-2.6}$.

by any galaxy in our sample.

The observed correlation with the 30 – 40 Myr timescale is the time between when stars form and when those stars leave an observable signature in the turbulence of the neutral ISM. However, that cycle consists of several steps: the timescale for SF to inject energy into the local environment, and timescale for that local energy input to be transferred into the larger reserve of the neutral medium. We now estimate each of these timescales. The first timescale describes the timescale for the peak energy release rate from SF, assuming a well-sampled IMF. However, this energy is released in powerful SNe, which shock heat the surrounding ISM, and may not be immediately observable as HI turbulence. The second timescale is related to the propagation of supernova remnants (SNR) through the ISM. A lower limit for the second timescale is the time for an individual SNR to merge with the ISM, approximately ~ 5 Myr (Cioffi et al., 1988). Similar behavior is also seen in the semi-analytic models by Braun & Schmidt (2012), where the ISM cools to pre-SF conditions ~ 5 Myr after the last SN progenitor. The back-of-the-envelope relationship between SF and HI energy should therefore be only ~ 15 Myr for SF regions that adequately sample the high-mass end of the ISM. On the other hand, X-ray observations of dwarf starburst galaxies indicate that the cooling timescale of hot gas ranges between $\sim 10 - 200$ Myr, though the results depend on the filling factor of this phase (Ott et al., 2005). Our results are consistent with SN-driven turbulence if the cooling timescale is $\sim 20 - 30$ Myr in these systems. However, it is unclear how to translate the simulations of individual SNRs or feedback in the case of a well-sampled IMF to the stochastic SF in our sample.

Because the timescale for peak energy input from SNe is not necessarily well-matched to the observed 30 – 40 Myr correlation, we also briefly consider the idea that HI line widths are powered by some other stellar mechanism where energy input occurs at later than SNe. Other proposed stellar sources of energy are stellar winds (e.g., Abbott, 1982; van Buren, 1985) and ionizing radiation (e.g., Kritsuk & Norman, 2002b,a). In dwarfs, simulations by Hopkins et al. (2012) show that radiation pressure from stellar winds has very little effect compared to SNe on the surrounding ISM due to low gas densities and metallicities. Mac Low & Klessen (2004) also estimate the energy input due to stellar winds, and suggest that a substantial energy input is seen only from the most massive Wolf-Rayet stars, which have

a much shorter lifetime than the timescale for peak energy input from SNe. In addition, winds from AGB stars typically have small wind velocities ($\ll 100 \text{ km s}^{-1}$; e.g., Knapp & Morris, 1985; Loup et al., 1993) and therefore cannot impart as much energy to the ISM (e.g., Oppenheimer & Davé, 2008). Similarly, ionizing radiation from stars is not expected to be a large source of energy for turbulence (e.g., Mac Low & Klessen, 2004). In addition, the ionizing radiation is stronger from the most massive stars, again with the shortest lifetimes, and thus does not explain the observed 30 – 40 Myr timescale. The other mechanisms for stellar energy input therefore seem unlikely as an explanation for the observed timescale.

5.5.2 *Coupling Efficiency between SF Energy and H I Energy*

Recent observations have shown that SF cannot provide enough energy to account for the observed energy in H I at low Σ_{SFR} (e.g., Tamburro et al., 2009; Chapter 4). However, these studies used FUV+24 μm emission to measure SFRs in the sample galaxies, which misses the correlation between $\Sigma_{\text{E,central}}$ and Σ_{SFR} as measured with ANGST on 30 – 40 Myr timescales (see Figure 5.9). We now measure whether the better measurement of SFR can fix the problem of unrealistic efficiencies in the low Σ_{SFR} regime.

We estimate the energy input from SNe over the 30 – 40 Myr timescale as follows:

$$\Sigma_{\text{E,SF}} = \eta [\Sigma_{\text{SFR}}(30 - 40 \text{ Myr}) \times 10 \text{ Myr}] E_{51}, \quad (5.12)$$

where η is the number of SN per unit solar mass formed. The quantity $\eta(\Sigma_{\text{SFR}} \times 10 \text{ Myr})$ represents the total number of SNe per area due to SF over the 30 – 40 Myr timescale. We set $\eta = 3.3 \times 10^{-3}$ to be the fraction of stars with $M > 8 M_{\odot}$ for a single-slope power law ($\alpha = -2.3$) with mass limits of $0.1 M_{\odot}$ and $120 M_{\odot}$. This equation gives us the total energy surface density from SNe due to SF that occurred over the past 30 – 40 Myr. We note that we have not included energy input due to SF that formed at more recent times. Our estimate of E_{SF} is therefore a lower limit, with the caveat that the fiducial dissipation timescale for turbulence is expected to be $\sim 10 \text{ Myr}$ Mac Low (1999). It is possible that SNe from stars that formed more recently than 30 Myr ago have contributed to the H I turbulent energy. If that were the case, however, we might have expected to see a stronger correlation with time ranges that also included more recent times.

In Figure 5.11, we plot the efficiency required to explain the observed H I energy with the energy input from SF. We define $\epsilon_{\text{SF}} \equiv \Sigma_{\text{E,H I}}/\Sigma_{\text{E,SF}}$. At $\Sigma_{\text{SFR}} < 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, we find that efficiencies of > 0.1 are required to couple SF energy to H I energy. At higher Σ_{SFR} , however, we find that the efficiency approaches a constant value of 0.11 with a standard deviation of 0.04 across our sample. The efficiencies at $\Sigma_{\text{SFR}} > 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ are also similar to those estimated from simulations (0.1; Thornton et al., 1998), though other simulations have estimated higher efficiencies (e.g., 0.5; Tenorio-Tagle et al., 1991). The $\Sigma_{\text{SFR}} = 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ limit is approximately the threshold where the relationship between SF energy and H I energy has been seen to break down (e.g., Dib et al., 2006; Tamburro et al., 2009; Chapter 4), so our results are consistent with these studies. However, the high efficiencies required at low Σ_{SFR} can exceed these estimates, and, at the lowest Σ_{SFR} , are higher than the unphysical limit of $\epsilon_{\text{SF}} > 1$ where H I has more energy than SF provides. As also discussed in Chapter 4, this behavior implies that the H I line widths in the lowest Σ_{SFR} regime are driven by processes other than SF even when SF is properly matched in timescale.

The above estimates of efficiency assume a well-sampled IMF. The galaxies with the largest $\Sigma_{\text{SFR}}(30 - 40 \text{ Myr})$ form $10^5 \text{ M}_{\odot}$ stars over that time range, with those with the smallest only form $\sim 250 \text{ M}_{\odot}$ of stars. Stochasticity may therefore be important for the galaxies with the smallest SFRs, as clusters of smaller mass are more likely to form more low mass stars instead of a few high mass stars compared to clusters of larger total mass. However, the simulated clusters discussed in § 5.5.1 with $M_{\text{total}} \sim 250 \text{ M}_{\odot}$ have only approximately 0 – 7 stars with $M > 8 \text{ M}_{\odot}$, with a peak at 2, compared to the expected 0.8 from Equation 5.12. To reach an efficiency similar to that observed at higher Σ_{SFR} , a larger number of SNe would be required than what we would expect from stochastic effects. The unphysical efficiencies at the lowest Σ_{SFR} values are therefore not likely to be remedied by stochasticity.

5.6 Summary

We have compared the energy in H I to the SF surface density, averaged over different timescales, in a number of nearby dwarf galaxies. We find that the H I energy surface

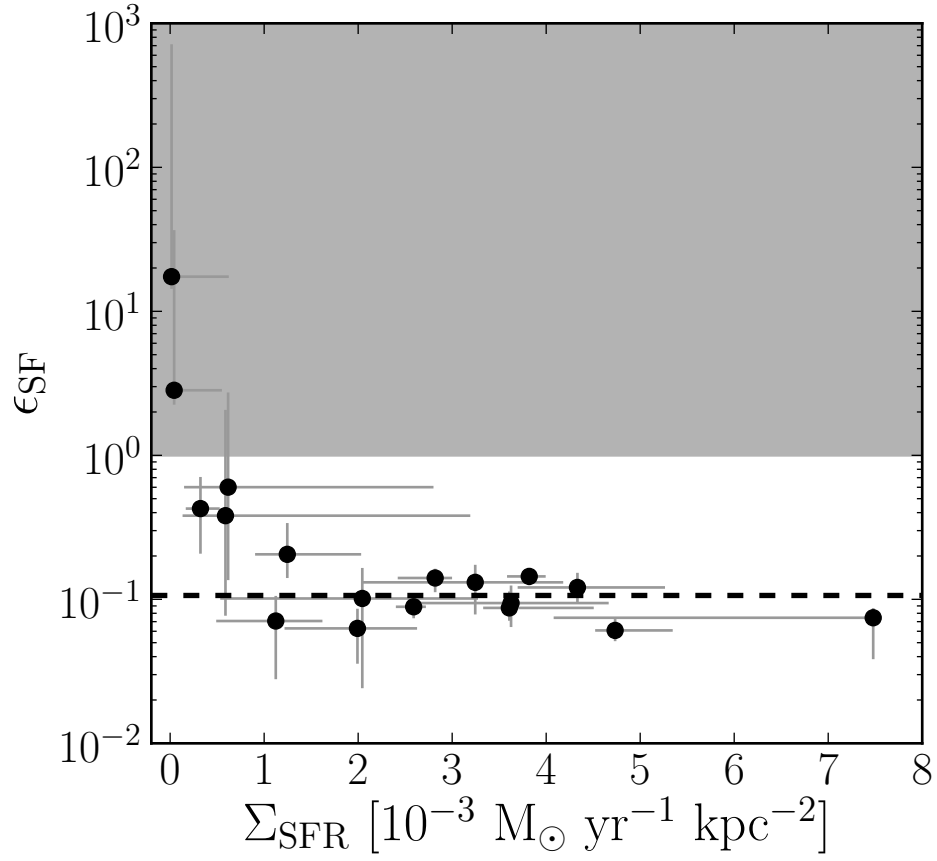


Figure 5.11 The implied coupling efficiency between SF energy and HI energy, where $\epsilon_{\text{SF}} \equiv \Sigma_{\text{E,HI}}/\Sigma_{\text{E,SF}}$. At $\Sigma_{\text{SFR}} < 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, the efficiencies approach and can exceed unphysical values of $\epsilon_{\text{SF}} > 1$. At higher Σ_{SFR} , we find constant efficiencies, with a mean and standard deviation of $\epsilon_{\text{SF}} = 0.10 \pm 0.04$ (shown as the dashed line).

density is correlated with SF that occurred 30 – 40 Myr ago and shows no correlations at times that do not include this range. These correlations are washed out when the broadband FUV+24 μ m tracer is used to measure SFR. This timescale is $\sim 3 - 4$ times longer than the turbulent dissipation timescale but is approximately equal to the lifetime of the lowest-mass supernova progenitor, supporting the idea that SNe are a contributing factor to turbulence in the neutral ISM. However, the stochastic nature of SF in the low SFR regime of our sample galaxies complicates a straightforward explanation. Second, we find that a constant coupling efficiency of 0.11 ± 0.04 galaxies with average $\Sigma_{\text{SFR}} > 10^{-3} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ between 30 – 40 Myr ago, while galaxies with lower Σ_{SFR} values require higher or unphysical efficiencies.

We note that we have averaged SF and H I energy properties over the entire ANGST aperture, which in some cases can cover a large area of the galactic disk with widely-varying SF properties. Similar studies that include spatially-resolved as well as time-resolved SF properties can place more stringent constraints on the timescale over which H I energy is affected by SF.

Chapter 6

CONCLUSIONS

H I provides an ideal tracer of the kinematics of the warm component of the interstellar medium (ISM), and exhibits a velocity structure that is often interpreted as turbulent. In the literature, the driver of this turbulence is thought to be supernova explosions (SNe) following recent star formation, but H I in dwarf galaxies and the outer regions of spirals often have higher energies than can be provided by SNe at realistic efficiencies. The question of what drives H I turbulence, especially in these low star formation regions, remains unknown. In this thesis, I have explored H I kinematics in relation to star formation in a sample of low-mass dwarf galaxies.

The second chapter presents the VLA-ANGST survey, which comprises the majority of data used in this thesis. The VLA-ANGST survey was undertaken to complement the ACS Nearby Galaxy Survey Treasury program (ANGST), which provides time-resolved star formation histories (SFHs) for all galaxies outside the Local Group but within ~ 4 Mpc. The combination of these detailed measures of star formation from ANGST with high-quality H I kinematics from VLA-ANGST provides a powerful tool for analyzing the relationship between star formation and ISM dynamics. In Chapter 2, I have discussed the observational setup of the survey, explained the data calibration and imaging pipeline, and presented an overview of the data available to the public. The survey spans a wide range of galaxy properties, including stellar, H I, and dynamical masses; luminosity; and star formation rate. The website where these data are hosted and publicly-accessible is currently located at <https://science.nrao.edu/science/surveys/vla-angst>.

I then presented a method for estimating H I kinematics on global scales by averaging individual line-of-sight spectra in Chapter 3. In this chapter, I outlined the methods used to average the individual spectra to generate H I “superprofiles.” These superprofiles are composed of a nearly-Gaussian central peak, representative of the average turbulent veloc-

ity in each galaxy, with higher-velocity wings to either side that represent H I moving faster than expected compared to the average turbulent velocities. The asymmetry of the superprofiles was also assessed. We found that the superprofiles were very similar when scaled to the same HWHM and amplitude, indicating that the H I kinematics in dwarf galaxies must be driven by similar processes. We also found that the kinematic parameters of the superprofiles were correlated with a variety of physical properties. First, the width of the central peak, σ_{central} , was correlated with $\langle \Sigma_{\text{HI}} \rangle$ but not $\langle \Sigma_{\text{SFR}} \rangle$ unless higher-mass galaxies were included. Second, the width of the wings, σ_{wings} , increasing with increasing $\langle \Sigma_{\text{SFR}} \rangle$, $\langle \Sigma_{\text{baryon}} \rangle$, and $\langle \Sigma_{\text{HI}} \rangle$, indicating that star formation could accelerate H I to velocities faster than expected compared to the central peak. The fraction of gas in the wings of the profiles, f_{wings} , is correlated with galaxy mass and with $\text{SFR} / M_{\text{HI}}$; galaxies that have high SFRs compared to their M_{HI} values could more easily accelerate the H I to faster velocities. Finally, the asymmetry of the profiles was primarily in the wing regions and correlated with both the mass and SFR of the galaxy, with more massive galaxies exhibiting more symmetric superprofiles. I also assessed the ability of the Wada et al. (2002) gravitational instability and star formation to drive H I kinematics, and found that only star formation can provide enough energy to drive kinematics at the levels seen over a single turbulent dissipation timescale.

In Chapter 4, I further explored the behavior of superprofiles that were generated on spatially-resolved scales. We examined superprofiles in regions determined both by radius and by the local Σ_{SFR} . The σ_{central} values of the superprofiles is correlated with all physical properties explored ($\langle \Sigma_{\text{HI}} \rangle$, $\langle \Sigma_{\text{baryon}} \rangle$, $\langle \Sigma_{\text{SFR}} \rangle$, and $\langle \text{SFR}/M_{\text{HI}} \rangle$), so it is difficult to determine which are drivers of turbulence in these systems. Star formation did not uniquely determine the H I velocity dispersion; σ_{central} values at low star formation intensities could be as large as $\sim 10 \text{ km s}^{-1}$, similar to the upper limit of superprofiles with larger star formation intensities. However, the average star formation intensity appeared to provide a lower limit below which the central velocity dispersion, σ_{central} , could not fall. We also found that the coupling efficiency between star formation and H I velocity dispersion decreased with increasing Σ_{SFR} , but it is unclear why Σ_{SFR} and coupling efficiency would show such a well-defined trend. Star formation was able to provide enough energy to drive

H I line widths where $\Sigma_{\text{SFR}} > 10^{-4} \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, but not at smaller Σ_{SFR} values. This last result is similar to that found by Tamburro et al. (2009) for larger spiral galaxies. We also found that σ_{wings} was strongly correlated with star formation intensity as well as mass surface density. Finally, f_{wings} and a_{full} showed no strong trends with any of the physical properties, so it is unclear what mechanism is able to drive H I into the wings of the profiles. As with Chapter 3, the spatially-resolved superprofiles are also similar in shape when scaled to the same width, regardless of the local ISM properties.

In Chapter 5, I combined H I kinematic information with time-resolved SFHs provided by ANGST to study the timescales over which star formation affects the ISM. The H I energy surface density contained in the central peak of the superprofiles is strongly correlated with star formation that occurred 30 – 40 Myr ago. No other timescale shows significant correlations. The energy surface density of the wings of the superprofiles are correlated with star formation 30 – 60 Myr ago, a larger spread than that of the central peak, implying that the gas in the wings of the superprofiles can persist for a longer time. I note that correlations between star formation and H I line widths presented in Chapter 3 became stronger when separated into spatially-resolved bins. Therefore, it would be beneficial to perform a similar study with spatially-resolved as well as time-resolved SFHs to separate regions of higher star formation from those with little to no star formation.

Taken together, the studies presented in this thesis support the current idea that H I turbulence is influenced by star formation, but cannot be fully dependent on it. Even in regions of low Σ_{SFR} , the H I velocity dispersions do not decrease below $\sim 5 \text{ km s}^{-1}$, a value similar to that expected from thermal arguments. H I tends to show larger line widths in regions with more star formation compared to those with less star formation, but the dynamic range of these line widths is only a factor of two. The efficiencies required to convert star formation energy to turbulent H I kinetic energy are typically on the order of $10^{-3} - 10^{-1}$, except in the lowest Σ_{SFR} regions where they can exceed 1. These unphysical efficiencies are not completely mitigated by considering only star formation that took place between 30 – 40 Myr ago, as H I gas can still have appreciable energies even in galaxies where little recent star formation has occurred. The efficiencies decline with increasing star formation rate, but with a different dependency than seen in simulations by Joung et al.

(2009). However, H I kinematics are also correlated with measures of surface mass density, such as Σ_{HI} or Σ_{baryon} . While gravitational instabilities have been proposed as potential drivers of turbulence, the Wada et al. (2002) instability tested in Chapter 3 is not efficient enough to provide enough energy to the H I at its observed line widths and masses. The fact that star formation does not uniquely determine H I velocity dispersions indicates that it cannot be the sole driver of H I line widths. Instead, it may be that galaxies exhibit a base level of H I velocity dispersion, possibly due to thermal broadening (e.g., Schaye, 2004), which can then be augmented by turbulence induced by star formation.

6.1 Future Work

Because star formation cannot provide enough energy to drive H I line widths in all regions of the disks of dwarf galaxies, more work is necessary to determine the cause of these line widths. The superprofiles presented in this thesis were generated by averaging H I line-of-sight spectra, and the spatial information in the contributing spectra is no longer distinct. Processes that operate on smaller scales may therefore be hidden by this averaging process. Our understanding of H I kinematics would therefore benefit from more spatially-resolved studies. For example, the ideas presented in Chapters 4 and 5 could be combined to explore H I kinematics compared to time-resolved star formation on spatially-resolved scales.

The studies presented in both Chapters 3 and 4 would also benefit greatly from rotation curve analysis, which can contribute to the energy budget of the galaxies. However, rotation curves for the smallest dwarfs in our sample may be difficult to obtain due to their complex velocity fields. If obtainable, rotation curve analysis would allow us to place limits on the amount of energy provided by the MRI or the many other gravitational instabilities that require shearing motions.

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VITA

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