

Simulating Multiphase Galactic Halos: The Impact of Cosmic Rays Through an
Observational Lens

Iryna Sotolongo Butsky

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

Doctor of Philosophy

University of Washington

2021

Reading Committee:

Thomas R. Quinn, Chair

Jessica K. Werk

Matthew McQuinn

Program Authorized to Offer Degree:
Astronomy

©Copyright 2021
Iryna Sotolongo Butsky

University of Washington

Abstract

Simulating Multiphase Galactic Halos: The Impact of Cosmic Rays Through an
Observational Lens

Iryna Sotolongo Butsky

Chair of the Supervisory Committee:
Professor Thomas R. Quinn
Astronomy

All galaxies evolve embedded in a vast gaseous halo — the circumgalactic medium (CGM) — that dwarfs the mass and spatial extent of the stars in the galactic disk. Recent ultraviolet (UV) absorption studies reveal that the CGM has a rich, multiphase structure shaped by metal-rich galactic winds that expel the byproducts of stellar evolution and pristine inflows from the intergalactic medium. Galaxy evolution is intricately tied to the state of its CGM, as galaxies depend on a consistent supply of cool gas in order to form new stars.

While current state-of-the-art simulations excel at reproducing galactic disk properties, most struggle to simultaneously reproduce the observed abundance, properties, and kinematic structure of multiphase CGM gas. In this thesis, I argue that the missing piece is likely a nonthermal component in the form of cosmic rays. I implement cosmic-ray physics into the ENZO and CHANGA simulation codes and use a combination of idealized, isolated-galaxy, and cosmological-zoom-in simulations to demonstrate the role of cosmic rays in driving galactic outflows and shaping the multiphase CGM. Throughout this work, I demonstrate how uncertainties in existing cosmic-ray transport models can lead to qualitatively different CGM structures, and motivate the need for more robust models of cosmic-ray hydrodynamics.

Additionally, I explore more direct techniques for comparing simulations against ob-

servations. Using synthetic spectroscopy, I demonstrate how cosmic rays can naturally explain the observed kinematic alignment of multiphase CGM gas. I then use synthetic observations to demonstrate the prevalence and observational signatures of cool and warm gas in the halos around the most massive galaxies, which are traditionally studied with X-ray emission from their hot, dense inner regions.

TABLE OF CONTENTS

	Page
List of Figures	vi
List of Tables	xxii
Chapter 1: Introduction	1
1.1 A Brief History	2
1.2 Observationally Motivated Science Drivers	4
1.2.1 What processes drive the galactic outflows that ultimately shape the multiphase CGM?	4
1.2.2 What supports cool CGM gas?	4
1.2.3 What drives the kinematic alignment between low, intermediate, and high ions?	5
1.3 Simulating Galaxy Evolution	5
1.3.1 Description of simulation methods	6
1.3.2 Successes and limitations of existing simulations	8
1.3.3 The case for cosmic rays	9
1.4 Simulating the CGM with Cosmic Rays	10
1.4.1 Simulating cosmic rays as a fluid	10
1.4.2 Cosmic Rays and the simulated CGM	11
1.5 Synthetic Spectroscopy: Comparing Apples to Apples	12
1.5.1 Description of Observational Methods	13
1.6 Dissertation Purpose and Outline	15
Chapter 2: The Role of Cosmic-ray Transport in Shaping the Circumgalactic Medium	17
2.1 Introduction	19
2.2 Cosmic rays in ENZO	22
2.2.1 Cosmic-ray Fluid	22

2.2.2	Cosmic-ray Streaming	25
2.2.3	Cosmic-ray Diffusion	26
2.2.4	Limiting the Gradient	27
2.3	Numerical Methods	27
2.3.1	Stellar Feedback	28
2.3.2	Chemistry and Cooling	29
2.3.3	Synthetic Observations	29
2.3.4	Initial Conditions	30
2.3.5	Description of Simulation Suite	31
2.4	Results	33
2.4.1	Outflows	33
2.4.2	Star Formation and Morphology	38
2.4.3	The Simulated Circumgalactic Medium	42
2.4.4	Temperature Distribution	47
2.4.5	Ionization Structure	49
2.4.6	The Distribution of Cosmic rays in the CGM	53
2.4.7	Tuning the Knobs: The Impact of Choosing Parameters	54
2.5	Discussion	55
2.5.1	Limitations and Future Work	58
2.6	Summary	61
2.7	Chapter Appendix: Cosmic-ray Physics in Enzo	64
2.7.1	Modified Sod Shock-tube	64
2.7.2	Brio Wu Shock-tube	66
2.7.3	Anisotropic Diffusion	66
2.7.4	Streaming	67
Chapter 3:	The Impact of Cosmic Rays on Thermal Instability in the Circumgalactic Medium	72
3.1	Introduction	74
3.2	Methods	77
3.2.1	Initial Conditions	79
3.2.2	Cooling and Heating	81
3.2.3	Parameter Survey Description	83

3.3	Physical Expectations	85
3.3.1	Classical Thermal Instability	85
3.3.2	Thermal Instability with Cosmic rays	86
3.4	Results	93
3.4.1	Thermal Instability Without Cosmic rays	94
3.4.2	Thermal Instability with Cosmic-ray Pressure	97
3.4.3	Thermal Instability and Cosmic-ray Transport	102
3.4.4	Impact of Cosmic rays on Gas Phase	106
3.4.5	Impact of Cosmic-ray Heating	112
3.4.6	Cold Gas Density Contrast	113
3.5	Discussion	116
3.5.1	The CGM Pressure Problem	116
3.5.2	Cold Cloud Sizes	118
3.5.3	Cold Mass Accretion Rates	120
3.5.4	Limitations of Idealized Setup	121
3.6	Conclusions	122
3.7	Chapter Appendix: Numerical Effects and Thermal Instability	124
3.7.1	Impact of Resolution	124
3.7.2	Impact of $T_{\min}$	126
3.7.3	Impact of halo profile	128
Chapter 4:	The Impact of Cosmic Rays on the Kinematics of the Circumgalactic Medium	130
4.1	Introduction	131
4.2	Methods	134
4.2.1	Description of Galaxy Simulations	134
4.2.2	Generating synthetic spectra	135
4.2.3	Analyzing synthetic spectra	137
4.3	Results	139
4.3.1	The physical state of the CGM	139
4.3.2	Physical insights from synthetic spectra	144
4.3.3	The Doppler-b Parameter	148
4.3.4	The kinematics of cool and warm gas	152

4.3.5	Relating Kinematic Alignment to Physical Absorbers	152
4.4	Discussion	155
4.4.1	Implications for CGM Kinematics	155
4.4.2	Uncertainty in Modeling cosmic rays	157
4.4.3	The Relationship Between Kinematic and Spatial Alignment	158
4.5	Summary	158
4.6	Chapter Appendix: Cosmic Rays in ChaNGa	160
4.6.1	Equations of Motion	160
4.6.2	Tests of CR performance	163
Chapter 5:	Ultraviolet Signatures of the Multiphase Intracluster and Circumgalactic Media in the RomulusC Simulation	166
5.1	Introduction	168
5.2	Methods	171
5.2.1	The RomulusC Simulation	171
5.2.2	Ion Fields and Synthetic Absorption Spectra	175
5.3	Multiphase ICM Properties in the RomulusC simulation	179
5.3.1	Evidence for the multiphase ICM	179
5.3.2	Radial distribution of the multiphase ICM	181
5.3.3	Covering fraction	182
5.3.4	Distribution of metals	184
5.4	The CGM of RomulusC Cluster Galaxies	189
5.5	The physical conditions of cool and warm gas in the ICM from synthetic spectra	194
5.6	Prospects of studying the cool and warm gas in Galaxy Clusters	199
5.7	Conclusions	202
Chapter 6:	Summary and Future Work	207
6.1	Summary	208
6.2	Future Work: Towards Better Models of Cosmic-ray Hydrodynamics	208
6.3	Future Work: Simulating Cool Gas with a New Subgrid Model	209
Bibliography		211

Chapter 7:	Vita	254
------------	----------------	-----

LIST OF FIGURES

Figure Number		Page
2.1	A comparison of the outflows between different galaxy models. Each row shows the edge-on, density-weighted projection of the gas entropy (top), z-component of the velocity (middle) and ratio of cosmic-ray and thermal pressures (bottom). Each column holds a simulated galaxy with different cosmic-ray treatment. From left to right, the columns show simulations with: no cosmic rays, cosmic-ray advection only, isotropic diffusion, anisotropic diffusion, and streaming. The snapshots were taken at $t = 2$ Gyr. Only models with cosmic-ray transport relative to the gas drive strong outflows by providing a nonthermal source of pressure to lift low-entropy gas out of the disk. The strength and morphology of the outflows is sensitive to the choice of cosmic-ray transport.	34
2.2	The time-evolution of the vertical velocity profile as a function of the height above the galactic disk for galaxy models NCR, ISOD, ANISD, and STREAM. Model NCR shows no signs of strong outflows. Model ISOD has the fastest outflow velocities but loses its galactic wind by $t = 4$ Gyr. Models ANISD drive weaker yet steadier galactic winds. Model STREAM is the only model to develop inflows near the galactic disk while simultaneously hosting outflows at larger radii.	35
2.3	The time-evolution of the integrated mass loading factor (the total ejected gas mass / total mass in stars), measured at 150 kpc from the galactic center. At late times, models with anisotropic cosmic-ray transport continue driving gas out of the galaxy, even when star formation is declining.	36
2.4	The face-on (top) and edge-on (bottom) density projections of the gas in our fiducial models after 13 Gyr of evolution. Although all galaxy models started from the same initial conditions, their morphologies depend on the cosmic-ray transport mechanism. The control model, NCR, is a MW-type spiral galaxy. Models ADV and STREAM have extended gas profiles and thick disks. Model ANISD has lost much of its gas to outflows. The top and bottom rows show physical scales of 52×52 kpc and 20×52 kpc respectively.	39

2.5	The star formation rate as a function of time for galaxy models with different cosmic-ray transport prescriptions. Model ADV quenches after the first episode of star formation. The star formation in model ISOD consistently lies just below that of the control model NCR with no cosmic rays. Model ANISD briefly matches the star formation in the control around $t = 2.5$ Gyr, but is quenched soon after at around $t = 10$ Gyr. Model STREAM has a variable star formation history with a period of roughly 2 Gyr.	40
2.6	A comparison of the state of the CGM between the fiducial galaxy models after 13 Gyr of evolution. The top two rows show the density-weighted metallicity and temperature and the bottom two rows show the unweighted column densities of H I and O VI. Our control model NCR drove weak outflows, so the state of its CGM is relatively unaltered from the initial conditions. Model ISOD has a spatially uniform distribution of warm, metal-rich, gas in its CGM. The galaxy model ANISD is surrounded by a reservoir of cool gas, traced by H I. The temperature and ionization structure of model ANISDH follows the morphology of that in model ANISD although the effect of cosmic-ray pressure is weakened through losses due to cosmic-ray heating. Galaxy model STREAM has a patchy, multiphase distribution of different temperature gas, traced by its H I and O VI column densities. The projection is generated from a 300 kpc cube.	43
2.7	The 2D histograms of temperature as a function of density for the six different galaxy models after 13 Gyr of evolution. The color in the plot shows the mass of O VI in each bin. Model ISOD has more diffuse gas at larger radii. Model STREAM creates a more dramatic multiphase medium, with a larger range of possible densities for each temperature. Model STREAM supports an abundance of O VI at both warm and cool temperatures.	44
2.8	The black line follows total enclosed mass as a function of spherical radius for six different galaxy models. The colors of the bars denote the fractional distribution of the gas temperature at different radial shells. We consider three temperature bins of gas: cold gas ($T < 10^5 K$) in dark purple, warm gas ($10^5 K < T < 10^6 K$) in medium purple, and hot gas ($T > 10^6 K$) in light purple. Only models with cosmic-ray transport relative to the gas have a substantial amount of warm or cold gas in their CGM. Model ANISD has an abundance of cool gas near the galactic center that persists at large radii. Model STREAM has a truly multiphase medium with an abundance of cold and warm at radii of 200 kpc.	46

2.9	Column densities of H I, Si IV, C III, and O VI as a function of impact parameter after 13 Gyr of evolution. Each point on the graph shows a column density measurement using TRIDENT from either the fiducial run described by the title, or its low-resolution counterpart. The overplotted black lines show the average column densities for the fiducial run (solid) and the low-resolution run containing the same physics (dashed). (Continued on next page.)	50
2.10	The unweighted ratio of cosmic-ray pressure to gas pressure as a function of spherical radius, measured from the galactic center after 13 Gyr of evolution. The color of the bins shows the density of the gas. The disk has been removed from the dataset in order to focus on the CGM structure. Model ISOD has a relatively flat and unvarying profile of cosmic-ray pressure in its CGM averaging around $P_c/P_g \simeq 1$. Models ANISD and ANISDH have a wide range of cosmic-ray pressure in the CGM, with the highest values peaking near the disk center, at high gas densities. The cosmic-ray pressure ratio in model STREAM peaks at larger radii, and at lower gas densities.	51
2.11	The density-weighted ratio of cosmic-ray pressure to gas pressure as a function of spherical radius after 3 Gyr of evolution. The black solid line represents the values for the fiducial run of that cosmic-ray transport method. Lines of different color and line style show variations from the fiducial run as described in the legend. The blue and green lines represent galaxy models with cosmic-ray injection fractions of 0.3 and 0.01 respectively. The purple line represents a diffusion coefficient of $\kappa_\epsilon = 10^{27} \text{cm}^2/\text{s}$ for galaxy models ISOD and ANISD and a streaming factor of $f_s = 1.0$ for model STREAM. The red line represents a diffusion coefficient of $\kappa_\epsilon = 10^{29} \text{cm}^2/\text{s}$ for model ANISD. For a description of the simulation parameters see Table 2.1. With this figure, we find that model ISOD is the most sensitive to parameter changes while model STREAM is the most robust.	52
2.12	The density, velocity, and pressure (thermal, cosmic-ray, and total pressures) as a function of position in a 1D simulation of the modified Sod shock-tube. Cosmic-ray pressure compliments thermal pressure while the total pressure remained unchanged in the rarefaction wave.	65

2.13	Various parameters of the modified Brio-Wu MHD shock-tube as a function of one dimensional position. (Top row) density, cosmic-ray, thermal, and total pressure, and thermal gas entropy. (Middle row) x-component of the velocity, y-component of the velocity and magnetic field, ratio of cosmic-ray density to thermal density. (Bottom row) the density-weighted x and y components of the velocity, and the total energy. Thermal gas is influenced by the pressure of both cosmic rays and magnetic field lines.	69
2.14	A 2D test of anisotropic diffusion of cosmic-ray energy density along circular magnetic field lines at an early time ($t = 10$; top row) and a late time ($t = 100$; bottom row). The columns are ordered from left to right by increasing resolution, ending with the analytic solution. With anisotropic diffusion, cosmic rays are confined to propagate solely along magnetic field lines. Increasing resolution decreases the amount of diffusion perpendicular to the magnetic field.	70
2.15	A comparison of the time evolution of a 1D Gaussian profile with cosmic-ray streaming (green) and diffusion (blue). A magnetic field of strength 0.25 code units lies in the x direction. The analytic solution for the cosmic-ray diffusion profile is overplotted as a black dotted line. Although no analytic solution exists for the cosmic-ray streaming case, our results qualitatively match previous studies.	71
3.1	Projections of the gas density for different initial values of $t_{\text{cool}}/t_{\text{ff}}$. The dimensions of each slice are $1H \times 2H$ in the $\hat{x}$ and $\hat{z}$ directions respectively and the projection depth in $\hat{y}$ is $1H$ (43.85 kpc). The simulations showcased above were initialized with $\beta = 100$ and no cosmic rays. Since the simulations are symmetric about the midplane, we only show the top half of the domain. The snapshots are taken at $t = 4t_{\text{cool}}$, which corresponds to longer physical times for simulations with higher $t_{\text{cool}}/t_{\text{ff}}$. As expected, there is a direct relationship between the value of $t_{\text{cool}}/t_{\text{ff}}$ and the condensation of dense, cold gas. Simulations evolved for longer physical times show signs of cold gas precipitating towards the midplane. However, in simulations with $t_{\text{cool}}/t_{\text{ff}} \geq 3$, insufficient condensation occurs to form appreciable amounts of cold gas.	92

- 3.2 The time evolution of the density fluctuation ($\langle\delta\rho/\rho\rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and infalling cold mass flux ($\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*). The different lines show different initial values of the ratio of cooling time to freefall time at the scale height. The black dashed line in the left panel shows the linear theory prediction for the density fluctuation growth with mass-weighted heating and a logarithmic cooling slope, $\alpha = -2/3$ (Eq. 3.16). All values are measured between 0.8 and 1.2 times the scale height. The fiducial simulations presented are initialized with $\beta = 100$. The x-axis values are scaled by the cooling time of the simulation, so that simulations with higher values of $t_{\text{cool}}/t_{\text{ff}}$ are evolved over longer physical times. This figure demonstrates thermal instability without cosmic rays: simulations with lower $t_{\text{cool}}/t_{\text{ff}}$ show higher density fluctuations and cold mass fractions. Although the cold mass fraction is significantly higher in simulations with $t_{\text{cool}}/t_{\text{ff}} = 0.1 - 0.3$ than in simulations with $t_{\text{cool}}/t_{\text{ff}} = 1$, their cold mass flux rates are comparable shortly after the saturation of the thermal instability. This is because simulations with longer $t_{\text{cool}}/t_{\text{ff}}$ have been evolved for longer physical time, and have developed a higher inflow velocity, $v_{\text{in}} = -\mathbf{v} \cdot \hat{z}$ 95
- 3.3 The average density fluctuation ($\langle\delta\rho/\rho\rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*) as a function of the initial $t_{\text{cool}}/t_{\text{ff}}$ for simulations with varying initial magnetic field strengths, in the absence of cosmic rays. The measurements are taken between 0.8 and 1.2 H and averaged over all outputs between 4 and 6 t_{cool} , which corresponds to the saturated phase of the thermal instability (see Figure 3.2). Magnetic fields suppress buoyancy oscillations, which simultaneously enhances the formation of cold gas through thermal instability for simulations with higher $t_{\text{cool}}/t_{\text{ff}}$ and decreases the inflowing cold mass flux in simulations with lower $t_{\text{cool}}/t_{\text{ff}}$ 96
- 3.4 2D slices of the 3D density (top) and temperature (bottom) for simulations with varying initial ratios of cosmic-ray pressure to gas pressure, $P_{\text{c}}/P_{\text{g}}$. Similarly to Figure 3.1, the dimensions of each panel are $1H \times 1.8H$. All simulations are initialized with $t_{\text{cool}}/t_{\text{ff}} = 1.0$, and the slices are taken at $t = 6t_{\text{cool}}$. Simulations with cosmic rays were run with advection as the only form of cosmic-ray transport. Increased cosmic-ray pressure support creates larger cold gas clouds with lower densities. The temperature of the cold gas does not change with increased cosmic-ray pressure since the temperature is set by the cooling function and our choice of T_{min} . With sufficiently high cosmic-ray pressure, cold gas remains in the atmosphere and does not precipitate. 98

- 3.5 The time evolution of the density fluctuation ($\langle \delta\rho/\rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($M_{\text{cold}}/M_{\text{ff}}$; *right*) near the scale height ($0.8H < z < 1.2H$). All of the depicted simulations have $t_{\text{cool}}/t_{\text{ff}} = 0.3$ and $\beta = 100$ but have different initial values of $P_{\text{c}}/P_{\text{g}}$. Increased cosmic-ray pressure decreases density fluctuation but has a modest effect on the cold mass fraction. Nonthermal cosmic-ray pressure support counteracts gravity and lowers the cold mass flux towards the midplane. Simulations with $P_{\text{c}} \geq P_{\text{g}}$ have more cold gas near the scale height at late times. 99
- 3.6 The average density fluctuation ($\langle \delta\rho/\rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($M_{\text{cold}}/M_{\text{ff}}$; *right*) as a function of the initial $t_{\text{cool}}/t_{\text{ff}}$ for simulations with $\beta = 100$ and varying initial ratios of $P_{\text{c}}/P_{\text{g}}$. The measurements are taken between 0.8 and 1.2 H and averaged over all outputs between 4 and 6 t_{cool} , which corresponds to the saturated phase of the thermal instability (see Figure 3.5). Increased cosmic-ray pressure decreases the gas density fluctuation. High cosmic-ray pressures increase the cold fraction in simulations with $t_{\text{cool}}/t_{\text{ff}} \geq 1$ by preventing cold gas from precipitating towards the midplane. Cold gas does not form in simulations with $t_{\text{cool}}/t_{\text{ff}} = 10$ 99
- 3.7 2D slices of the 3D cosmic-ray pressure for simulations with different implementations of cosmic-ray transport: advection, diffusion, and streaming. Similarly to Figures 3.1 and 3.4, the dimensions of each panel are $1H \times 1.8H$. All simulations are initialized with $t_{\text{cool}}/t_{\text{ff}} = 0.3$ and $P_{\text{c}}/P_{\text{g}} = 1$. Except for the rightmost panel, all simulations have $\beta = 100$. The slices are taken at $t = 6 t_{\text{cool}}$. Cosmic-ray transport redistributes cosmic-ray pressure from regions of high density to low density. When cosmic-ray transport is more efficient (diffusion with $t_{\text{diff}}/t_{\text{ff}} = 3$ or streaming with $\beta = 10$), the cosmic-ray pressure approaches a more homogeneous distribution. 102

- 3.8 Similar to Figures 3.3 and 3.6, the panels above measure the mean density fluctuation ($\langle \delta\rho/\rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($M_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*) as a function of their initial $t_{\text{cool}}/t_{\text{ff}}$. The data points are measured between 0.8 and 1.2 H and averaged over all simulation outputs between $4t_{\text{cool}} \leq t \leq 6t_{\text{cool}}$. The error bars show 1 standard deviation. Starting from the top, the rows vary the initial cosmic-ray pressure ratio, $P_{\text{c}}/P_{\text{g}} = 0.01, 0.1, 1, 10$. The green lines show simulations with cosmic-ray advection for different initial values of β , the red lines show simulations with cosmic-ray diffusion for three different diffusion time scales, and the blue lines show simulations with cosmic-ray streaming for three different initial values of β . Cosmic-ray transport redistributes cosmic-ray pressure so that the resulting density fluctuation, cold mass fraction, and cold mass flux tend to lie between those of MHD-only simulations and simulations with only cosmic-ray advection. (Continued on next page.) 103
- 3.9 The mass-weighted 2D histograms of density and temperature for simulations with $t_{\text{cool}}/t_{\text{ff}} = 0.3$ with various cosmic-ray transport prescriptions. The data presented here are an accumulation from all outputs between $t = 4 - 6t_{\text{cool}}$, measured between 0.8 and 1.2 H to minimize the influence of stochastic processes. The top-left panel shows the phase histogram of a simulation without cosmic rays and $\beta = 100$. The remaining panels all have an initial $P_{\text{c}}/P_{\text{t}} = 1.0$ and $\beta = 100$, but differ in their models of cosmic-ray transport: advection (top-right), diffusion (bottom-left), and streaming (bottom-right). The dashed lines show contours of constant thermal pressure and entropy. Without cosmic rays, gas cools at constant thermal pressure. With sufficient cosmic-ray pressure support, gas cools isochorically. Cosmic-ray transport widens the gas temperature-density phase space into low-density, low-temperature regimes that are not present in either simulations without cosmic rays or simulations without efficient cosmic-ray transport. 107

3.10 The mass-weighted probability density functions (PDFs) of the gas density, temperature, and cosmic-ray pressure ratio for simulations with $P_c/P_g = 1$ and $t_{\text{cool}}/t_{\text{ff}} = 0.3$ (above) and $t_{\text{cool}}/t_{\text{ff}} = 1.0$ (next page). The data in the PDFs is an aggregate from all simulation outputs between $t = 4 - 6t_{\text{cool}}$, measured between 0.8 and 1.2 scale heights. The PDFs are normalized so that the area under each distribution integrates to 1. Different implementations of cosmic-ray transport change the distribution of the ratio of cosmic-ray pressure to gas pressure, which in turn sets the distribution of gas densities. When cold gas has high cosmic-ray pressures, the density contrast between the cold and hot gas phases decreases. When cooling times are short ($t_{\text{cool}}/t_{\text{ff}} \leq 1$), cosmic-ray physics does not have a significant impact on the distribution of gas temperatures. However, when cooling times are long enough for the freefall time to be important ($t_{\text{cool}}/t_{\text{ff}} \gtrsim 1$), cosmic-ray pressure prevents precipitation and keeps cold gas near the scale height. This effect is strongest for simulations with cosmic-ray advection and modest in simulations with efficient cosmic-ray transport. (Continued on next page) . 108

3.11 The average density contrast between the cold and hot gas phases ($\langle \rho_{\text{cold}} \rangle / \langle \rho_{\text{hot}} \rangle$) as a function of the average ratio of P_c/P_g in cold gas clumps. The points show data from all simulations described in the fiducial parameter suite (Section 3.2.3) that form cold gas, both at fiducial and high resolution. The data were measured between 0.8 and 1.2 scale heights and averaged over 20 outputs between $t = 4 - 6t_{\text{cool}}$. The different colors indicate simulations with different prescriptions of cosmic-ray transport: advection (green), diffusion (red), and streaming (blue). The black lines show predictions for the density contrast for various possible scalings of cosmic-ray pressure with gas density, assuming $\Theta = 20$ and $\beta_{\text{cold}} = 3$ (Eq. 3.25). In all cases, the density contrast between the cold and hot gas phases decreases with increased cosmic-ray pressure. However, the rate of that decrease depends on the transport model, which effectively changes the degree to which cosmic-ray pressure scales with gas density. 114

- 3.12 The average density fluctuation ($\langle \delta\rho/\rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*) as a function of the initial $t_{\text{cool}}/t_{\text{ff}}$ for simulations with varying ratios of $P_{\text{c}}/P_{\text{g}}$. The solid lines, repeated from Figure 3.6, show simulations with the fiducial resolution ($64 \times 64 \times 256$). The dashed lines show simulations with half the fiducial resolution, and the dotted lines show simulations with double the fiducial resolution. The points show each quantity averaged between $t = 4 - 6t_{\text{cool}}$ and measured between 0.8 and 1.2 scale heights. All simulations have an initial $\beta = 100$. The properties of thermal instability are reasonably well converged in our fiducial simulations. 124
- 3.13 The average density contrast ($\langle \rho_{\text{cold}} \rangle / \langle \rho_{\text{hot}} \rangle$) as a function of the ratio of cosmic-ray pressure to gas pressure in cold gas. The scattered points show all simulations with cosmic-ray physics (advection, diffusion, and streaming) run with different resolutions: high resolution (triangles), fiducial resolution (circles) and low resolution (squares). The lines and shaded regions show the corresponding median and one standard deviation. When cosmic-ray pressure dominates, cold cloud structure is sufficiently resolved, even with our lowest resolution simulations. 125
- 3.14 The average density contrast between the cold and hot gas phases ($\langle \rho_{\text{cold}} \rangle / \langle \rho_{\text{hot}} \rangle$) as a function of the average ratio of $P_{\text{c}}/P_{\text{g}}$ in cold gas clumps. The points show data averaged from 20 outputs between $t = 4 - 6t_{\text{cool}}$, measured between 0.8 and 1.2 scale heights. The different colors indicate simulations with different minimum temperatures allowed by the idealized cooling curve: $T_{\text{min}} = 5 \times 10^4 \text{K}$ (green), and $T_{\text{min}} = 10^4 \text{K}$ (orange), corresponding to expected temperature contrasts of $\Theta = T_{\text{cold}}/T_0$ of 20 and 50 respectively. The different curves show predictions for the density contrast using Eq. 3.25, assuming $P_{\text{c}} \propto \rho^{4/3}$, for different possible values of the temperature contrast, Θ . Our simulations exactly match the predicted density contrast profiles at high cosmic-ray pressures but underpredict the high density contrast needed for purely thermal pressure equilibrium. 127
- 3.15 The average density fluctuation ($\langle \delta\rho/\rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*) as a function of the initial $t_{\text{cool}}/t_{\text{ff}}$ for simulations with varying ratios of $P_{\text{c}}/P_{\text{g}}$. The solid lines are repeated from Figure 3.6 and the dotted lines show the same simulations run with an isothermal gas density and temperature profile. The points show each quantity averaged between $t = 4 - 6t_{\text{cool}}$ and measured between 0.8 and 1.2 scale heights. All simulations have an initial $\beta = 100$. The choice of halo profile does not qualitatively impact our results. 129

4.1	(Top) The projected paths of the 100 synthetic spectra in the x-y plane, centered on the galaxy center. The open circles show the projected position of the impact parameter – the closest point between the sightline and the galactic center. (Bottom) The random distribution of impact parameters between 10 and 50 kpc. Note that the minimum impact parameter is 10 kpc, and the appearance of impact parameters < 10 kpc in the top panel is due to projection effects.	136
4.2	The mass-weighted projections of density, temperature and line-of-sight velocity for P0 (top) and P0+CR (bottom) at $z = 0.25$. The width and depth of the projection are 100 kpc. Relative to P0, the simulation with cosmic rays has a cooler CGM in the inner ~ 40 kpc and a larger rotating extended disk.	139
4.3	The mass-weighted projection of the ratio of cosmic-ray pressure to gas pressure in P0+CR. Cosmic-ray pressure is significantly larger than thermal pressure in the inner CGM. The cosmic-ray pressure gradient counteracts gravity to maintain hydrostatic equilibrium, allowing cool, low-entropy gas to fill the inner CGM.	140
4.4	The O VI, Si III, and column densities at $z = 0.25$ for P0 (top) and P0+CR (bottom). The width (and depth) of the projection is 100 kpc. Compared to P0, the CGM of P0+CR has lower overall O VI column densities and higher column densities of Si III and in the inner 50 kpc.	142
4.5	The ion-mass weighted 2D histograms of gas temperature and number density for P0 (left) and P0+CR (right). The data for these plots is generated from a spherical shell between 10 and 50 kpc from the galactic center. The additional pressure support from cosmic rays moves the gas to lower densities. P0 has a substantial amount of O VI absorption at temperatures above the collisional ionization equilibrium temperature of $T \sim 10^{5.5}$ K.	143

- 4.6 Example synthetic spectra from P0 and the gas properties along their line of sight. (Top row) The normalized flux corresponding to Si III and O VI absorbers in velocity space. The gray lines show the raw synthetic spectra and the green and red lines show the Voigt profile fits for Si III and O VI respectively. (Remaining rows) The gas density, temperature, metallicity, line-of-sight velocity, and fractional ion column densities as a function of position along the line of sight. The points are colored by their LOS velocity, which helps discern which absorber they contribute to. The fractional ion column densities in the bottom row are divided by the total ion column density, to help discern which particles contributed the most to the absorbers in the top row. In the light ray trajectory, 0 always represents the impact parameter (point of closest approach to the galaxy center). While O VI-bearing gas tends to form large, resolved structures, Si III-bearing gas tends to form dense, resolution-limited structures. By matching fractional column densities of Si III and O VI to the absorbers in the spectra, we can see that kinematic alignment does not necessarily imply physical alignment (left). Conversely, the right panel shows an example of Si III and O VI absorbers that are spatially aligned but kinematically misaligned. 145

- 4.7 Similar to Figure 4.6, the figure above shows example synthetic spectra from P0+CR and the gas properties along their line of sight. There is an additional panel to show the ratio of cosmic-ray pressure to gas pressure, P_c/P_g , along the line of sight. (Right) An example of kinematic alignment in P0+CR in which both Si III and O VI absorbers come from the same physical structures. In all P0+CR spectra that have both O VI and Si III absorbers, there is at least one O VI component that is kinematically aligned with Si III. P0+CR has higher incidences of kinematic alignment between Si III and O VI. In most cases in P0+CR, Si III absorption comes from large, ~ 50 kpc, clouds that are enveloped by O VI absorbers. Unlike in P0, low-density Si III-bearing gas in P0+CR is resolved by many gas particles. 146

4.8	(Left) The column density of O VI absorbers as a function of Doppler- b parameter for P0 (top) and P0+CR (bottom). Purple squares indicate O VI absorbers that are matched with a Si III absorber within 35 km/s in line-of-sight velocity space. Gray diamonds indicate O VI absorbers that have no corresponding Si III absorber within 35 km/s. We include data from Werk et al. (2016) for comparison in black. Upward arrows indicate upper limits on the measured column density. (Right) The histograms of the Doppler- b parameters of O VI absorbers in P0 (top) and P0+CR (bottom) compared against observations. All histograms are normalized to have an area of 1. Both simulations have a distinct lack of very broad ($b > 60$ km/s) O VI absorbers.	149
4.9	(Left) The column density of Si III absorbers as a function of Doppler- b parameter for P0 (top) and P0+CR (bottom). Green squares indicate Si III absorbers that are matched with a O VI absorber within 35 km/s in line-of-sight velocity space. Gray diamonds indicate Si III absorbers that have no corresponding O VI absorber within 35 km/s. We include data from Werk et al. (2016) for comparison in black. Upward arrows indicate upper limits on the measured column density. (Right) The histograms of the Doppler- b parameters of Si III absorbers in P0 (top) and P0+CR (bottom) compared against observations. All histograms are normalized to have an area of 1. P0+CR better reproduces the observed broad Si III absorbers but over-predicts the abundance of narrow, high-column Si III absorbers.	150
4.10	The histograms of the minimum velocity differences between O VI and Si III absorbers for P0 (top) and P0+CR (bottom). This excludes sightlines that have O VI but no Si III absorbers. All histograms are normalized to have an area of 1. P0+CR better reproduces the observed kinematic link between O VI and Si III absorbers.	153
4.11	The mass-weighted 2D histogram of radial velocity as a function of temperature for cool (blue) and warm (orange) CGM gas for P0 (left) and P0+CR (right). The data is taken from gas that is between 10 and 50 kpc from the galactic center. Without cosmic rays, cool gas in the inner CGM tends to be on a radially inward trajectory. With substantial cosmic-ray pressure support, low entropy cool gas is supported against gravity and has a very similar velocity distribution to that of the warm gas, leading to kinematic alignment of multiphase absorbers.	154

4.12	The Wasserstein distance between O VI and Si III line-of-sight velocities and positions along the sightline. The color of the points indicates the impact parameter of the sightline. P0+CR has a clear relationship between the kinematic and spatial alignment of O VI and Si III absorbing gas. In contrast, O VI and Si III gas in P0 are less likely to be kinematically or spatially aligned.	156
4.13	The SOD shocktube. The state of the gas density (left), velocity (middle), and pressure (right) at $t = 0.31$ seconds. The dashed line shows the analytic solution for the gas density, velocity, and total pressure, which is a sum of gas and cosmic-ray pressures. The shocktube was initialized with a contact discontinuity at $x = 250$ cm at $t = 0$. To the left of the discontinuity, the gas density, pressure, and cosmic-ray pressure are initialized to $\rho = 1\text{g/cm}^3$, $P_g = 2/3$ kPa, $P_c = 4/3$ kPa. To the right of the discontinuity, the gas density, pressure, and cosmic-ray pressure are initialized to $\rho = 0.2\text{g/cm}^3$, $P_g = 267.2$ Pa, $P_c = 267.2$ Pa. The velocity is initialized to zero everywhere.	161
4.14	Demonstration of cosmic-ray diffusion. An initial Gaussian overdensity of cosmic-ray energy decays overtime as cosmic rays diffuse down their energy gradient with a constant diffusion coefficient. The y-axis shows radially-averaged values of the cosmic-ray energy as a function of position, $r = x^2 + y^2$. The black dashed lines show analytic solutions for $t = 0$ and $t = 0.24$ Myr.	164
5.1	A 5×5 Mpc snapshot (in physical units) of the ROMULUSC simulation at $z = 0.31$. The dashed circles show the extent of $2 R_{200}$. <i>Top row</i> : The density-weighted projections of gas density, temperature, and metallicity. <i>Bottom row</i> : The integrated X-ray intensity, O VI column density, and H I column density. The color scaling of the images in the bottom row is roughly consistent with the sensitivity of existing instruments. Compared to X-ray emission, the structure probed by UV absorption studies (O VI and H I column densities) better traces cluster outskirts and small-scale structure within R_{200}	172
5.2	The total gas mass (left) and metal mass (right) fractions in the cold ($T < 10^4\text{K}$), cool ($10^4 < T < 10^5\text{K}$), warm ($10^5 < T < 10^6\text{K}$), and hot ($T > 10^6\text{K}$) gas phases as a function of radial distance from the cluster center in the ROMULUSC simulation at $z = 0.31$. Although hot gas dominates within R_{200} of the cluster, warm and cool gas comprise the majority of the gas mass at the cluster outskirts. Additionally, the cool and warm gas phases hold the majority of metals in the cluster outskirts.	176

5.3	The covering fraction of H I (<i>left panel</i>), C IV (<i>middle panel</i>), and O VI (<i>right panel</i>) as a function of the impact parameter measured from the cluster center at $z = 0.31$. Each line represents the covering fraction for different observational column density thresholds. With existing observational thresholds of <i>HST/COS</i> (10^{13}cm^{-2} for H I, $10^{13.1}\text{cm}^{-2}$ for C IV and $10^{13.3}\text{cm}^{-2}$ for O VI), we can expect covering fractions above 0.5 and 0.15 for H I and O VI respectively within 1.5 Mpc of the cluster center. For reference, the R_{200} of the cluster at this redshift is 810 kpc. At existing observational column density sensitivities, the expected covering fraction for C IV, is below 0.1. Improving the observational threshold by an order of magnitude would result in roughly a 2x increase in the covering fraction of O VI.	177
5.4	The distribution of the mass-weighted, average metallicity as a function of the temperature and hydrogen number density of the gas. The plot data was taken from a snapshot of RomulusC at $z = 0.31$, within $3 R_{200}$ of the cluster center. Gas probed by X-rays exists in a disjoint temperature and density phase from gas probed by UV-lines. The metallicity inferred from X-ray observations is likely to be higher and more uniform than the metallicity probed by UV lines.	185
5.5	The 3D radial profiles of the median metallicity in cold ($T < 10^4\text{K}$), cool ($10^4 < T < 10^5\text{K}$), warm ($10^5 < T < 10^6\text{K}$), and hot ($T < 10^6\text{K}$) gas phases at $z = 0.31$. The shaded regions represent the 68.8% confidence intervals. The gray pixels in the background show the normalized mass distribution of all of the particles in the simulation within $3 R_{200}$ of the cluster center. The red squares denote the X-ray derived metallicities from Urban et al. (2017).	186
5.6	<i>Left to right:</i> The column density of H I, C IV, and O VI as a function of impact parameter for all galaxies with stellar masses $M_* > 10^9 M_\odot$ within $4 R_{200}$ of the cluster center. The lines plot the median column density profiles of galaxies within certain bins of distance from the cluster center as indicated in the legend. The shaded regions indicate the 68.8% confidence interval of the distribution. The orange shapes show the observed detections (squares) and upper limits (triangles) of H I and O VI in cluster galaxies from Burchett et al. (2018).	187

5.7	The covering fractions of H I, C IV, and O VI as a function of halo-centric impact parameter for all galaxies with $M_* > 10^9 M_\odot$ at $z = 0.31$. The different lines represent halos within the indicated distance bins from the cluster center. Covering fractions measure the fraction column densities above some threshold column density. We assume column density thresholds of 10^{13}cm^{-2} for H I, $10^{13.1} \text{cm}^{-2}$ for C IV, and $10^{13.3} \text{cm}^{-2}$ for O VI. The covering fraction of all ions is lower for galaxies nearer to the cluster center.	189
5.8	The O VI column density overplotted with locations of sightlines for which we extracted synthetic spectra. The R_{200} of cluster galaxies with stellar masses of $M_* > 10^9 M_\odot$ are indicated by circles (centered on each galaxy). .	190
5.9	The O VI column density around the regions of the sightlines presented in Figure 5.10. Each sightline was chosen at an arbitrary location, in-between galaxies at the $z = 0.31$ snapshot of ROMULUSC. It is not required that a sightline directly intersect the CGM of a galaxy for there to be detectable amounts of O VI in the ICM.	191
5.10	Synthetic spectra of sightlines generated using TRIDENT through the ROMULUSC cluster. From left to right, the panels correspond to Sightlines 2, 7, and 12 marked in Figure 5.9. Each subpanel shows absorption (or lack thereof) for the transition labelled in its lower right corner, relative to $z = 0.31$. The blue curves mark Voigt profile fits to the visually identified absorption components. Note that the apparent absorption at > 1000 and < 1000 km/s in the Sightline 2 and 7 H I 1025, O VI 1031, and O VI 1038 panels are actually O VI 1031, O VI 1037, and O VI 1031 lines, respectively, due to the large velocity range plotted. These spectra show the diversity of absorbers predicted by our simulation, including broad and narrow H I components with and without corresponding O VI and C III.	192
5.11	Temperatures (<i>top</i>) and column densities of H I and O VI (<i>middle</i> and <i>bottom</i> , respectively) intercepted along Sightline 7 through the RomulusC volume. In the bottom two panels, the small green circles show the column density of each ion recorded at each point along the ray's trajectory, and the purple squares reflect the cumulative column densities along this trajectory. Horizontal dashed lines show the H I and O VI column densities measured by Voigt profile fitting from the Trident-generated (Hummels et al., 2017) synthetic spectra. The cumulative column densities exhibit sharp increases where localized overdensities of these ions occur. Furthermore, the column densities we measure from the synthetic spectra are consistent with those directly integrated from the simulation.	195

5.12	The detectability (at 3σ) of H I Ly α (solid) and O VI λ 1032Å (dashed) lines over a range of column densities and temperatures (via the Doppler b parameter) given several levels of S/N achieved (see color-coding in legend). Our predicted covering fractions of H I and O VI for three column density thresholds (for $\rho < 2$ Mpc) are indicated by horizontal dotted lines, and a given column density is considered detectable if a colored curve falls at or below that value in the plot. For example, a S/N = 10 spectrum should return a covering fraction $\gtrsim 17\%$ for O VI (dashed purple line) across the warm temperature regime but $f_c = 50 - 70\%$ for H I (solid purple line) across this same temperature range.	203
5.13	Signal-to-noise (S/N) ratio achieved under the current <i>LUVOIR</i> 15m telescope concept when observing UV-bright sources at various exposure times (color coding indicated in legend). The horizontal lines indicate covering fractions of H I and O VI assuming the column densities detectable of each ion at the indicated S/N (see Figure 5.12).	204

LIST OF TABLES

Table Number	Page
2.1 Simulation Parameters	32
2.2 Initial conditions for the modified Sod Shock-tube	65
2.3 Modified Brio-Wu Shock-tube	66
5.1 Voigt profile fitting results for identified absorption components in	198

ACKNOWLEDGMENTS

This dissertation marks the official end of my time as a student, a milestone that would not have been nearly as successful or enjoyable without the help of my teachers, mentors, friends, and family along the way.

First and foremost, I would like to thank Tom Quinn and Jess Werk for their mentorship and unwavering support over the past six years. It has been a pleasure to learn from you and to collaborate with you. I would also like to thank Matt McQuinn for serving on my various graduate school committees and for his valuable advice over the years. I am fortunate to have found collaborators outside of UW — Cameron Hummels, Chris Hayward, Drummond Fielding, Joe Burchett, Daisuke Nagai — who have been valuable mentors in my growth as a scientist. I am grateful to Juliette Becker for her friendship, help writing proposals, and unending supply of astronomy puns. And, of course, I am grateful for the community I have found in the N-body Shop, DiGG, and the Enzo collaboration.

I would like to thank the graduate students at UW for their collaborative spirit, competitive foosball games, and community W(h)ine Times. Thank you to my UW office mates, Dino Bektesevic and Hayden Smotherman for the lively conversations, and to my work-from-home office mates, Mink and Finn, for the cuddles and impromptu games of fetch. I am especially grateful for the close friendship of Margaret Lazzarini, who has joined me for countless pre-colloquium chats over coffee, and whose company in my quarantine bubble made finishing grad school during a global pandemic less isolating.

And finally, I am thankful for the support of my family. I want to thank my sister, Vika, for being my number one fan throughout the years. Last, but certainly not least, I am grateful for my husband, Dan. Thank you for your unhesitating support, for moving

across the country (multiple times) with me, and most of all, for your friendship.

DEDICATION

In loving memory of my parents, Marina and Volodymyr Butsky, who had the courage to start a new life in order to give their children the opportunities they never had.

Chapter 1

INTRODUCTION

For many of us, when we think of a galaxy, we imagine the brilliant light of its stars, its mesmerizing spiral arm structure, or perhaps the intricate patterns of dust extinction in its interstellar medium (ISM). However, these “visible” components that make up the galactic disk comprise only a small fraction of the mass and spatial extent of a galaxy. Galactic disks are embedded in a vast dark matter halo that extends roughly ten times farther than its stars, filling over 1000 times more volume. Aside from invisible dark matter, the galactic halo is filled with a massive reservoir of diffuse gas known as the circumgalactic medium (CGM). In the last decade, astronomers have confirmed that the CGM contains the vast majority of all galactic baryons and has a complex physical structure, shaped by the flow of gas into and out of galaxies. Although the importance of the CGM in governing galaxy evolution is now unquestionable, many aspects of the CGM, including a comprehensive interpretation of its physical properties, remains one of the biggest theoretical challenges in astronomy.

1.1 A Brief History

Lyman Spitzer Jr. first hypothesized the existence of the CGM (which he named the “galactic corona”) in 1956 (Spitzer, 1956), after being shown preliminary observations of Na I and Ca II absorption in the spectra of stars high above the galactic disk (Münch and Zirin, 1961). Spitzer inferred that these cool clouds, traced by Na I and Ca II absorption, must be embedded in a hot¹ gaseous galactic atmosphere that is in hydrostatic equilibrium with the gravitational potential well of the galaxy. After the discovery of quasi-stellar objects (also known as quasars or simply QSOs; Schmidt, 1963), astronomers used similar absorption spectroscopy techniques to infer the presence of cool and warm gas in the halos of other galaxies (e.g., Bahcall and Spitzer, 1969; Bergeron and Stasińska, 1986; Steidel and Sargent, 1992; Chen et al., 1998). The presence of the hot CGM corona was not directly con-

¹The classifications of gas temperatures can vary greatly between subfields in astronomy. In this dissertation, unless otherwise stated, I define cold gas to be $\sim 10^4$ K, cool gas to be 10^{4-5} K, warm gas to be 10^{5-6} K, and hot gas to be $> 10^6$ K.

firmed until the early 2000s, using soft X-ray emission (e.g., [Kuntz and Snowden, 2000](#)).

Meanwhile, early theoretical works predicted that the CGM was a hot, quiet remnant of galaxy formation — a by-product of the interactions between cooling and accretion in a young galaxy ([Binney, 1977](#); [Rees and Ostriker, 1977](#); [Silk, 1977](#)). This hot CGM phase ($\sim 10^6$ K for a Milky Way-sized galaxy) was expected to be long-lived as radiative cooling rates are inefficient at those temperatures. Observations of cold high-velocity clouds just above the Milky Way galactic disk motivated various “two-phase” models of the CGM, in which cold clouds condense out of a hot medium due to various hydrodynamic instabilities (e.g., [Field, 1965](#); [Mo and Miralda-Escude, 1996](#); [Maller and Bullock, 2004](#)). A key assumption in these models, and an assumption which I will continually revisit throughout this dissertation, is that the cool clouds are in thermal pressure equilibrium with the hot halo gas,

$$P_{\text{cold}} \equiv n_{\text{cold}} k_B T_{\text{cold}} = P_{\text{hot}} \equiv n_{\text{hot}} k_B T_{\text{hot}}, \quad (1.1)$$

where P, n, T are the gas pressure, number density, and temperature, and k_B is the Boltzmann constant. A key implication of this assumption is that the density contrast between the cool and hot gas phases is determined by the inverse of their temperatures,

$$\frac{n_{\text{cold}}}{n_{\text{hot}}} = \frac{T_{\text{hot}}}{T_{\text{cold}}}. \quad (1.2)$$

The installation of the Cosmic Origins Spectrograph (COS) on board the Hubble Space Telescope (HST) revolutionized the study of the low-redshift CGM, as it offered a $30\times$ increase in sensitivity compared to previous UV instruments. Using HST-COS and ground-based instruments like the Cosmic Web Imager on the Keck Telescope, astronomers made great advancements in characterizing the physical state of the CGM around high-redshift (e.g., [Steidel et al., 2010](#); [Rudie et al., 2012](#); [Turner et al., 2014](#); [Zahedy et al., 2019](#)) and low-redshift (e.g. [Prochaska et al., 2011](#); [Tumlinson et al., 2011](#); [Werk et al., 2013](#); [Borthakur et al., 2015](#); [Burchett et al., 2019](#)) galaxies in the previous decade.

Developing a comprehensive theory of galaxy evolution that can reproduce these ob-

servations, particularly those relating to the CGM of low-redshift L^* galaxies, is the driving motivator for this thesis.

1.2 Observationally Motivated Science Drivers

This dissertation aims to address the following three science drivers.

1.2.1 *What processes drive the galactic outflows that ultimately shape the multiphase CGM?*

CGM absorption studies often detect metals hundreds of kiloparsecs from their host galaxies (Tumlinson et al., 2017a). Since galaxies have very low metallicities at early cosmic times ($z > 3$), these metals, ejected by supernovae, serve as excellent tracers of outflowing material. In fact, galaxies retain only about $\sim 20\text{--}25\%$ of the metals they produce in their stars and ISM (Peeples et al., 2014). The remaining metals appear to have been lost to outflows into the CGM (Tremonti et al., 2004).

Contrary to predictions from the early “two-phase” models, the CGM is full of metal-rich gas that spans orders of magnitude in temperature and density. Surprisingly, most of the “multiphase” CGM exists in the form of cool and warm gas (Werk et al., 2013), which has very short radiative cooling times relative to galactic timescales. It remains unclear how this material survives in such abundance.

1.2.2 *What supports cool CGM gas?*

Recent observations of cool gas around low-redshift L^* galaxies infer that the densities of cool CGM gas are significantly lower than those expected from thermal pressure equilibrium in “two-phase” CGM models (Werk et al., 2014; Stern et al., 2016). If cool CGM gas is out of pressure equilibrium, then we expect it to be very short-lived. If this is the case, then we need to understand which physical mechanisms are capable of regenerating $\sim 25 - 40\%$ of all galactic baryons on very short time scales. However, an alternative explanation is that the cool phase is out of *thermal* pressure equilibrium but in *total* pres-

sure equilibrium, supported by a nonthermal source of pressure like turbulent, magnetic, or cosmic-ray pressure.

The origin and fate of cool CGM gas is particularly interesting for its expected role in galaxy star formation. Galaxies rely on an ample supply of cold molecular gas, which is ultimately accreted from the CGM. It is therefore surprising why the halos of massive quenched galaxies are observed to have massive reservoirs of cool gas in their CGM (Gauthier et al., 2010; Thom et al., 2012), and it is a mystery how this gas is prevented from contributing to ongoing star formation.

1.2.3 What drives the kinematic alignment between low, intermediate, and high ions?

Most absorption spectra of the low-redshift CGM contain at least one case of kinematic alignment of multiphase ions — absorption features different temperatures, all moving with similar line-of-sight velocities (Werk et al., 2016). While it is difficult to interpret three-dimensional physical structures from one-dimensional absorption spectra, the prevalence of kinematically aligned ions hints at a physical relationship between different temperature CGM gas.

Comprehensive theoretical models must be capable of explaining both, the origin of the CGM's complex structure, and its relationship with its host galaxy.

1.3 Simulating Galaxy Evolution

Simulations are a powerful tool for running experiments on galactic scales. Simulations capable of reproducing observed galactic features can constrain the physical processes governing galaxy evolution and offer predictions for future observations. In the following section, I will describe the basic methods used to simulate galaxies and highlight why even the most advanced galaxy simulations struggle to reproduce CGM structure.

1.3.1 Description of simulation methods

Modern hydrodynamics simulations of galaxies start with the assumption that on large scales, gas behaves like a fluid. In my thesis work, I use both grid-based and particle-based approaches to simulating fluid dynamics.

In the grid-based approach, the simulation volume is discretized into individual cells, each of which keeps track of certain fluid properties, for example, the density, velocity, and energy. Most grid-based simulation codes employ a form of adaptive mesh refinement (AMR) that can selectively increase the resolution in a region of interest (typically selected by gas density) in order to prioritize computational power. The evolution of these fluid properties over time is described by a set of conservation equations that require that the change of a quantity over some time ($\partial/\partial t$) is equal to the flux of that quantity through the cell walls ($\nabla \cdot ()$), in addition to any source or loss terms.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (1.3)$$

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}^T) + \nabla P_g = -\rho \mathbf{g} \quad (1.4)$$

$$\frac{\partial \varepsilon_g}{\partial t} + \nabla \cdot (\mathbf{v} \varepsilon_g) = -P_g \nabla \cdot \mathbf{v} - \mathcal{S} \quad (1.5)$$

In the equations above, ρ is the gas density, $\mathbf{v}$ is the gas velocity vector, $\mathbf{g}$ is the gravitational acceleration, and t is the time variable. $\mathcal{S}$ encompasses all source and sink terms to the gas energy, for example, injection of heat due to supernova feedback or loss of energy due to radiative cooling. ε_g is the gas energy density (energy per volume). $P_g = (\gamma - 1)\varepsilon_g$ describes the relationship between the gas pressure and energy density via the adiabatic index, $\gamma = 5/3$.

In the smoothed-particle hydrodynamics (SPH) approach, the total mass of the fluid is discretized into a finite number of particles of fixed mass. The conservation equations

governing gas behavior are similar to those in the grid based approach, but are presented in the reference frame of the moving particles.

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{v} \quad (1.6)$$

$$\frac{\rho D\mathbf{v}}{Dt} + \nabla(P_g) = \mathbf{g} \quad (1.7)$$

$$\frac{\rho D\varepsilon_g}{Dt} + P_g \nabla \cdot \mathbf{v} = \mathcal{S}, \quad (1.8)$$

where $D/Dt = \partial/\partial t + \mathbf{v} \cdot \nabla$ denotes the convective derivative.

In addition to modeling gas motion, a key component of galaxy simulations is how they model star formation and stellar feedback. Since the typical resolution in the ISM is much too coarse to resolve individual stars, simulations use “star particles” to represent the cumulative behavior of a collection of stars ($\sim 10^5 M_\odot$) over time. Star particles form when the gas in the ISM of a galaxy simulation meets a set of criteria, set by the gas temperature, density, velocity flow, and a tuned efficiency parameter. To model stellar feedback, these star particles inject thermal energy² into the surrounding cells. Stellar feedback is arguably the most important aspect of galaxy evolution, as it drives galactic winds and regulates star formation by heating the ISM.

To create a galaxy simulation, one starts with a set of initial conditions — a configuration of gas particles or cells that describes a physically realistic starting point. Those initial conditions are evolved by the simulation code, typically on a supercomputer, following the conservation equations and additional physics modules. The program periodically generates “outputs” — files containing a complete description of the state of the gas and stars at a given cosmological time. Astronomers then use post-processing tools to generate images and inspect gas properties.

²In some prescriptions, stellar feedback can also inject kinetic, magnetic, and/or cosmic-ray energy in addition to thermal energy

1.3.2 *Successes and limitations of existing simulations*

When the first observations from HST-COS became available, state-of-the-art galaxy simulations struggled to reproduce the observed multiphase ion structure in their CGM (Hummels et al., 2013; Marasco et al., 2015; Fielding et al., 2017; Gutcke et al., 2017). Until then, supernova feedback models had been calibrated by their ability to reproduce galactic disk properties such as the morphology, Tully-Fisher relation, and star formation rate density (Schaye et al., 2010; Davé et al., 2011; Puchwein and Springel, 2013; Stinson et al., 2013; Christensen et al., 2014). However, purely thermal supernova feedback models fell short when it came to driving far-reaching multiphase galactic outflows.

This inspired the galaxy simulation community to investigate a wide variety of wind-launching mechanisms, including radiation pressure from massive stars (Kim et al., 2011; Murray et al., 2011; Hopkins et al., 2012; Sharma and Nath, 2012a; Wise et al., 2012), thermal supernova feedback (Abadi et al., 2003; Joung et al., 2009; Hummels and Bryan, 2012; Creasey et al., 2013), kinetic supernova feedback (Hopkins et al., 2012; Springel and Hernquist, 2003; Agertz et al., 2013), supernova superbubble models, (Keller et al., 2015, 2016), and subgrid models tuned to generate strong outflows (e.g. Springel and Hernquist, 2003; Stinson et al., 2006; Oppenheimer and Davé, 2006; Governato et al., 2012). In more massive galaxies, feedback from active galactic nuclei (AGN) was invoked to regulate flow of gas into and out of the galactic disk (e.g. Suresh et al., 2015; Tremmel et al., 2017; Oppenheimer et al., 2017).

Using a combination of these methods, many galaxy simulations can now reproduce the observed abundance of warm gas, typically judged by comparing simulated O VI column densities against observations (e.g., Oppenheimer et al., 2018; Nelson et al., 2018; Sanchez et al., 2019). However, most galaxy simulations still under-predict the observed abundance of cool gas. Those that do produce high column densities of H I or low ionization metal lines (Schaye et al., 2015; Hummels et al., 2019; Suresh et al., 2019; Peeples et al., 2019b; van de Voort et al., 2019; Nelson et al., 2020) do not show convergence with reso-

lution or reproduce the inferred low densities of cool low-redshift CGM gas (Werk et al., 2014).

Throughout this dissertation, I will argue that the missing key is likely a nonthermal component: cosmic rays.

1.3.3 *The case for cosmic rays*

Cosmic rays are charged particles (mostly GeV protons) that have been accelerated to relativistic velocities in extreme shocks like supernovae (Ackermann et al., 2013). Due to their charge, cosmic rays cannot freely stream out of the galaxy, as their motion is confined to helical paths around tangled magnetic field lines. Cosmic rays are therefore trapped in the galactic disk for tens of millions of years (likely much longer in the CGM), where they interact with the thermal gas. In the galactic disk, cosmic-ray energy is comparable in strength to thermal and magnetic energies (Boulares and Cox, 1990). However, the contribution of cosmic-ray energy is unconstrained in the CGM of L^* galaxies.

Despite being an important source of energy in the ISM, cosmic rays are often neglected in galaxy simulations. Due to past computational constraints, cosmic rays have only recently been included in three-dimensional galaxy-scale simulations. When included, even modest amounts of cosmic-ray pressure can drive galactic outflows that are qualitatively different from thermally-driven outflows (e.g., Uhlig et al., 2012; Booth et al., 2013; Simpson et al., 2016; Girichidis et al., 2016). Furthermore, cosmic rays are a source of nonthermal pressure that may support the observed low-density CGM gas.

For these reasons, cosmic rays offer a promising explanation of low-redshift CGM structure. In the following section, I describe how cosmic rays are modeled as a fluid in galaxy-scale simulations, how that fluid interacts with the ‘regular’ gas fluid, and the implications for CGM structure.

1.4 Simulating the CGM with Cosmic Rays

1.4.1 Simulating cosmic rays as a fluid

On scales much larger than the cosmic-ray gyroradius (~ 1 AU for GeV proton around a microGauss magnetic field line), cosmic rays behave like a fluid. Similar to the gas fluid introduced in the previous section, the cosmic-ray fluid conserves its energy density according to the following conservation equations,

$$\frac{\partial \varepsilon_c}{\partial t} + \nabla \cdot \mathbf{F}_c = -P_c \nabla \cdot \mathbf{v} + \mathcal{S}_c \quad (1.9)$$

where ε_c is P_c is the cosmic-ray energy density, and $P_c = (\gamma_c - 1)\varepsilon_c$ is the cosmic-ray pressure. The cosmic-ray adiabatic index is $\gamma_c = 4/3$. $\mathcal{S}_c$ is a shorthand for all cosmic-ray source and sink terms, including injection of cosmic-ray energy during supernova feedback and, in some cases, the transfer of cosmic-ray energy to heat the thermal gas.

$\mathbf{F}_c$ describes the flux of cosmic-ray energy density due to thermal gas motions (advection) or to cosmic ray transport around magnetic field lines (streaming or diffusion),

$$\mathbf{F}_c = \underbrace{\mathbf{v}\varepsilon_c}_{\text{advection}} + \underbrace{\mathbf{v}_s(\varepsilon_c + P_c)}_{\text{streaming}} - \underbrace{\kappa_c \mathbf{b}(\mathbf{b} \cdot \nabla \varepsilon_c)}_{\text{diffusion}} \quad (1.10)$$

where $\mathbf{v}_s$ is the cosmic-ray streaming velocity, κ_c is the constant cosmic-ray diffusion coefficient, and $\mathbf{b}$ is the magnetic field direction, $\mathbf{b} = \mathbf{B}/|\mathbf{B}|$. While cosmic-ray advection is entirely dictated by the motions of the thermal gas, streaming and diffusion describe the motion of the cosmic-ray fluid *relative* to the thermal gas. Streaming and diffusion are both approximations of how cosmic-ray particles are scattered due perturbations in the magnetic field lines. The difference lies in the origin of the magnetic field line perturbations. In the case of diffusion, the perturbations are caused by twisting of the magnetic field lines due to extrinsic turbulence, in the streaming approximation, cosmic-ray streaming itself drives an instability that causes the perturbations to grow. In the fluid approach,

both streaming and diffusion act to redistribute cosmic-ray pressure out of regions where it is concentrated. Throughout this thesis, I will make the assumption that cosmic-ray transport happens either as streaming or diffusion to gain insight into the behavior of the cosmic-ray fluid in these limits. I will often refer to either cosmic-ray streaming or diffusion with the agnostic “cosmic-ray transport”.

1.4.2 *Cosmic Rays and the simulated CGM*

Although we know cosmic rays make up a large fraction of the energy budget in the ISM, we have no such constraints for the CGM around L^* galaxies.³ However, we do have constraints on the injection rate of cosmic-ray energy from supernovae. Using gamma-ray observations from the galactic disk, we also have some constraints on the overall cosmic-ray transport rate (i.e. the diffusion coefficient; [Chan et al., 2019](#)). It is therefore very likely that cosmic rays play an important role in the CGM, especially around L^* galaxies, which have the perfect combination of supernova activity and relatively low gravitational potential wells that allow cosmic rays to have a strong effect.

There are several ways in which cosmic rays can alter the structure of the CGM:

1. *Cosmic rays drive galactic outflows.* As ongoing supernova feedback injects cosmic rays into the surrounding gas, cosmic-ray pressure builds up in the galactic disk. Cosmic-ray transport gradually allows cosmic rays to escape the galactic disk, generating a cosmic-ray pressure gradient that contributes to maintaining hydrostatic equilibrium with the galactic potential well. This nonthermal pressure gradient lifts gas out of the ISM, creating galactic outflows that are cooler, smoother, and more mass-loaded than their thermally-driven counterparts ([Girichidis et al., 2016](#)). Since these gentle cosmic-ray-driven outflows are less likely to destroy cool gas, they may explain the abundance of multiphase gas in the CGM. Additionally, because cosmic rays do not lose energy to

³Radio observations indicate that cosmic rays make up roughly 1% of the energy in the intracluster medium, but there are no such direct constraints around lower mass galaxies. Simulations predict that cosmic rays have a much more important dynamical role in L^* galaxies than in massive clusters.

adiabatic expansion as readily as regular gas, cosmic-ray pressure can continue accelerating outflows hundreds of kiloparsecs above the galactic disk (Hopkins et al., 2021a).

2. *Cosmic rays offer nonthermal pressure support to cool gas.* In the presence of nonthermal pressure support, gas does not need to maintain *thermal* pressure equilibrium. Instead, the system must achieve *total* pressure equilibrium, $P_{\text{tot}} = P_{\text{g}} + P_{\text{c}}$. This nonthermal pressure support allows cool gas to exist at low densities, consistent with observations of low-redshift galaxies. Additionally, low-density cool gas is more buoyant and therefore less likely to “sink” in its gravitational well. This buoyancy has implications for the kinematic structure of the CGM and may explain why some quenched galaxies have massive reservoirs of cool gas in their CGM.
3. *Cosmic rays can heat the gas.* In the streaming approximation of cosmic-ray transport, cosmic rays heat the gas at a rate that is proportional to the Alfvén velocity and the cosmic-ray pressure gradient. Although the total energy injected due to this cosmic-ray heating is small relative to the total energy lost by radiative cooling in the CGM, this perturbative heating is important at the boundary of cool clouds and may produce a unique ionization signature.

In chapters 2, 3, and 4, I use a variety of simulation types (idealized plasma, isolated galaxy, cosmological zoom-in) to study the role of cosmic rays in addressing the three science drivers presented in section 1.2.

1.5 Synthetic Spectroscopy: Comparing Apples to Apples

In addition to cosmic rays, another major theme of this dissertation is developing more direct methods for comparing simulated CGM properties against observations. Traditionally, the success of galaxy simulations is judged by comparing known simulated quantities against *inferred* properties from observations. For example, although properties like

the density or metallicity are exact quantities in a simulation, they cannot be directly observed. Instead, gas properties are derived from real observables — the strength and ratios of multiphase ion absorbers.

In what follows, I describe the information we directly derive from absorption spectroscopy and discuss how simulations can use *synthetic* spectroscopy to better compare their predictions against observations.

1.5.1 Description of Observational Methods

Because the CGM is so diffuse, much of what we know about its composition comes from absorption-line studies, in which the sightline to a bright background source (typically a quasar) intersects a galaxy’s CGM. The atoms in the CGM interact with the light from the quasar, creating absorption-line features in the spectra from which we can infer the chemical composition and physical state of the absorbing gas.

In the CGM literature, observed ions are often categorized according to their ionization state: “low-ions” have an ionization potential of less than 40 eV and trace gas with temperatures between $10^4 - 10^{4.5}$ K, “intermediate ions” have ionization potentials between 40 and 100 eV and trace gas with temperatures between $10^{4.5} - 10^{5.5}$ K, and “high-ions” have ionization potentials over 100 eV and trace gas with temperatures greater than $10^{5.5}$ K (Tumlinson et al., 2017a).

Each absorption feature traces a distinct electron energy transition in an atom. The shape of the absorption feature is well modelled by a Voigt profile, which is a convolution of Gaussian and Lorentzian profiles due to thermal and nonthermal broadening processes. Astronomers fit absorption features with Voigt profiles to determine the following three properties:

- *Column density.* The column density is the total number of atoms of a given ion, summed up along the line of sight, divided by the area of the observation. This quantity is typically expressed in units of cm^{-2} and is used to trace the overall abundance of different

ions. If an absorption line is saturated, then we can only derive a lower limit to the column density. Conversely, if an absorption feature is not present, then we can derive an upper limit to the column density we would have been able to detect as a function of the noise in the spectrum.

- *Doppler- b parameter.* The Doppler- b parameter characterizes the width of a spectral line and is a combination of both thermal and nonthermal broadening processes. If we can estimate the temperature of the absorbing gas, we can then place constraints on the contribution of nonthermal broadening due to gas motions along the line of sight.
- *Velocity offset.* After accounting for cosmological redshift and the redshift of the host galaxy, the transition wavelength of an absorber may still be offset from its rest wavelength due to the motion of the gas relative to the galaxy restframe. This wavelength offset can be converted into a relative line-of-sight velocity offset for each absorber.

In order to estimate the temperature or density of CGM gas — quantities that are trivially available in simulations — observers must do additional post-processing and compare ratios of various line strengths against theoretical models. This approach is sensitive to a variety of model assumptions and can have large uncertainties.

Rather than manipulating one-dimensional observed data to fit three-dimensional simulated data, it is much simpler to do the inverse. For example, many CGM simulation studies generate ion column density maps that they compare against observations. Although this is a good first step, this method cannot be used to compare the column densities of individual absorbers along a line of sight or the other sightline properties, like the Doppler- b parameter or velocity offsets. In chapters 4 and 5 I tackle this issue by generating *synthetic* absorption spectra from my simulations and analyzing them using observational Voigt-profile-fitting tools.

I use the TRIDENT ([Hummels et al., 2017](#)) analysis tool to generate synthetic spectra. To do so, TRIDENT first draws a one-dimensional ray through the simulation volume and in-

terpolates the gas properties along that sightline. From those gas properties, it generates an absorption spectrum. To make the synthetic spectrum more directly comparable to observations, TRIDENT adjusts the resolution, adds noise, and mimics instrument-specific line-spread functions. The end result is a spectrum that can be directly compared against spectra taken with HST-COS. However, because the synthetic spectra comes from simulated data, we can link back each absorption feature to the exact gas properties that produced it. This method is powerful tool for constraining the origin and physical structure of the multiphase CGM.

1.6 Dissertation Purpose and Outline

The goals of this dissertation are twofold. First, I explore the impact of cosmic rays on the multiphase structure of the CGM and cool gas properties using a simulation-focused approach. Second, I use synthetic spectroscopy to make detailed comparisons of CGM kinematics with and without cosmic rays. I then extend the synthetic spectroscopy approach to demonstrate the observational signatures and dynamical role of multiphase gas in the halos of the most massive galaxies.

In chapter 2, I implement anisotropic cosmic-ray physics in to the ENZO hydrodynamics simulation code. Using this new implementation, I generate a suite of simulated Milky Way-type galaxies and demonstrate how cosmic-ray driven outflows can reproduce the observed multiphase ion abundances (1.2.1). A key result in this chapter is how different models for cosmic-ray transport can create *qualitatively different* CGM properties. Using these results, I motivate the need for detailed parameter studies to constrain models of cosmic-ray transport.

In chapter 3, I demonstrate how cosmic rays impact the properties of cool CGM gas that condenses out of thermally-unstable hot CGM gas. I find that the addition of nonthermal cosmic-ray pressure support results in larger cool gas clouds that have lower densities and are less likely to accrete to the galaxy. These results simultaneously explain the inferred low-densities of cool CGM gas and the prevalence of cool gas around massive quenched

galaxies (1.2.2). In this chapter I also quantify the impact of cosmic ray transport on cool gas properties and make analytic predictions for the densities and sizes of cool gas clouds as a function of nonthermal pressure support from cosmic rays and magnetic fields.

In chapter 4, I introduce the synthetic spectroscopy approach to study the impact of cosmic rays on the kinematics of multiphase CGM gas. I show that in a cosmic-ray-pressure supported CGM, cool gas is buoyant, which naturally leads to kinematic alignment between cool and warm gas phases (1.2.3). Furthermore, by linking synthetic absorption features to the gas particles that created them, I demonstrate how cosmic rays change the physical interpretations we can draw from kinematic alignment in observed spectra.

In chapter 5, I apply synthetic spectroscopy to study multiphase properties of the intracluster medium (the ‘CGM’ of massive galaxies; ICM). Unlike the CGM, the inner regions of the ICM are so hot and dense that they emit X-rays. For this reason, most of our understanding of ICM structure comes from X-ray emission studies. In this work, I use an extremely high resolution simulation of a galaxy cluster to demonstrate that there is a substantial amount of cool and warm gas present throughout the ICM. I make synthetic observation maps to demonstrate that this cool/warm gas, which can be observed using UV absorption spectroscopy, traces a fundamentally different and complementary ICM structure than that observed with X-rays. Finally, I make observational predictions of ICM structure for both existing and future UV telescopes.

Chapter 2

THE ROLE OF COSMIC-RAY TRANSPORT IN SHAPING THE CIRCUMGALACTIC MEDIUM

Portions of this chapter were originally published in collaboration with Thomas R. Quinn in the November 2018 edition of The Astrophysical Journal (Butsky and Quinn, 2018, ApJ, Vol. 868, 108; 2018 ©American Astronomical Society, DOI: 10.3847/1538-4357/aaeac2), and are reproduced below with the permission of the American Astronomical Society.

Summary

The majority of galactic baryons reside outside of the galactic disk in the diffuse gas known as the circumgalactic medium (CGM). While state-of-the art simulations excel at reproducing galactic disk properties, many struggle to drive strong galactic winds or to match the observed ionization structure of the CGM using only thermal supernova feedback. To remedy this, recent studies have invoked nonthermal cosmic-ray stellar feedback prescriptions. However, numerical schemes of cosmic-ray transport are still poorly constrained. We explore how the choice of cosmic-ray transport affects the multiphase structure of the simulated CGM. We implement anisotropic cosmic-ray physics in the astrophysical simulation code, ENZO and simulate a suite of isolated disk galaxies with varying prescriptions for cosmic-ray transport: isotropic diffusion, anisotropic diffusion, and streaming. We find that all three transport mechanisms result in strong, metal-rich outflows but differ in the temperature and ionization structure of their CGM. Isotropic diffusion results in a spatially uniform, warm CGM that underpredicts the column densities of low-ions. Anisotropic diffusion develops a reservoir of cool gas that extends further from the galactic center, but disperses rapidly with distance. Cosmic-ray streaming projects cool gas out to radii of 200 kpc, supporting a truly multiphase medium. In addition, we find that streaming is less sensitive to changes in constant parameter values like the cosmic-ray injection fraction, transport velocity, and resolution than diffusion. We conclude that cosmic-ray streaming is a more robust implementation of cosmic-ray transport and motivate the need for detailed parameter studies of cosmic-ray transport.

2.1 Introduction

The majority of baryons in galactic halos, including the majority of metals, reside in the circumgalactic medium (CGM) of galaxies (Werk et al., 2013, 2014). Loosely defined, the CGM refers to the diffuse, multiphase gas that extends to the virial radius of galaxies. The CGM is shaped by the interplay between outflows from the star-forming disk and inflows from the pristine intergalactic medium (IGM) and provides constraints to theories of galaxy formation and evolution.

Early theoretical works predicted the existence of the CGM as a by-product of the interactions between cooling and accretion during galaxy formation (Binney, 1977; Rees and Ostriker, 1977; Silk, 1977). Due to its low density, the CGM is extremely difficult to observe directly in emission. Instead, recent observations, such as those taken with The Cosmic Origins Spectrograph (COS) (Green et al., 2012) on board the Hubble Space Telescope (HST), have studied the CGM through absorption lines in quasar spectra that intersect the halos of galaxies along the line-of-sight. Using the quasar absorption method, different groups have greatly advanced our knowledge of the CGM both in high-redshift (e.g. Steidel et al. 2010; Rudie et al. 2012; Turner et al. 2014), and low-redshift (e.g. Chen et al. 2010; Gauthier et al. 2010; Kacprzak et al. 2010; Bordoloi et al. 2011; Prochaska et al. 2011; Tumlinson et al. 2011; Nielsen et al. 2013; Stocke et al. 2013; Werk et al. 2013; Zhang et al. 2016) galaxies. Today, we understand the CGM to have an intricate and complex temperature, density, and kinematic structure that is shaped by galactic outflows.

Simulations play an integral role in understanding the physical processes that govern galactic outflows by allowing astronomers to perform experiments testing the validity of different feedback prescriptions. The success of a simulation has traditionally been marked by its ability to reproduce observed galactic disk properties, such as the morphology, Tully-Fisher relation, and star formation rate density (Schaye et al., 2010; Davé et al., 2011; Puchwein and Springel, 2013; Stinson et al., 2013; Christensen et al., 2014). Requiring that simulations also match the observed structure of the CGM will place strong

additional constraints to stellar feedback models.

One such constraint is that stellar feedback must drive galactic outflows that carry a substantial amount of metals along with the gas they expel. Although metals are produced within galactic disks, galaxies retain only $\sim 20 - 25\%$ of these metals in their stars and ISM (Peeples et al., 2014). Data from the Sloan Digital Sky Survey suggest that metals have been lost to outflows (Tremonti et al., 2004). Since galaxies have very low metallicities at early cosmic times ($z > 3$), the metals ejected by supernovae serve as excellent tracers of outflowing material and can be used to make predictions for future observations.

These outflows must not only enrich the CGM but also reproduce its multiphase ionization structure. For example, the CGM of galaxies at low redshift contains a substantial amount of metal-enriched, cool gas at $10^4 - 10^5$ K (Werk et al., 2013, 2014). However, cooling times of $\simeq 10^5$ K gas are very short compared to galactic timescales, and it is unclear how this material survives in such abundance. The data seem to imply an additional unknown source of nonthermal pressure that supports the warm gas against condensation.

Recent studies have investigated various types of thermal wind-launching mechanisms, including radiation pressure from massive stars (Kim et al., 2011; Murray et al., 2011; Hopkins et al., 2012; Sharma and Nath, 2012a; Wise et al., 2012), thermal supernova feedback (Abadi et al., 2003; Joung et al., 2009; Hummels and Bryan, 2012; Creasey et al., 2013), kinetic supernova feedback (Hopkins et al., 2012; Springel and Hernquist, 2003; Agertz et al., 2013), supernova superbubble models, (Keller et al., 2015, 2016), and subgrid models tuned to generate strong outflows (e.g. Springel and Hernquist, 2003; Stinson et al., 2006; Oppenheimer and Davé, 2006; Governato et al., 2012)). However, many of these feedback prescriptions still struggle to produce sufficiently strong galactic outflows. Those that do succeed in expelling gas from the galactic disk underpredict the observed column densities of H I, O VI, and low ions in the CGM. (Hummels et al., 2013; Marasco et al., 2015; Fielding et al., 2017; Gutcke et al., 2017). This discrepancy is amplified in massive galaxies for which thermal supernova feedback also struggles to quench star formation (Pontzen et al., 2013a). In such galaxies, feedback from active galactic nuclei (AGN) is of-

ten invoked to regulate the baryon cycling process (e.g. [Suresh et al., 2015](#); [Tremmel et al., 2017](#); [Oppenheimer et al., 2017](#)). Although AGN help recreate some observable properties for massive galaxies, they cannot account for discrepancies in galaxies (such as the Milky Way) that host a small supermassive black hole (SMBH) at their core. It is likely that the missing key is a nonthermal component.

Cosmic rays are charged particles that have been accelerated to relativistic speeds in shocks (e.g. SNe [Ackermann et al. 2013](#), structure formation shocks [Pfrommer et al. 2008](#) radio-loud AGN [McNamara and Nulsen 2007](#)) and are observed to be roughly in equilibrium with the thermal and magnetic pressures in our galaxy ([Boulares and Cox, 1990](#)). Due to past computational constraints, cosmic rays have only recently been included in 3-D hydrodynamical simulations of galactic structure. These simulations have shown that cosmic-ray feedback drives strong, mass-loaded outflows and suppresses star formation (e.g. [Miniati et al., 2001](#); [Enßlin et al., 2007](#); [Jubelgas et al., 2008](#); [Socrates et al., 2008](#); [Uhlig et al., 2012](#); [Vazza et al., 2012](#); [Booth et al., 2013](#); [Salem and Bryan, 2014](#); [Girichidis et al., 2016](#); [Simpson et al., 2016](#); [Samui et al., 2018](#)). Furthermore, cosmic rays provide pressure support to the thermal gas, which may explain the presence of the observed structures in the CGM that appear to be out of thermal equilibrium.

[Salem et al. \(2016\)](#) were the first to show that stellar feedback models that included cosmic-ray energy were better at matching COS-Halos data for low-ion column densities than those with purely thermal feedback. However, these results depended on the choice of a constant diffusion coefficient, which is only loosely constrained by observations. Furthermore, their simulations neglected magnetic fields, which are crucial for accurate modeling of cosmic-ray transport. Traditionally, implementations of cosmic-ray transport have been separated into two approximations: diffusion and streaming. Although both approaches have been successful at driving galactic outflows, the strength and mass-loading factor of cosmic-ray driven winds depends on the invoked transport mechanism ([Ruszkowski et al., 2017](#); [Wiener et al., 2017](#)).

In this chapter, we investigate the role of different cosmic-ray transport prescriptions

in shaping the multiphase structure of the CGM. This chapter is structured as follows. In §2.2, we describe the implementation of cosmic-ray physics in *ENZO*. In §2.3, we describe the simulation suite and the relevant initial conditions and physical modules used in our isolated disk setup. We present our results in §2.4, focusing on the generated outflows, temperature structure, and column densities of the different galaxy models. We outline the qualitative differences between cosmic-ray diffusion and streaming and discuss future prospects in §2.5. Finally, we provide a summary of our work in §2.6.

2.2 Cosmic rays in ENZO

In the following section, we describe our implementation of the cosmic-ray fluid into the different Riemann solvers in the adaptive mesh refinement (AMR) magnetohydrodynamics (MHD) simulation code *ENZO*. Our implementation builds on the work of [Salem and Bryan \(2014\)](#), which described the integration of a cosmic-ray fluid in the *ZEUS* finite-difference solver ([Stone and Norman, 1992](#)). Because the current implementation of the *ZEUS* solver in the public version of *ENZO* does not support MHD, the primary advantage of our work is the ability to model the interaction of cosmic rays with magnetic field lines. In §2.2.1, we describe the new set of conservation equations. In §2.2.2 and §2.2.3, we describe the algorithm for anisotropic cosmic-ray streaming and diffusion. In §2.2.4 we discuss our approach for avoiding unphysical values of cosmic-ray energy.

2.2.1 Cosmic-ray Fluid

As an Eulerian code, *ENZO* models gas as a fluid moving through grid cells that are fixed in space. At every timestep, *ENZO* advances the state of the fluid in the simulation by numerically approximating a solution to the equations below. These equations encompass the conservation of mass (Equation 2.1), conservation of momentum (Equation 2.2), the induction equation (Equation 2.3), and the energy equation (Equation 2.4). In simplified terms, these equations assert that the change over time in the value of a given conserved

quantity in one cell (the $\frac{\partial}{\partial t}$ term) is equal to the flux of that conserved quantity through the boundaries of that cell (the $\nabla \cdot ()$ term). Source terms, which encompass both energy gains and losses (for example, an injection of cosmic-ray energy after a supernova explosion) appear on the right-hand-side of the equality. Traditionally, the evolution of thermal gas is encompassed in Equations 2.1 - 2.4 (setting the cosmic-ray pressure term, P_c to zero). We model the evolution of cosmic rays as an additional ultra-relativistic proton fluid with adiabatic index $\gamma_c = 4/3$ (Jun et al., 1994; Drury and Falle, 1986) in Equation 2.5.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (2.1)$$

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}^T + P_g + P_c) = -\rho \nabla \Phi \quad (2.2)$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{B} \mathbf{v}^T - \mathbf{v} \mathbf{B}^T) = \mathbf{0} \quad (2.3)$$

$$\frac{\partial \varepsilon_g}{\partial t} + \nabla \cdot (\mathbf{v} \varepsilon_g) = -P_g \nabla \cdot \mathbf{v} + H_c + \Gamma_g + \Lambda_g \quad (2.4)$$

$$\frac{\partial \varepsilon_c}{\partial t} + \nabla \cdot \mathbf{F}_c = -P_c \nabla \cdot \mathbf{v} - H_c + \Gamma_c + \Lambda_c. \quad (2.5)$$

$$\mathbf{F}_c = \mathbf{v} \varepsilon_c + \mathbf{v}_s (\varepsilon_c + P_c) - \kappa_\varepsilon \mathbf{b} (\mathbf{b} \cdot \nabla \varepsilon_c) \quad (2.6)$$

Here, we define Φ to be the gravitational potential (where $\nabla^2 \Phi = 4\pi G \rho_{tot}$), ρ_{tot} to be the total density, and ρ , $\mathbf{v}$ to be the gas density and velocity. $\mathbf{B}$ is the magnetic field strength, and $\mathbf{b} = \mathbf{B}/|\mathbf{B}|$ is the magnetic field direction. The superscript T denotes the vector transpose. The internal gas pressure, P_g is related to the internal thermal energy density $\varepsilon_g = (\gamma_g - 1)P_g$, where $\gamma_g = 5/3$. Similarly, the cosmic-ray pressure is related to the cosmic-ray energy density, $\varepsilon_c = (\gamma_c - 1)P_c$, with $\gamma_c = 4/3$. From here on out, we use the subscript ‘g’ to refer to properties of the thermal gas, and the subscript ‘c’ to refer to

properties of the cosmic-ray fluid. We model the diffusion coefficient, κ_ε as a constant, which is observationally constrained to be on the order of $\kappa_\varepsilon \simeq 10^{28} \text{ cm}^2 \text{ s}^{-1}$ (Ptuskin et al., 2006; Strong and Moskalenko, 1998; Tabatabaei et al., 2013). Although we neglect cosmic-ray transport perpendicular to the magnetic field, it could have observable effects (Kumar and Eichler, 2014). Γ and Λ are energy source and sink terms respectively. In our simulations, the source of cosmic-ray energy is supernova events. We do not implement hadronic cosmic-ray energy losses.

Equation 2.6 encompasses the three modes of cosmic-ray transport that we have implemented. The first term on the left represents advection, in which the cosmic-ray fluid moves with the bulk velocity of the thermal gas. This term is solved explicitly in the Riemann solvers of ENZO. The next two terms describe cosmic-ray streaming and diffusion respectively. These are approximations to cosmic-ray motion relative to the gas and are therefore solved separately from the advection equation. The implementation of these transport methods is described in detail in sections 2.2.2 and 2.2.3.

In the streaming approximation, cosmic rays move relative to the gas with a velocity given by

$$\mathbf{v}_s = -sgn(\mathbf{b} \cdot \nabla \varepsilon_c) \cdot f_s \mathbf{v}_A \quad (2.7)$$

Here, f_s is the constant streaming factor described in Ruszkowski et al. (2017). The Alfvén velocity, $\mathbf{v}_A = \mathbf{B}/\sqrt{4\pi\rho}$ represents the transverse waves propagating along the magnetic field lines in a plasma. The function sgn returns the sign of the enclosed expression. In this limit, cosmic rays also transfer momentum to the thermal gas through the heating term, H_c , where

$$H_c = |\mathbf{v}_A \cdot \nabla P_c|. \quad (2.8)$$

Although this term appears only in the streaming approximation, we follow the example of Wiener et al. (2017) and include it in some simulations with cosmic-ray diffusion to isolate the underlying differences in the different transport mechanisms (see Table 2.1).

2.2.2 Cosmic-ray Streaming

Both cosmic-ray streaming and diffusion are approximations to cosmic rays scattering off of Alfvén waves. The difference lies in the source that is generating these waves. In the streaming approximation, cosmic rays are assumed to drive the growth of Alfvén waves through the streaming instability [Kulsrud and Pearce \(1969\)](#). This is often referred to as the “self-confinement” case ([Zweibel, 2017](#)).

We isolate the streaming behavior from the general cosmic-ray transport equation (Eqn. 2.6) using

$$\frac{\partial \varepsilon_c}{\partial t} - \nabla \cdot [\mathbf{v}_s(\varepsilon_c + P_c)] = 0. \quad (2.9)$$

At each simulation timestep, we calculate cosmic-ray streaming by updating the value of the cosmic-ray energy density in each cell. The evolution of the cosmic-ray energy density in cell i is given by

$$\varepsilon_{c,i}^{n+1} = \varepsilon_{c,i}^n - \Delta t \sum_j -\text{sgn}(\mathbf{b}_{ij} \cdot \nabla \varepsilon_{c,ij}^n) \mathbf{v}_{A,ij} \cdot \mathbf{n}_{ij} (\Delta x_{ij})^{-1}, \quad (2.10)$$

where $\varepsilon_{c,i}^n$ is the value of the cosmic-ray energy density in cell i before streaming is applied. Δt is the timestep, and the terms $\mathbf{b}_{ij}$ and $\nabla \varepsilon_{c,ij}^n$ are the direction of the magnetic field and the gradient of cosmic-ray energy density computed at cell face j . $\mathbf{n}_{ij}$ describes the plane parallel to face j , and Δx_{ij} is the length of the cell’s axis that is perpendicular to face j . If the cells in the simulation are constructed as cubes, then Δx can be treated as a constant and moved out of the summation term.

The streaming time step is set by the bulk motion of the gas and the Alfvén velocity, so that $t_{\text{stream}} < \frac{\Delta x}{\mathbf{v}_g + f_s \mathbf{v}_a}$. We avoid instabilities near local extrema of cosmic-ray energy density by employing the regularization described in [Sharma et al. \(2009\)](#) and [Ruszkowski et al. \(2017\)](#) where

$$\mathbf{F}_c = -(e_c + p_c) \mathbf{u}_A \tanh(h_c \hat{\mathbf{v}} \cdot \nabla e_c / e_c). \quad (2.11)$$

We follow the recommendation of [Ruszkowski et al. \(2017\)](#) and set the free regularization parameter, h_c , to 10 kpc.

2.2.3 Cosmic-ray Diffusion

In the “extrinsic turbulence” case, Alfvén waves are excited by turbulent motions in the thermal gas. Since the gyroradius of cosmic rays around magnetic field lines is significantly smaller than the best-resolved cells in our simulation, cosmic-ray transport in this regime is modeled as diffusion parallel to the direction of magnetic field lines. At each timestep, in addition to solving the conservation equations, ENZO computes cosmic-ray diffusion according to

$$\frac{\partial \varepsilon_c}{\partial t} - \nabla \cdot [\kappa_\varepsilon \mathbf{b}(\mathbf{b} \cdot \nabla \varepsilon_c)] = 0. \quad (2.12)$$

With diffusion, the updated cosmic-ray energy density in a grid cell, i follows the prescription

$$\varepsilon_{c,i}^{n+1} = \varepsilon_{c,i}^n + \Delta t \sum_j \kappa_\varepsilon (\mathbf{b}_{ij} \cdot \nabla \varepsilon_{c,ij}^n) \mathbf{b}_{ij} \cdot \mathbf{n}_{ij} (\Delta x_{ij})^{-1}, \quad (2.13)$$

where Δt is the diffusion timestep.

In the case of isotropic diffusion, Equation 2.13 becomes

$$\varepsilon_{c,i}^{n+1} = \varepsilon_{c,i}^n + \Delta t \sum_j \kappa_\varepsilon \nabla \varepsilon_{c,ij}^n \cdot \mathbf{n}_{ij} (\Delta x_{ij})^{-1}. \quad (2.14)$$

We employ an explicit diffusion scheme because we find that our simulation time step is not limited by the diffusion time step constraint of $t_{\text{diff}} < \frac{1}{2N} \frac{\Delta x^2}{\kappa_\varepsilon}$, where N is the dimensionality of our simulation. For a detailed discussion on numerically modeling semi-implicit anisotropic cosmic-ray diffusion, see [Pakmor et al. \(2016a\)](#).

2.2.4 Limiting the Gradient

For some geometrical configurations, using a simple estimate of the cosmic-ray energy gradient when calculating anisotropic diffusion violates the second law of thermodynamics and leads to an unphysical flow of cosmic-ray energy from cells with lower energy density to cells with higher energy density. In more extreme cases, this leads to some cells developing unphysical (negative) values of cosmic-ray energy. To combat this issue, we employ a limited gradient as described in [van Leer \(1977\)](#).

The simple gradient only considers the flux through a given cell face, so that

$$\nabla \varepsilon_c = \frac{\varepsilon_{c,i+1} - \varepsilon_{c,i}}{\Delta x_i} \quad (2.15)$$

where i and $i + 1$ are the indices of neighboring cells.

Where the simple gradient produces an unphysical flux, we estimate the limited cosmic-ray energy density gradient on the interface ([Sharma and Hammett, 2007](#); [Pakmor et al., 2016a](#)) to be

$$\nabla \varepsilon_c = \frac{4}{\sum_n (\nabla \varepsilon_{cr}^n)^{-1}}. \quad (2.16)$$

This approximation takes into account the component of the gradient that is parallel to the cell face, n .

2.3 Numerical Methods

We conduct our work using ENZO, an open source multi-physics MHD astrophysical simulation code that employs AMR to resolve areas of interest ([Collins et al., 2010](#); [Bryan et al., 2014](#)). At each time step, ENZO solves the Riemann conservation equations. We employ the local Lax-Friedrichs Riemann solver (LLF; [Kurganov and Tadmor 2000](#)) to compute the flux at cell interfaces and spatial reconstruction is performed with the piecewise linear method (PLM; [van Leer 1977](#)). Time stepping is carried out with the total variation diminishing (TVD) 2nd order Runge-Kutta (RK) scheme ([Shu and Osher, 1988](#)). To avoid

creating unphysical magnetic monopoles, we employ a hyperbolic divergence cleaning approach first described by [Dedner et al. \(2002\)](#). Interested readers should see [Wang et al. \(2008\)](#); [Wang and Abel \(2009\)](#) for detailed discussions and extensive testing of the MHD formulation in ENZO.

2.3.1 *Stellar Feedback*

Star formation in our simulations follows the prescription described in [Cen and Ostriker \(1992\)](#) with minor modifications. Stars particles are only formed in grids at the maximum level of refinement that meet predetermined density, mass, and minimum dynamical time thresholds: $\rho_{\text{cell}} > \rho_{\text{thres}}$, $M_{\text{cell}} > M_{\text{thres}}$, $t_{\text{cool,cell}} < t_{\text{dyn,min}}$. The exact values for ρ_{thres} , M_{thres} , $t_{\text{dyn,min}}$ depend on the resolution of the simulation, because a very resolved cell may not be capable of holding sufficient mass to satisfy the formation criteria. In our simulations, we choose $\rho_{\text{thres}} = 3.0 \times 10^{-26} \text{ g cm}^{-3}$, $M_{\text{thres}} = 3.0 \times 10^5 M_{\odot}$, $t_{\text{dyn,min}} = 10 \text{ Myr}$. Additionally, the gas in the parent cell must be collapsing (determined by measuring negative velocity divergence) and Jeans unstable. If all conditions are met, the parent cell produces a star cluster particle with 10% mass efficiency so that the initial mass is given by $M_{\text{SC}}^{\text{init}} = 0.1 \rho_g \Delta x^3$.

Over the course of 120 Myr, 25% of that mass is ejected into the cell in which the star cluster particle resides, modeling the effects of Type II supernovae. We inject 10^{51} ergs of energy for every $42 M_{\odot}$, so that a star cluster particle of $M = 3.0 \times 10^5 M_{\odot}$ expels a total of $E_{\text{tot}} = 5.4 \times 10^{54}$ ergs of energy. In our model, this total energy is comprised of thermal, magnetic, and cosmic-ray energy so that $E_{\text{th}} = f_{\text{th}} E_{\text{tot}}$, $E_B = f_B E_{\text{tot}}$, and $E_{\text{cr}} = f_{\text{cr}} E_{\text{tot}}$, where $f_{\text{th}} + f_B + f_{\text{cr}} = 1$. We adopt a conservative estimate of $f_B = 0.01$, $f_{\text{cr}} = 0.1$ ([Wefel, 1987](#); [Ellison et al., 2010](#)) and assume 2% of the ejecta to be metals.

2.3.2 Chemistry and Cooling

In our simulations, we explicitly track all ion species of hydrogen. All other species are tracked together in a metallicity variable. We calculate cooling using the GRACKLE chemistry library (Bryan et al., 2014; Smith et al., 2017) that is integrated with ENZO. It uses pre-computed tables of metal cooling rates as functions of the gas density and temperature generated by CLOUDY (Ferland et al., 2013). In addition, we consider uniform photoelectric heating of $8.5 \times 10^{-26} \text{ ergs s}^{-1} \text{ cm}^{-3}$ without selfshielding (Tasker and Bryan, 2008). In our idealized isolated disk setup, we do not consider the ultraviolet background radiation from distant quasars and galaxies.

2.3.3 Synthetic Observations

We use TRIDENT (Hummels et al., 2017), a python based tool integrated with yt (Turk et al., 2012) to construct ion densities and generate synthetic spectra from our simulated datasets. For ions that are not explicitly tracked by the simulation, we can determine their number densities, n_X , in post processing with

$$n_X = n_H Z \left(\frac{n_X}{n_H} \right)_{\odot}, \quad (2.17)$$

where n_H is the total hydrogen number density, Z is the metallicity (a value that is kept track of throughout the simulation), and (n_X/n_H) is the solar number abundance for any element that is not explicitly tracked.

TRIDENT computes relative ion abundances in a simulation cell by considering both photoionization from an extragalactic UV background (Haardt and Madau, 2012), and collisional ionization within the gas. The collisional ionization rate is determined by the cell's temperature, density, and metallicity, using an extensive set of lookup tables pre-calculated by CLOUDY, which assume ionization abundances as predicted by collisional ionization equilibrium (CIE). CIE holds even when cosmic-ray pressure dominates over

thermal pressure because the underlying assumption of our model is that the cosmic-ray fluid is collisionless. Any deviations from CIE (which is more likely in the dense regions of the galactic disk than in the CGM) would likely increase of the ionization rate in low temperature gas (Oppenheimer and Schaye, 2013).

We use this functionality in TRIDENT to plot column densities of different ions as a function of impact parameter in Figure 2.9. We calculate the column densities by defining sight-lines through the simulation box. The ion number density is then calculated in each length element, dl , along this projected ray. The column density along the line-of-sight is then given by the summation $n_{\text{col}} = \sum dl \cdot n$.

2.3.4 Initial Conditions

We simulate a suite of idealized isolated disk galaxies with initial conditions described by the AGORA collaboration (Kim et al., 2014). The fixed dark matter halo of mass $M_{200} = 1.074 \times 10^{12} M_{\odot}$ follows the Navarro-Frenk-White (NFW; Navarro et al. 1997) profile and is situated in a hot (10^6 K), stationary, uniform density box of $(1.31 \text{ Mpc})^3$. The concentration and spin parameters are respectively defined to be $c = 10$, $\lambda = 0.04$. The gaseous disk has a total mass of $M_d = 4.297 \times 10^{10} M_{\odot}$ and follows the analytic exponential profile

$$\rho(r, z) = \rho_0 e^{-r/r_d} e^{-|z|/z_d}$$

where $r_d = 3.432 \text{ kpc}$, $z_d = 343.2 \text{ pc}$, and $\rho_0 = M_d f_{\text{gas}} / 4\pi r_d^2 z_d$. We define $f_{\text{gas}} = 0.2$ to be the gas mass fraction of the disk. The rest of the disk mass (80%) is contained in 10^5 stellar particles. The stellar bulge has a stellar mass of $4.297 \times 10^9 M_{\odot}$ and follows the Hernquist density profile (Hernquist, 1990).

We include an initial toroidal magnetic field of strength $B_0 = 1 \mu\text{G}$ in the disk and a toroidal field of $B_0 = 10^{-15} \text{ G}$ in the halo. The strong initial field in the disk follows the example of Ruszkowski et al. (2017) to achieve sufficiently fast cosmic-ray streaming velocities at early simulation times. The strength of the initial halo field lies in the accepted theoretical range of primordial magnetic fields, $10^{-20} - 10^{-9} \text{ G}$ (Cheng et al., 1994; Durrer

and Neronov, 2013). To avoid numerical interpolation errors, galaxy models that include cosmic-ray physics are initialized with an isotropic background cosmic-ray energy density of 0.1 erg/cm^3 . This background cosmic-ray pressure is 15 orders of magnitude weaker than the initial conditions of the gas pressure and does not alter the thermal gas in any significant way. Because we are interested in tracing the cycling process of metals, we set the initial metallicities of the disk and halo to be $0.3Z_\odot$ and $10^{-3}Z_\odot$ respectively.

2.3.5 Description of Simulation Suite

Our simulation suite is designed to isolate the effect of different implementations of cosmic-ray transport. All of the galaxy models share the initial conditions described above. The fiducial models differ from each other only in their cosmic-ray transport prescription and are described below:

- Model NCR does not include cosmic-ray physics and serves as our control model.
- Model ADV only simulates cosmic-ray advection with the bulk motion of the gas.
- Model ISOD assumes isotropic cosmic-ray diffusion using the algorithm described in Salem and Bryan (2014) with a constant diffusion coefficient of $\kappa_\epsilon = 3 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$.
- Model ANISD assumes anisotropic cosmic-ray diffusion along magnetic field lines with a constant diffusion coefficient of $\kappa_\epsilon = 3 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$.
- Model ANISDH builds on model ANISD with an added cosmic-ray heating term, H_c .
- Model STREAM assumes cosmic-ray streaming with a streaming factor of $f_s = 4$ (Ruszkowski et al., 2017).

Run ID	Min. grid size (pc)	Cosmic-ray Parameters				
		f_c	Transport Mode	$\kappa_\epsilon [\times 10^{28} \text{ cm}^2/\text{s}]$	f_s	H_c
NCR	160	-	no CRs	-	-	no
	320	-	no CRs	-	-	no
ADV	160	0.1	advection only	0	-	no
	320	0.01	advection only	0	-	no
	320	0.1	advection only	0	-	no
	320	0.3	advection only	0	-	no
ISOD	160	0.1	isotropic diffusion	3	-	no
	320	0.01	isotropic diffusion	3	-	no
	320	0.1	isotropic diffusion	3	-	no
	320	0.3	isotropic diffusion	3	-	no
	320	0.1	isotropic diffusion	1	-	no
^a ANISD	160	0.1	anisotropic diffusion	3	-	no
	320	0.01	anisotropic diffusion	3	-	no
	320	0.1	anisotropic diffusion	3	-	no
	320	0.1	anisotropic diffusion	10	-	no
	320	0.3	anisotropic diffusion	3	-	no
	320	0.1	anisotropic diffusion	1	-	no
ANISDH	160	0.1	anisotropic diffusion	3	-	yes
	320	0.1	anisotropic diffusion	3	-	yes
STREAM	160	0.1	streaming	-	4	yes
	160	0.1	streaming	-	1	yes
	320	0.01	streaming	-	4	yes
	320	0.1	streaming	-	1	yes
	320	0.1	streaming	-	2	yes
	320	0.1	streaming	-	4	yes
	320	0.3	streaming	-	4	yes

^aA summary of the simulation initial conditions. The run ID and the corresponding boldface entries describe the fiducial runs discussed in depth throughout this chapter. The fiducial runs differ from each other only by the invoked cosmic-ray transport mechanism. We deviate from the fiducial runs by changing the resolution, the fraction of supernova energy injected as cosmic rays (f_c), the diffusion coefficient (κ_ϵ), the streaming factor (f_s), and including the cosmic-ray heating term (H_c). Figure 2.11 compares the effect of these variables on the cosmic-ray pressure distribution in the CGM.

Table 2.1 Simulation Parameters

All of our fiducial models that include cosmic-ray physics (in bold font in Table 2.1) inject 10% of their supernova ejecta in the form of cosmic-ray energy. See Table 2.1 for a summary of the different models.

2.4 Results

2.4.1 Outflows

The CGM in the isolated galaxy models is enriched solely by the outflows that expel gas from the disk. For this reason, we first turn our attention to analyzing the cosmic-ray-driven winds and their dependence on the cosmic-ray transport mechanism.

In broad strokes, a cosmic-ray-driven wind begins when cosmic rays move down their gradient, out of the midplane of the galaxy. Cosmic-ray pressure support then lifts low-entropy gas out of the galactic potential well, triggering outflows. Figure 2.1 displays the relationship between gas entropy (top row), the vertical component of the velocity of the galactic winds (middle row), and the ratio of cosmic-ray to thermal pressures (bottom row) after 2 Gyr of evolution. From left to right, the columns show models with: No cosmic-ray physics (NCR), cosmic-ray advection (ADV) only, isotropic cosmic-ray diffusion (ISOD), anisotropic cosmic-ray diffusion (ANISD, and cosmic-ray streaming (STREAM)).

Although models NCR and ADV experienced a brief period of weak gas expulsion, by $t = 2$ Gyr these galaxies have lost all signs of outflows and show no signs of strong inflows. This is reinforced by the gas entropy profiles, which resemble the initial conditions. The main difference between models NCR and ADV at this time is near the midplane of the galaxy, where the cosmic-ray pressure of model ADV has created a thicker vertical disk profile. Confined to move solely through advection, the cosmic rays in model ADV have no efficient mechanism for escaping the disk.

Models with cosmic-ray transport relative to the gas (ISOD, ANISD, and STREAM) all drive strong outflows with velocities reaching 10^2 km/s, consistent with previous works (e.g. Salem et al., 2016; Pakmor et al., 2016b; Wiener et al., 2017).

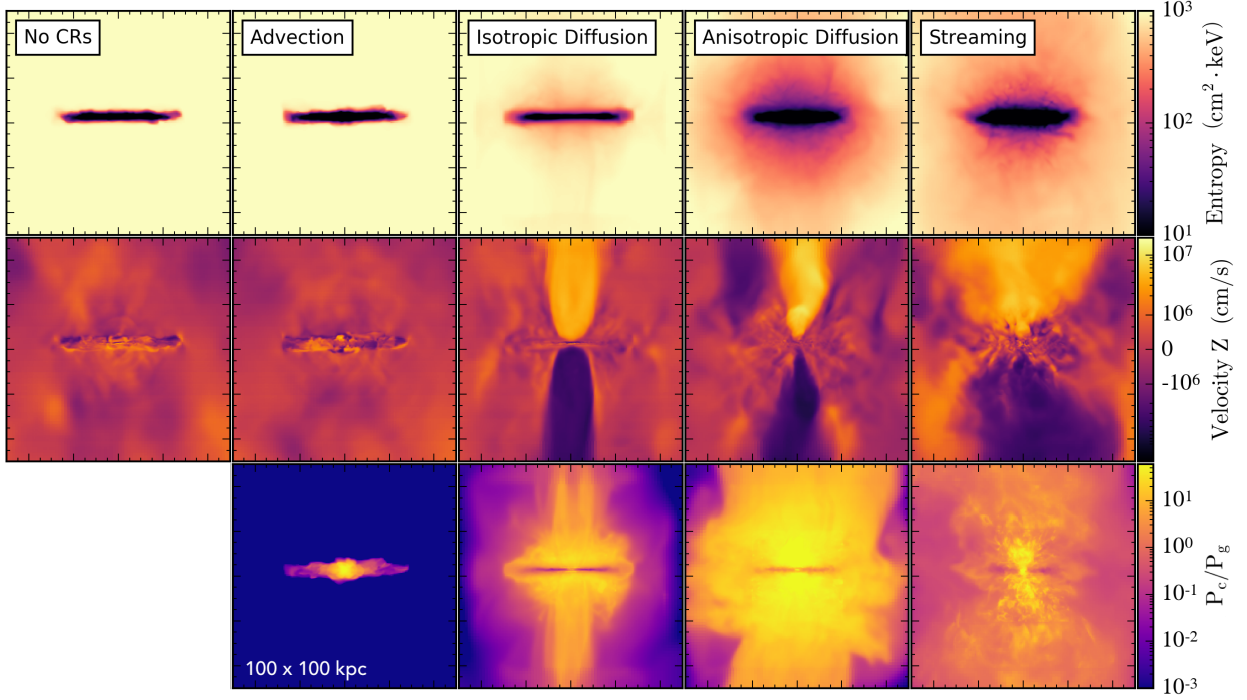


Figure 2.1 A comparison of the outflows between different galaxy models. Each row shows the edge-on, density-weighted projection of the gas entropy (top), z-component of the velocity (middle) and ratio of cosmic-ray and thermal pressures (bottom). Each column holds a simulated galaxy with different cosmic-ray treatment. From left to right, the columns show simulations with: no cosmic rays, cosmic-ray advection only, isotropic diffusion, anisotropic diffusion, and streaming. The snapshots were taken at $t = 2$ Gyr. Only models with cosmic-ray transport relative to the gas drive strong outflows by providing a nonthermal source of pressure to lift low-entropy gas out of the disk. The strength and morphology of the outflows is sensitive to the choice of cosmic-ray transport.

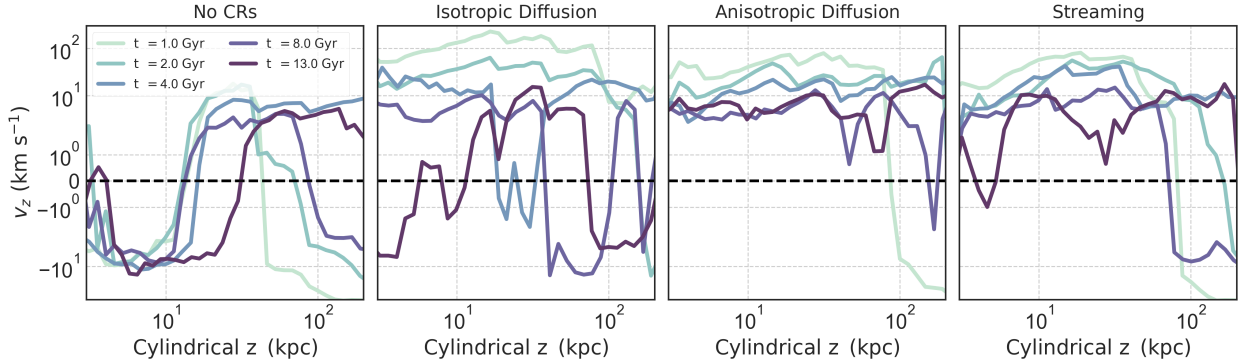


Figure 2.2 The time-evolution of the vertical velocity profile as a function of the height above the galactic disk for galaxy models NCR, ISOD, ANISD, and STREAM. Model NCR shows no signs of strong outflows. Model ISOD has the fastest outflow velocities but loses its galactic wind by $t = 4$ Gyr. Models ANISD drive weaker yet steadier galactic winds. Model STREAM is the only model to develop inflows near the galactic disk while simultaneously hosting outflows at larger radii.

Model ISOD drives relatively thin and uniform conical outflows. The gas entropy profile is relatively unaltered, reaching values near $5 \times 10^2 \text{ cm}^2 \text{ keV}$ near the midplane of the disk. Cosmic-ray pressure dominates over thermal pressure, tracing the shape of the outflows out to a cylindrical radius of 10 kpc. Outside of the active outflow region, the cosmic-ray pressure is below one tenth of the gas pressure.

The outflows generated with anisotropic cosmic-ray diffusion in model ANISD have a thinner radial profile and reach higher velocities compared to those driven by isotropic diffusion. For $z > 20$ kpc outside of the midplane, there are signs of infalling gas surrounding the outflow. The cosmic-ray pressure dominates over thermal pressure for nearly all radii in the 100×100 kpc projection. The gas entropy reaches values of $50 \text{ cm}^2 \text{ keV}$ just outside the disk, roughly an order of magnitude lower than that in model ISOD.

Compared to both of the diffusion models, the outflows generated by cosmic-ray streaming start higher above the midplane of the disk and have a wider horizontal extent, reaching radii of nearly 40 kpc at a vertical height of 50 kpc. Near the galactic center, there are

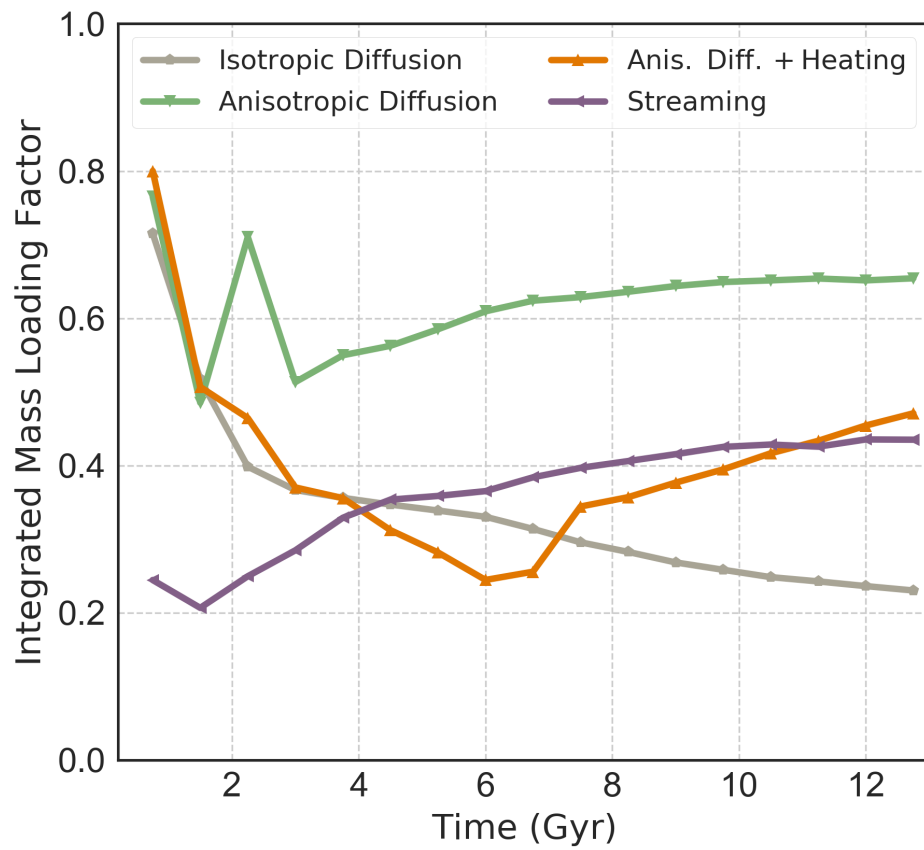


Figure 2.3 The time-evolution of the integrated mass loading factor (the total ejected gas mass / total mass in stars), measured at 150 kpc from the galactic center. At late times, models with anisotropic cosmic-ray transport continue driving gas out of the galaxy, even when star formation is declining.

several filaments of inflowing gas. Compared to model ANISD, model STREAM has lower gas entropy immediately outside the disk and at larger radii, maintaining values around $5 \times 10^2 \text{ cm}^2 \text{ keV}$ at radii 50 kpc. Unlike either of the diffusion models, the distribution of the cosmic-ray pressure ratio in model STREAM is patchy, ranging from 0.2 - 50 times that of the thermal pressure.

Figure 2.2 follows the time evolution of the density-weighted outflow velocity as a function of the height above the galactic disk, for models with different cosmic-ray transport prescriptions. At early times, gas in our control model, NCR, is inflowing at all radii within 200 kpc of the galactic center. After 2 Gyr, weak ($v_z = 10 \text{ km/s}$) outflows develop at heights above 30 kpc. As we shall see in Figure 2.6, these weak outflows fail to enrich the CGM with metals. Instead, we turn our attention to models ISOD, ANISD, and STREAM, for which 10% of supernova feedback was injected as cosmic-ray energy.

Model ISOD has the strongest outflows at $t = 1 \text{ Gyr}$, with radially-averaged velocities surpassing 100 km/s. By $t = 4 \text{ Gyr}$, these outflows weaken significantly, with average velocities hovering around 10 km/s. After 8 Gyr, notable inflows develop at radii above 30 kpc and persist for the rest of the simulation time.

This galactic wind is consistent with expectations of isotropic cosmic-ray diffusion. The initial burst of supernova feedback in model ISOD creates a steep gradient of cosmic-ray energy density. With isotropic diffusion, cosmic rays drag gas out of the galaxy as they travel down their own gradient, uninhibited by the presence of magnetic fields. This process continues until the cosmic-ray gradient flattens, slowing down the diffusion process. At later times, the star formation has decreased enough that the newly-injected cosmic rays can no longer create a gradient steep enough to drive a strong wind. As the cosmic rays in the CGM continue to stream away from the galaxy, they cannot provide enough pressure support to the gas they expelled and it begins to collapse back down on to the galaxy.

Model ANISD retains consistent outflow velocities within 50 kpc of the disk throughout its evolution. Beyond 50 kpc, the winds are sensitive to the star formation history. For

example, the double-valley feature at $t = 8$ Gyr traces the suppressed star formation at $t = 7$ Gyr (see Figure 2.5).

The steady nature of the galactic outflows in model ANISD is fueled by anisotropic cosmic-ray diffusion. In this approximation, the velocity with which cosmic rays can escape the disk is regulated by the complex geometry of magnetic field lines. Therefore, the galaxy releases its built-up cosmic-ray energy slowly over time. Although the galaxy is quenched after $t = 10$ Gyr, weak outflows in model ANISD persist out to $t = 13$ Gyr.

Like in model ANISD, the key to sustained outflows in model STREAM is its anisotropic cosmic-ray transport. Unlike any other fiducial run, model STREAM shows signs of inflow near the disk while simultaneously hosting outflows at larger radii.

The integrated mass loading factor (IMLF), defined as the ratio of the total injected gas mass over the total stellar mass, quantifies the expelled gas content. Figure 2.3 shows the evolution of the IMLF in models ISOD, ANISD, ANISDH, and STREAM. We exclude models NOCR and ADV, which did not drive outflows, from this analysis.

For the first 1.5 Gyr, the IMLF is nearly indistinguishable between models ISOD, ANISD and ANISDH. The low IMLF at early times in model STREAM is most likely due to the later onset of the galactic wind as well as the wind's location above the galactic midplane.

At later times, the IMLF decreases in model ISOD, yet increases in the other three models. Model ANISD reaches the highest IMLF due to the accumulated reservoir of cosmic-ray energy near the galactic disk that continues to drive outflows even after star formation has ceased. Models ANISDH and STREAM have weaker IMLFs than model ANSID due to higher star formation rates and losses in cosmic-ray energy through the heating term.

2.4.2 *Star Formation and Morphology*

The relationship between cosmic-ray transport and a galaxy's star formation rate (SFR) can dramatically influence a galaxy's morphology. The outflows generated by different cosmic-ray transport prescriptions remove gas from the disk which would have otherwise

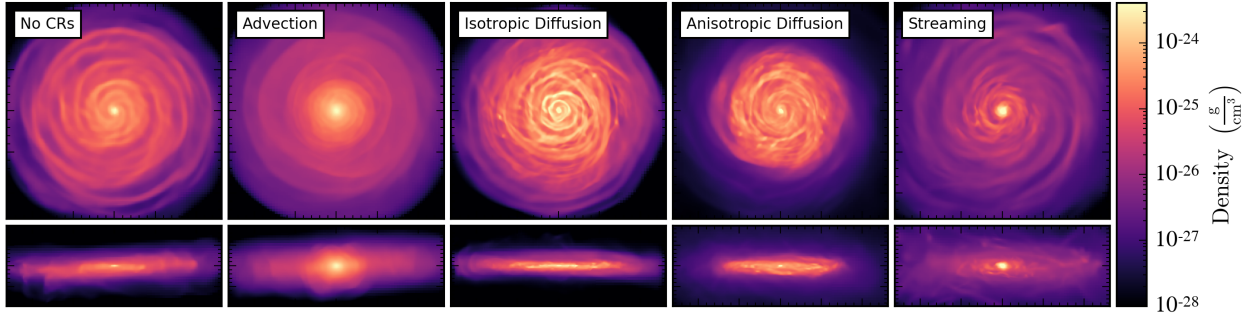


Figure 2.4 The face-on (top) and edge-on (bottom) density projections of the gas in our fiducial models after 13 Gyr of evolution. Although all galaxy models started from the same initial conditions, their morphologies depend on the cosmic-ray transport mechanism. The control model, NCR, is a MW-type spiral galaxy. Models ADV and STREAM have extended gas profiles and thick disks. Model ANISD has lost much of its gas to outflows. The top and bottom rows show physical scales of 52×52 kpc and 20×52 kpc respectively.

been available for star formation. In addition, the presence of strong cosmic-ray pressure in the disk can prevent star formation by stabilizing the thermal gas against collapse. In this section, we contrast the morphologies of our fiducial galaxy models after evolving the simulations for 13 Gyr. Because a galaxy’s morphology is so intricately tied to its star formation history, we describe Figures 2.4 and 2.5 simultaneously.

Figure 2.4 displays the density-weighted face-on and edge-on projections of the gas density in our fiducial galaxy models after 13 Gyr of evolution. In the left panel, model NCR serves as the benchmark example of a MW-type disk galaxy. This galaxy has a clear spiral structure, with the disk extending to a radius of roughly 25 kpc and a vertical height of roughly 3 kpc. The star formation rate of model NCR begins with one solar mass per year and slowly decreases over time, hovering around a few tenths of a solar mass at later times. With a modest star formation history and no galactic winds, model NCR retains much of its gas in its disk, with average density values around $3 \times 10^{-25} \text{ g/cm}^3$.

Although model ADV has had a similar outflow history as NCR, its star formation history has dramatically altered its morphology. Model ADV quenched only 200 Myr after

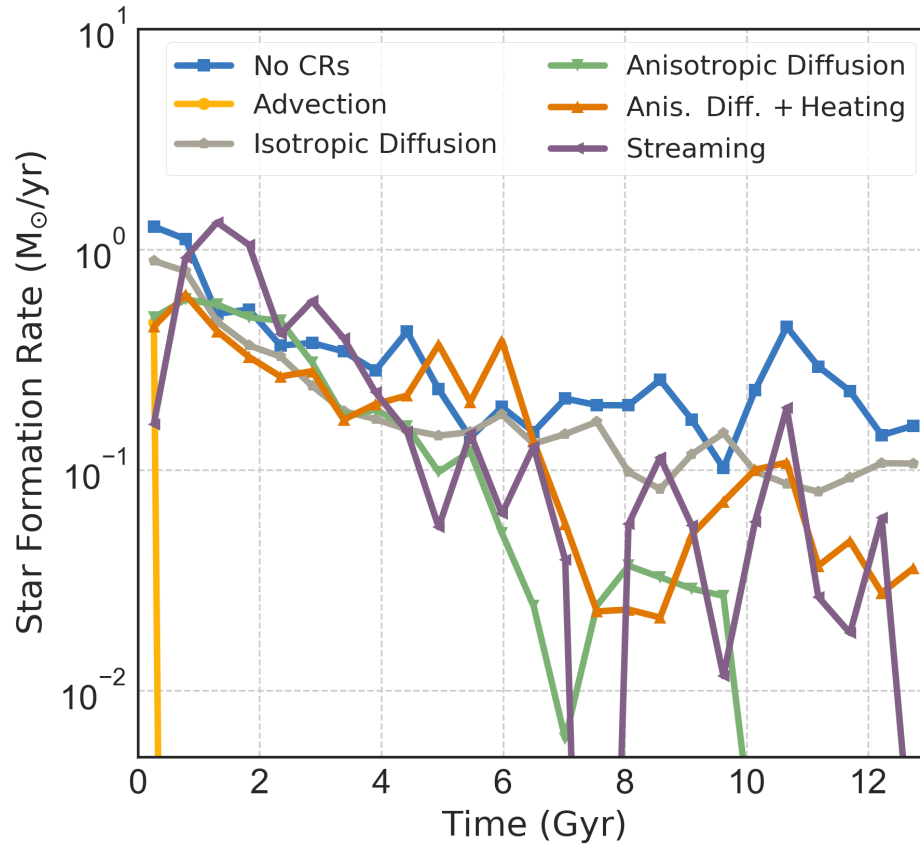


Figure 2.5 The star formation rate as a function of time for galaxy models with different cosmic-ray transport prescriptions. Model ADV quenches after the first episode of star formation. The star formation in model ISOD consistently lies just below that of the control model NCR with no cosmic rays. Model ANISD briefly matches the star formation in the control around $t = 2.5$ Gyr, but is quenched soon after at around $t = 10$ Gyr. Model STREAM has a variable star formation history with a period of roughly 2 Gyr.

its initial burst of star formation (see Figure 2.5). Confined to advection-only transport, the cosmic rays in this galaxy are trapped inside the galactic disk. After the first episode of star formation induces cosmic-ray feedback, cosmic-ray pressure dominates over gas pressure (see the bottom-left panel of Figure 2.1 and the discussion in §2.4.1). This additional pressure stabilizes the gas against collapse, halting future star formation. Without galactic outflows to carry cosmic rays out of the disk and without any new stars to create supernovae that could potentially drive outflows, this galaxy will remain quenched. Although model ADV has a substantial reservoir of gas in its disk, cosmic-ray pressure expands its vertical profile keeping the gas at lower average densities.

The star formation history of model ISOD most closely follows that of model NCR. Episodes of star formation that expel cosmic rays into the disk keep the SFR of model ISOD consistently below that of the control. However, because isotropic diffusion is efficient at removing cosmic rays from the galactic disk, star formation is only weakly suppressed in this galaxy. The morphology of model ISOD is qualitatively similar to that of model NCR out to a cylindrical radius of 15 kpc. Having expelled much of its ISM through outflows, model ISOD has a shorter radial and vertical extent to its gas.

Anisotropic cosmic-ray transport in model ANISD retains cosmic-ray pressure in the disk, which suppresses star formation at early times. As galactic outflows develop, the cosmic-ray pressure is lifted out of the disk, allowing for star formation to resume. After roughly 2 Gyr of evolution the star formation in model ANISD briefly matches that of the control model. The injected cosmic-ray pressure following this star formation episode decreases future star formation, ultimately quenching the galaxy after 10 Gyr. Cosmic-ray heating in model ANISDH relieves some of the cosmic-ray pressure in the disk, leading to a higher star formation rate than that in model ANISD. Although at the time of the snapshot in Figure 2.4 model ANISD has been quenched for 3 Gyr, this galaxy model retains some spiral structure and high gas densities within a 15 kpc radius of its center. The lingering cosmic-ray pressure from past star formation creates an extended low-density gas profile around the disk.

Both models ANISD and STREAM have extended, thick gaseous profiles that are most apparent in the edge-on view. Model ANISD has a bimodal distribution of gas, with a core around $2 \times 10^{25} \text{ g/cm}^3$ extending to 15 kpc, surrounded by a less dense gaseous halo extending to 25 kpc. Although some spiral structure is present, it is significantly less pronounced than in model ISOD. Model STREAM has relatively low gas density in the disk with a spiral arm structure that is thinner than that of models NCR or ISOD.

Because of the toroidal geometry of the initial magnetic field, the cosmic rays in model STREAM suppress star formation for the first 500 Myr. Once the magnetic field develops a sufficiently strong vertical component, the cosmic rays escape the disk, dragging thermal gas along with them. The outflows relieve the ISM of the cosmic-ray pressure, allowing star formation to resume. Filaments of inflowing gas near the midplane of the disk (see Figure 2.1) supply the additional gas necessary for extended episodes of star formation. Compared to the other galaxy models, model STREAM has the lowest gas densities and the most extended vertical and radial disk profile.

2.4.3 *The Simulated Circumgalactic Medium*

We now turn our attention to the different ionization structures within the CGM of the simulated galaxy models. Our control model, NCR, has limited amounts of metals outside of the galactic disk. This is an unrealistic result and we will not dwell on its implications here. Our goal is to isolate the effects of cosmic-ray transport on the CGM's temperature and ionization structure, and so the following figures and discussions will focus on models ISOD, ANISD, and STREAM. Where relevant, we discuss model ANISDH, which includes the heating term H_c , that is present in the cosmic-ray streaming prescription. Although the heating term is an unphysical addition to cosmic-ray diffusion, its presence helps isolate which aspect of the cosmic-ray streaming or diffusion mechanism is responsible for observed differences in temperature and ionization states (Wiener et al., 2017).

Figure 2.6 shows the density-weighted projections of gas metallicity and temperature

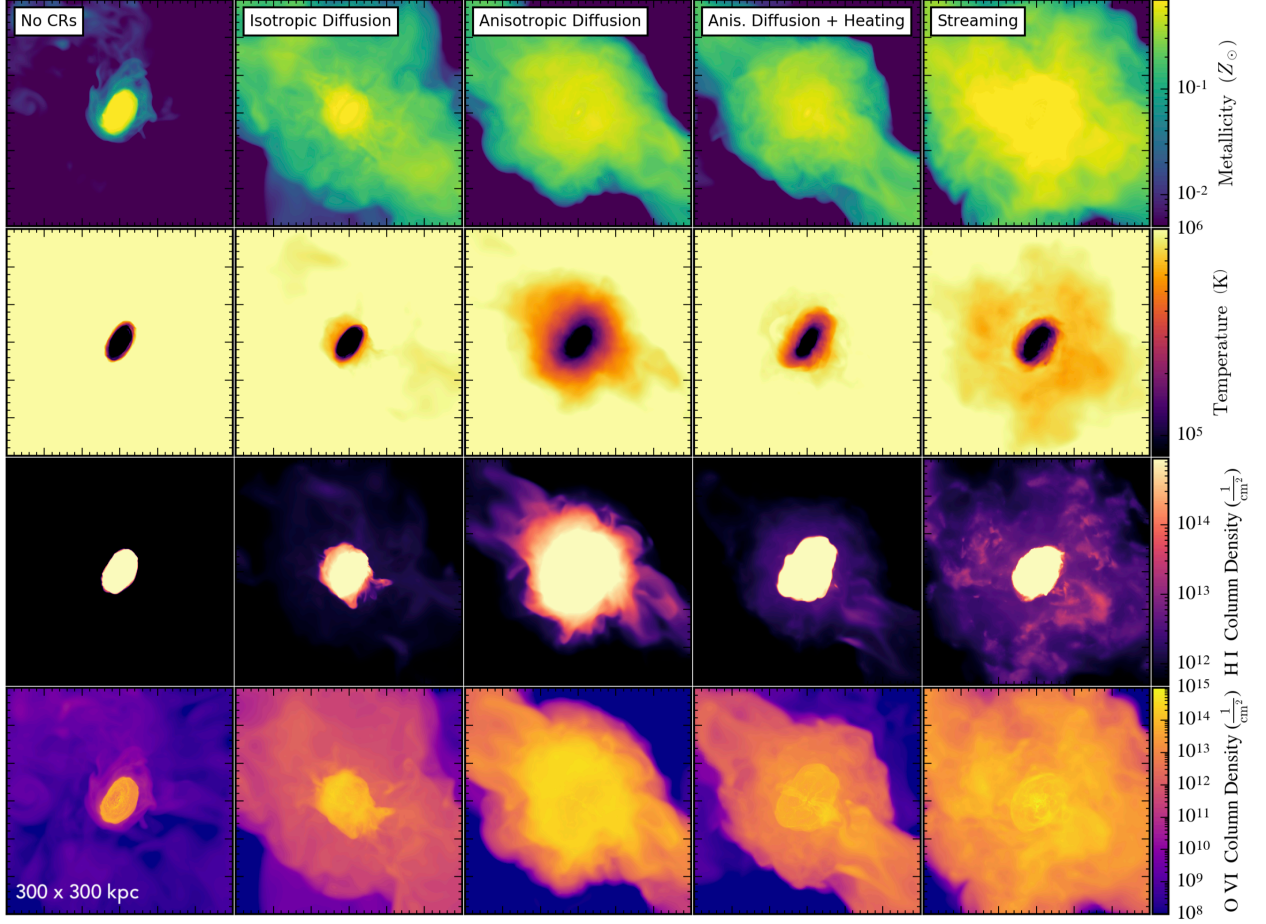


Figure 2.6 A comparison of the state of the CGM between the fiducial galaxy models after 13 Gyr of evolution. The top two rows show the density-weighted metallicity and temperature and the bottom two rows show the unweighted column densities of H I and O VI. Our control model NCR drove weak outflows, so the state of its CGM is relatively unaltered from the initial conditions. Model ISOD has a spatially uniform distribution of warm, metal-rich, gas in its CGM. The galaxy model ANISD is surrounded by a reservoir of cool gas, traced by H I. The temperature and ionization structure of model ANISDH follows the morphology of that in model ANISD although the effect of cosmic-ray pressure is weakened through losses due to cosmic-ray heating. Galaxy model STREAM has a patchy, multiphase distribution of different temperature gas, traced by its H I and O VI column densities. The projection is generated from a 300 kpc cube.

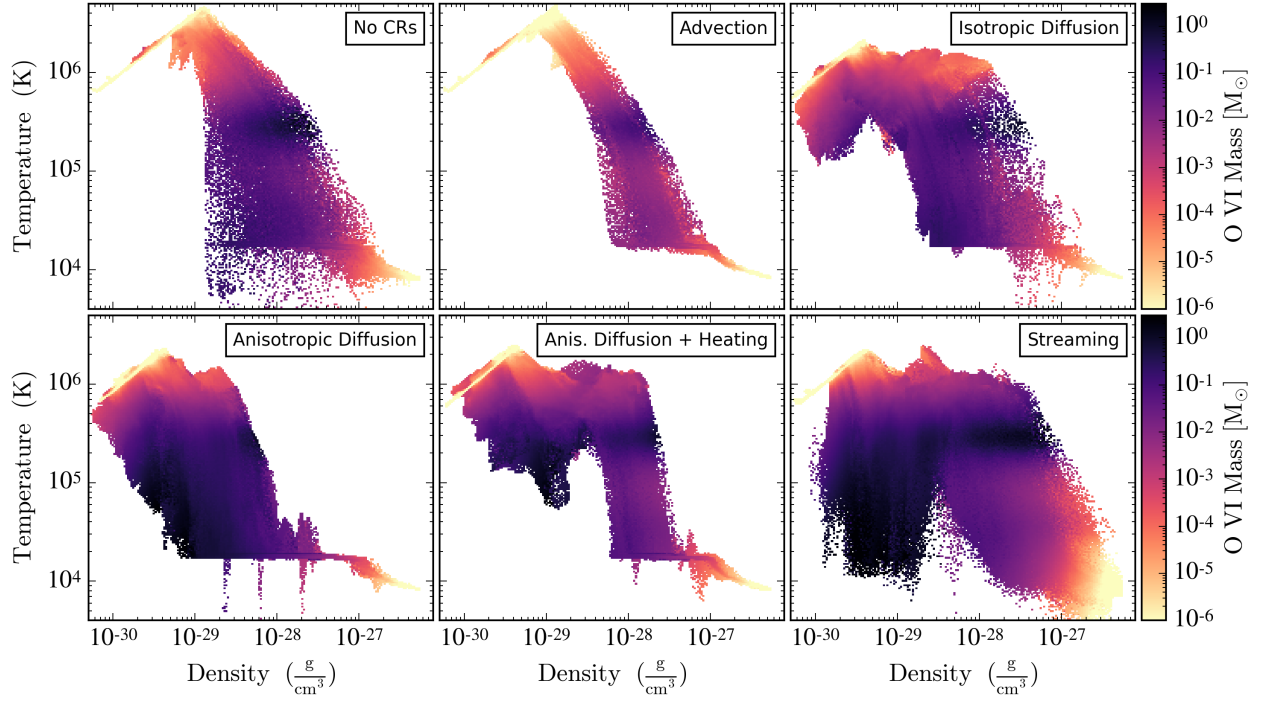


Figure 2.7 The 2D histograms of temperature as a function of density for the six different galaxy models after 13 Gyr of evolution. The color in the plot shows the mass of O VI in each bin. Model ISOD has more diffuse gas at larger radii. Model STREAM creates a more dramatic multiphase medium, with a larger range of possible densities for each temperature. Model STREAM supports an abundance of O VI at both warm and cool temperatures.

and the unweighted projections of H I and O VI column densities after 13 Gyr of evolution. Each column holds a different mode of cosmic-ray transport. Starting from the left, the columns show results for galaxy models NCR, ISOD, ANISD, ANISDH, and STREAM.

The outflows in models with cosmic-ray diffusion or streaming have populated their CGM with metals from the disk out to radii surpassing 200 kpc. Model ISOD has a relatively uniform distribution of metallicity in its CGM, with a density-weighted average value around $0.2 Z_{\odot}$. Similarly, its temperature, H I and O VI column densities are also spatially uniform. cosmic-ray pressure support creates a cooler temperature profile (roughly 3×10^5 K) compared to the control. The cooler temperatures result in stronger column densities of H I and O VI compared to model NCR.

Anisotropic diffusion in model ANISD produces a steep temperature and H I column density gradient. The temperature of the gas is coolest near the disk, where cosmic-ray pressure is strongest, and decreases radially outwards. The H I column density follows the shape of the temperature profile, extending out to where the density-weighted temperature is 10^6 K. The O VI column density is sensitive to metallicity, so the column density profile traces the radial extent of the outflows. Compared to the other fiducial runs, model ANISD has the strongest column densities of H I and O VI. We point out that although this model has been quenched for 3 Gyr, the gradual release of cosmic-ray pressure results in the accumulation of cold gas just outside the disk.

The metallicity distribution of model ANISDH is qualitatively similar to that of model ANISD. However, the added heating term dramatically decreases the impact of cosmic-ray pressure, resulting in warmer temperatures and weaker column densities of H I and O VI than those in model ANISD.

The outflows in model STREAM reach larger radii than those in model ANISD. The temperature profile is dominated by clumps of cool and warm gas extending out to radii of 150 kpc. Model STREAM has a patchy distribution of both H I and O VI column densities, with both coexisting in relative abundance at radii above 100 kpc from the galactic center.

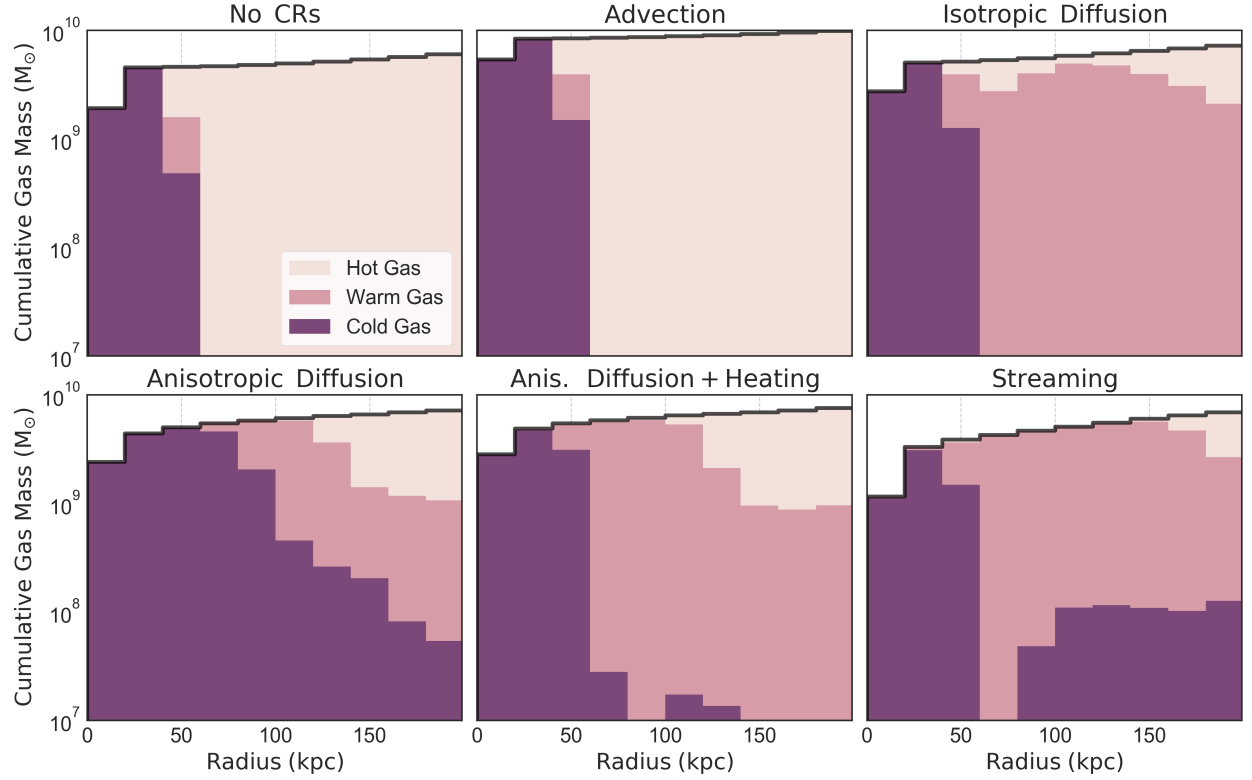


Figure 2.8 The black line follows total enclosed mass as a function of spherical radius for six different galaxy models. The colors of the bars denote the fractional distribution of the gas temperature at different radial shells. We consider three temperature bins of gas: cold gas ($T < 10^5 K$) in dark purple, warm gas ($10^5 K < T < 10^6 K$) in medium purple, and hot gas ($T > 10^6 K$) in light purple. Only models with cosmic-ray transport relative to the gas have a substantial amount of warm or cold gas in their CGM. Model ANISD has an abundance of cool gas near the galactic center that persists at large radii. Model STREAM has a truly multiphase medium with an abundance of cold and warm at radii of 200 kpc.

2.4.4 Temperature Distribution

To better understand the CGM structure, we analyze the abundance of O VI as a function of temperature and density in Figure 2.7. Since we are primarily interested with the gas in the CGM, we exclude data points contained within a cylindrical radius of 25 kpc and a vertical height of 3 kpc of the galactic center.

The CGM of models NCR and ADV has low masses of O VI and scarce amounts of low-density gas compared to the other models. Since low density values trace large radii in the CGM, the artificially high density floors are due to the lack of outflows. Suppressed star formation in model ADV is responsible for the low metallicities in its disk that ultimately result in low masses of O VI.

Models with additional cosmic-ray transport drive strong outflows that enrich the CGM with metals (see Figure 2.6). This enrichment creates higher column densities of O VI at large radii. However, the different prescriptions for cosmic-ray transport result in varied phase structures within the CGM.

One such difference is the shape of the temperature-density phase diagram. Models with weak cosmic-ray pressure support (models ISOD and ANISDH) have less cool gas at low densities than models ANISD and STREAM. The strong cosmic-ray pressure support in models ANISD and STREAM supports a wide range of temperatures at each density. This feature is most pronounced at low densities in model STREAM.

cosmic-ray transport also affects the abundance of O VI and the temperature of the gas that produces it. Both models STREAM and ANISD predict an a reservoir of O VI ionized with the help of cosmic-ray pressure support in low-density gas. However, only model STREAM predicts an abundance of O VI photoionized with gas temperatures around 3×10^5 K, consistent with predictions in [McQuinn and Werk \(2017\)](#).

Figure 2.8 shows the total enclosed mass as a function of spherical radius for six different galaxy models. The colors of the bars denote the fractional distribution of the gas temperature at different radial shells. We consider three temperature bins of gas: cold

gas ($T < 10^5 K$) in dark purple, warm gas ($10^5 K < T < 10^6 K$) in medium purple, and hot gas ($T > 10^6 K$) in light purple. The colored gas fraction is not cumulative since the cold mass contribution from the disk would dominate the distribution in some cases.

Having driven weak outflows, model NCR has trace amounts of cold or warm gas outside of the disk. In contrast, although model ADV had similarly weak winds, the presence of cosmic-ray pressure keeps the gas immediately around the disk below 10^6 K. The influence of cosmic-ray pressure drops abruptly after a radius of 50 kpc. Because the cosmic-ray pressure in the disk for this model stopped star formation almost immediately, model ADV has more gas available both inside and outside the disk of this model.

Models in which cosmic rays can move relative to the gas (via diffusion or streaming) have an altered temperature structure in their CGM. Model ISOD is dominated by warm gas out to large radii. Since isotropic diffusion depends solely on the direction and magnitude of the cosmic-ray energy density gradient, the cosmic-ray pressure distribution is nearly uniform throughout the halo. Over time, with more stellar feedback releasing cosmic rays into the disk, the cosmic-ray pressure accumulates in the halo, providing pressure support to the thermal gas.

Models with anisotropic cosmic-ray transport exhibit a multiphase temperature structure. Models ANISD and ANISDH are both dominated by cold gas near the disk. In both models, the cold gas extends out to radii of 125 kpc and the warm gas extends to radii of 200 kpc.

Comparing this result with Figure 2.6, we see the cool gas, traced by H I column densities, decrease radially away from the center. The added heating term in model ANISDH converts some cosmic-ray pressure, which is responsible for supporting the warm and cold gas, into heating the gas, consistent with results in Wiener et al. (2017). Even with the heating term, the distribution of warm gas in model ANISDH is still similar to that of ANISD.

Model STREAM shows signs of a true multiphase medium. This model has the lowest cumulative gas mass in its disk, likely due to its low gas densities and recent episodes of

star formation (see Figure 2.5). Although warm gas dominates its CGM out to radii of 150 kpc, cold gas survives in abundance 200 kpc away from the galactic center. Using Figure 2.6, we see that the temperature structure in model STREAM does indeed result in a patchy, multiphase medium.

2.4.5 Ionization Structure

Figure 2.9 holds the column densities of H I, Si IV, C III, and O VI as a function of the spherical radius from the center of the galaxy. Each scatter point in the plot represents one column density measurement at that radius. In each panel, we include points from both the fiducial model and its low-resolution counterpart. The solid black lines show the average column densities for the fiducial run while the dashed black lines show the average column densities for the lower resolution run with the same physics. For details on how the column densities were constructed, see §2.3.3.

To sufficiently sample our simulation space, we calculate the column densities at randomly-oriented sightlines passing through the CGM. To generate a sightline, we first select a random point on the sphere of radius $r \in [10, 200]$ kpc from the galaxy center. We then chose a sightline by selecting a random angle in the plane tangent to the sphere at that point.

The control model, NCR, underpredicts the column densities of all four ions. This is both due to the lack of metals in its CGM and a deficit of cool gas.

Of the remaining models, model ISOD has the weakest column densities with a flat distribution across impact parameter. This picture is consistent with weak and spatially uniform cosmic-ray pressure in the CGM. Model ANISD has stronger column densities with a wider spread at large radii. This is likely due to the uneven distribution of metallicity (see Figure 2.6). Model STREAM predicts column densities that are similar in strength to model ANISD. However, the column density measurements in model STREAM are more tightly clustered around the average value, which is qualitatively similar to observations.

For all models, lower resolution predicts stronger column densities, possibly due to

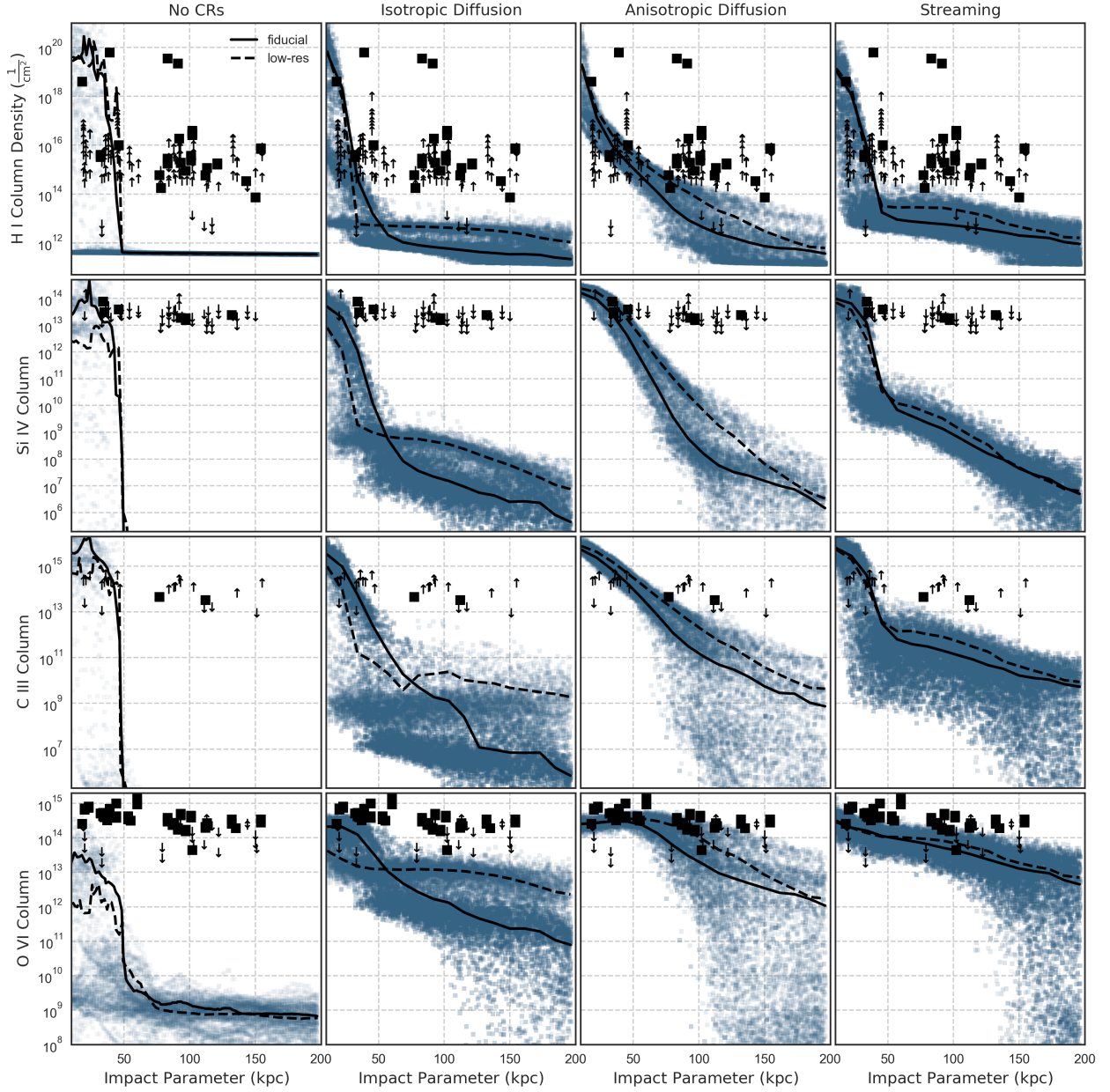


Figure 2.9 Column densities of H I, Si IV, C III, and O VI as a function of impact parameter after 13 Gyr of evolution. Each point on the graph shows a column density measurement using TRIDENT from either the fiducial run described by the title, or its low-resolution counterpart. The overplotted black lines show the average column densities for the fiducial run (solid) and the low-resolution run containing the same physics (dashed). (Continued on next page.)

Figure 2.9 (Continued) The black squares and arrows represent observed column densities and upper and lower limits from [Werk et al. \(2013\)](#). The control model underpredicts the observed column densities of all ions in this plot. Model ISOD has a flat column density profile with respect to impact parameter. The column densities in models ANISD and ANISDH decrease with radius. Model STREAM predicts the strongest column densities and is least sensitive to changes in resolution.

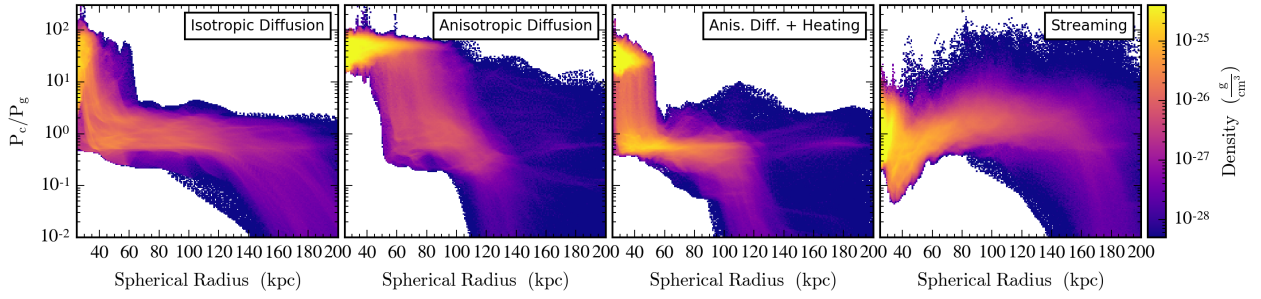


Figure 2.10 The unweighted ratio of cosmic-ray pressure to gas pressure as a function of spherical radius, measured from the galactic center after 13 Gyr of evolution. The color of the bins shows the density of the gas. The disk has been removed from the dataset in order to focus on the CGM structure. Model ISOD has a relatively flat and unvarying profile of cosmic-ray pressure in its CGM averaging around $P_c/P_g \simeq 1$. Models ANISD and ANISDH have a wide range of cosmic-ray pressure in the CGM, with the highest values peaking near the disk center, at high gas densities. The cosmic-ray pressure ratio in model STREAM peaks at larger radii, and at lower gas densities.

under-resolving the complicated structure of magnetic field lines. The column densities in model STREAM are the least sensitive to changes in resolution.

The column densities presented here are a qualitative example of the differences in ionization structure between different models of cosmic-ray transport. In reality, the exact values of ion column densities would be influenced by the metallicity and inflows from the IGM. Therefore, in order to better match observations, we would need to simulate galaxies in a cosmological context.

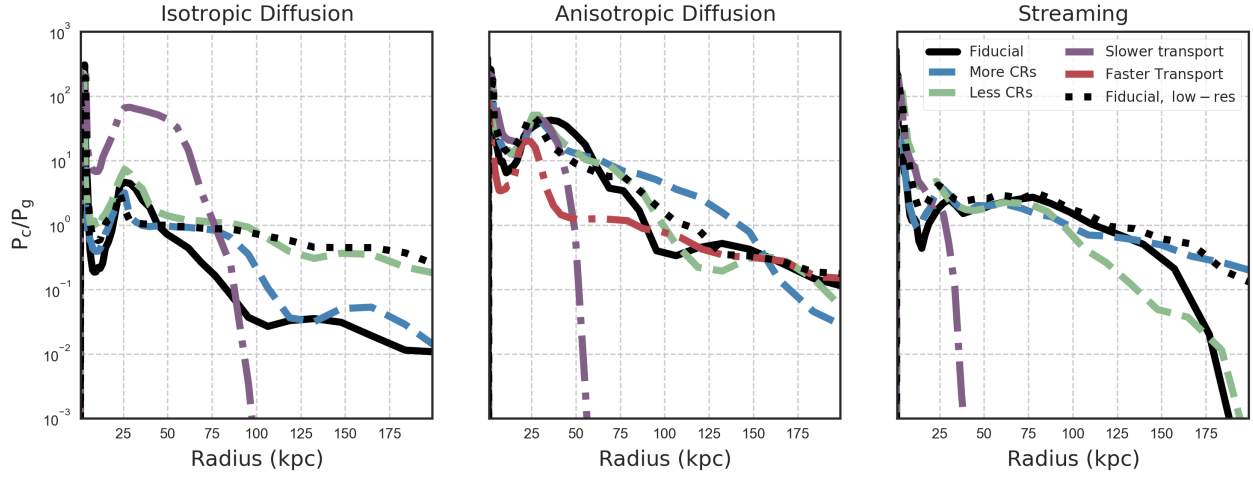


Figure 2.11 The density-weighted ratio of cosmic-ray pressure to gas pressure as a function of spherical radius after 3 Gyr of evolution. The black solid line represents the values for the fiducial run of that cosmic-ray transport method. Lines of different color and line style show variations from the fiducial run as described in the legend. The blue and green lines represent galaxy models with cosmic-ray injection fractions of 0.3 and 0.01 respectively. The purple line represents a diffusion coefficient of $\kappa_{\epsilon} = 10^{27} \text{cm}^2/\text{s}$ for galaxy models ISOD and ANISD and a streaming factor of $f_s = 1.0$ for model STREAM. The red line represents a diffusion coefficient of $\kappa_{\epsilon} = 10^{29} \text{cm}^2/\text{s}$ for model ANISD. For a description of the simulation parameters see Table 2.1. With this figure, we find that model ISOD is the most sensitive to parameter changes while model STREAM is the most robust.

2.4.6 *The Distribution of Cosmic rays in the CGM*

Cosmic-ray pressure in the CGM impacts the temperature and ionization structure of the gas. For this reason, we investigate the role of cosmic-ray transport mechanisms in altering this cosmic-ray pressure distribution.

In Figure 2.10 we explore the distribution of cosmic-ray pressure as a function of spherical radius for models ISOD, ANISD, ANISDH and STREAM. The pixels in the phase plot are colored by the density of the gas. Like in Figure 2.7, we cut out the disk from our data sample.

Model ISOD has a flat and narrow profile of cosmic-ray pressure as a function of radius, with the ratio P_c/P_g ranging between 0.5 and 5. At larger radii, the cosmic-ray pressure ratio widens considerably, revealing regions where cosmic-ray pressure is sparse.

Model ANISD has a much wider range of cosmic-ray pressure ratios across all radii. Compared to isotropic diffusion, anisotropic diffusion creates cosmic-ray pressure ratios that are nearly an order of magnitude higher across all radii. In this model, the cosmic-ray pressure dominates over thermal pressure near the galactic disk and at high gas densities. The heating term in model ANISDH lowers the cosmic-ray pressure ratio at all radii. However, this model still retains the same qualitative shape of the cosmic-ray pressure distribution that is present in model ANISD.

Although model STREAM also has a wide spread of cosmic-ray to thermal gas pressure ratios, the distribution of that spread is qualitatively different from that in model ANISD. In this model, cosmic-ray pressure in and near the disk is roughly 1.5 dex lower, spanning nearly 2 dex in strength. Unlike in model ANISD, the cosmic-ray pressure is low near the galactic disk and dominates over thermal pressure at large radii (and low gas densities).

2.4.7 Tuning the Knobs: The Impact of Choosing Parameters

Figure 2.11 shows the density-averaged ratio of cosmic-ray to thermal pressure as a function of impact parameter, measured after 3 Gyr of evolution. The solid black line represents the low-resolution runs of our fiducial models. All other lines differ from this run only in the parameter specified in the label. Blue and green lines represent galaxy models in which supernova feedback injected 1% and 30% of its energy as cosmic rays, respectively. Purple lines represent slower cosmic-ray transport velocities with either a diffusion coefficient of $\kappa_\epsilon = 10^{27} \text{cm}^2/\text{s}$ in models ISOD and ANISD or a streaming factor of $f_s = 1.0$ in model STREAM. To better compare models with anisotropic diffusion to those with isotropic diffusion, we explore faster cosmic-ray transport ($\kappa_\epsilon = 10^{29} \text{cm}^2/\text{s}$) in the middle panel, depicted by the red line. Finally, the black dotted line is the high-resolution fiducial run. For a summary of the parameters described above, see Table 1.

Varying the injected cosmic-ray fraction does not correspond with a linear change in the ratio of cosmic-ray to thermal pressure in the CGM. For example, increasing f_{CR} to 0.3 only marginally increases cosmic-ray pressure in model ISOD. Counter-intuitively, increasing f_{CR} in models ANISD and STREAM actually decreases the cosmic-ray pressure ratio in the CGM by suppressing star formation in the disk and thus preventing the injection of additional cosmic rays. On the flip side, decreasing the injected cosmic-ray fraction by a factor of 10 from the fiducial value does decrease the cosmic-ray pressure in model ISOD by roughly an order of magnitude at radii above 100 kpc. However, this decrease in f_{CR} does not significantly alter the cosmic-ray pressure ratio for models ANISD and STREAM.

The cosmic-ray pressure distribution in all three models depends strongly on their transport velocities. Decreasing the diffusion coefficient by a factor of 10 limits the reach of outflows to 100 kpc in model ISOD and 60 kpc in model ANISD. Similarly, decreasing the streaming factor by four limits the reach of cosmic-ray pressure to 40 kpc in 3 Gyr. In addition to limiting the radial extent of cosmic-ray pressure, the decrease in transport velocity in model ISOD increases the cosmic-ray pressure ratio by a factor of 10 at small

radii. Increasing the transport velocity in model ANISD decreases the cosmic-ray pressure within 75 kpc of the galactic center, but has no discernible effects at larger radii.

Doubling the resolution decreases the cosmic-ray pressure ratio by roughly an order of magnitude for models ISOD and ANISD. In model STREAM, the cosmic-ray pressure ratio of the higher resolution run only deviates from the fiducial run above 150 kpc.

Model ISOD is the most sensitive to changing parameters. In this approximation of cosmic-ray transport, cosmic rays can only move relative to the gas by diffusing down their own gradient. This motion is very sensitive to the injection fraction of cosmic rays, which defines the strength of the cosmic-ray gradient. Anisotropic diffusion is moderated by transport along magnetic field lines. The complicated geometry of the magnetic field lines slows anisotropic diffusion near the disk, making model ANISD less sensitive to the cosmic-ray injection fraction and star formation history than model ISOD. The most robust model is STREAM, in which the cosmic-ray transport depends on the cosmic-ray gradient, magnetic field strength, and alfvén wave velocity. The cosmic-ray pressure ratio in all three models decreases with slower cosmic-ray transport and increased resolution. Breaking this degeneracy will require additional parameter studies.

2.5 Discussion

With our suite of isolated disk galaxy simulations, we have shown that the density, temperature, and ionization structures of the simulated CGM depend on the choice of cosmic-ray transport mechanism. This discrepancy stems from the nature of the cosmic-ray transport approximation and cannot be trivially remedied by altering constant parameters. In the following section, we will summarize the qualitative nature of each cosmic-ray transport prescription and discuss potential improvements for future simulations.

The mere presence of cosmic rays alongside thermal gas is not enough to drive galactic outflows. This point is demonstrated with model ADV, in which cosmic rays are confined to propagate only through advection with the bulk motion of the thermal gas. These cosmic rays provide pressure support to the gas within the disk but have no efficient mecha-

nism through which to escape into the CGM. This added pressure stabilizes the gas against collapsing to form stars and thus quenches the galaxy almost immediately after the first episode of star formation. Although some cosmic rays ultimately do escape the disk, there is no significant cosmic-ray influence in the CGM after 13 Gyr of evolution.

Cosmic-ray transport *relative* to the thermal gas is necessary to drive galactic winds or to reproduce the observed column densities of ions in the CGM. As cosmic rays move out of the disk, they provide pressure support which lifts low-entropy gas out of the gravitational potential well (see Figure 2.1). This additional cosmic-ray pressure lowers the temperature and increases the ionization state of low ions, such as C III and Si IV, at large radii. However, the CGM structure depends on the distribution of cosmic-ray pressure, which varies substantially between different cosmic-ray transport models.

In the isotropic diffusion approximation, cosmic rays move down their energy gradient with a velocity that is determined by both the strength of the gradient and the constant diffusion coefficient, κ_ϵ . The resulting galactic outflows and CGM are therefore sensitive to recent star formation, which injects cosmic-ray energy into the ISM. The newly-ejected cosmic rays propagate away from the galactic disk until the cosmic-ray energy gradient is sufficiently flattened. Therefore, at late times, additional cosmic-ray pressure injected by ongoing star formation can no longer drive strong outflows. Ultimately, the cosmic-ray pressure in the CGM is unable to support the gas that it expelled at earlier times, triggering inflows. Varying the value of the constant diffusion coefficient alters the time scales on which the cosmic-ray energy gradient flattens and the radial extent of cosmic-ray energy, but not the qualitative shape of the cosmic-ray distribution.

Although isotropic diffusion is a crude approximation to the true interactions between cosmic rays and magnetic fields, it is a computationally frugal choice as it circumvents the need for fully MHD galaxy models. Simulations with isotropic cosmic-ray diffusion have been successful at driving strong outflows and increasing the column densities of low ions in the CGM (Salem and Bryan, 2014; Wiener et al., 2017). However, in our simulations, model ISOD was the least effective at producing a multiphase medium and the

most sensitive to the choice of constant parameter values.

Anisotropic diffusion improves upon isotropic diffusion by approximating cosmic-ray transport as a random walk down the cosmic-ray energy density gradient, along the magnetic field. This transport around magnetic field lines modulates the velocity of cosmic-ray transport. Near the disk, where the magnetic field lines are the most tangled, some cosmic rays become trapped in their motion around magnetic field loops and make slow radial progress away from the disk. Simultaneously, cosmic rays near magnetic field lines pointing out of the disk escape to larger radii. Therefore, anisotropic diffusion is capable of driving large-scale outflows while keeping a substantial presence of cosmic-ray pressure near the disk. In this model, cosmic-ray pressures are strongest near the galactic center and decrease rapidly at large radii. This cosmic-ray pressure suppresses star formation in the disk and supports an abundance of cool gas in the the halo. The strength and radial extent of the cosmic-ray pressure depends on the constant diffusion coefficient, magnetic field topology, and the star formation history.

Increasing the diffusion coefficient in models with anisotropic diffusion counteracts the effect of tangled magnetic field lines near the galactic center. However, the resulting models are still not directly comparable to models with isotropic diffusion with a lower diffusion coefficient. The difference lies in the variable timing of the cosmic-ray propagation. In anisotropic diffusion models, the cosmic-ray pressure distributes itself preferentially along magnetic field lines, so the nominally constant diffusion coefficient becomes a function of the magnetic field geometry. There is no single ratio of diffusion coefficients that results in the same distribution of cosmic-ray energy in both anisotropic and isotropic diffusion models.

Cosmic-ray streaming is the first-order approximation to cosmic-ray transport. Streaming cosmic rays move along magnetic field lines with a velocity that depends on the shape, *direction*, and *strength* of the magnetic field. This mode of transport creates a cosmic-ray distribution in the CGM that supports a truly multiphase medium, with cold gas clumps surviving alongside a warm and hot medium. We find that compared to diffusion, stream-

ing is less sensitive to changes in star formation history or the choice of constant parameter values.

A key component of the streaming approximation is the additional heating term, through which cosmic rays give up their momentum to heat thermal gas. This transfer prevents simulations from overestimating cosmic-ray pressure in the disk and halo. To discern the effect of the heating term from the streaming behavior, we simulated a galaxy with both anisotropic cosmic-ray diffusion and cosmic-ray heating (Wiener et al., 2017). Although the additional heating term increased temperatures and lowered the column densities of H I and O VI, the cosmic-ray distribution in the CGM remained qualitatively the same. Therefore, we conclude that the key differences between the streaming and diffusion models lie in the transport approximations.

2.5.1 *Limitations and Future Work*

In this chapter, we explored the qualitative impact of the choice of cosmic-ray transport on the simulated CGM. However, before simulations with cosmic-ray physics can hold predictive power, several improvements must be made to constrain the details of this transport. We discuss these factors in greater detail below.

Magnetic Fields

Magnetic fields are the media along which cosmic rays propagate and are therefore crucially important for robust implementations of cosmic-ray physics. The shape of the magnetic field dictates cosmic-ray transport in the anisotropic diffusion and streaming approximations while the magnetic field strength sets the streaming velocity and the rate of heat transfer from cosmic rays to the thermal gas. In addition, magnetic pressure is inversely proportional to the length scale of thermal instabilities in the CGM (Ji et al., 2017). Therefore, simulating cosmic-ray transport and recreating the multiphase CGM requires a realistic treatment of magnetic fields.

Simulating the co-evolution of cosmic rays and magnetic fields is complicated at early simulation times. The cosmic rays streaming velocity depends on the magnetic field strength, yet primordial fields are believed to be no stronger than 10^{-9} G (Cheng et al., 1994; Durrer and Neronov, 2013). If newly-injected cosmic rays cannot escape the galactic disk before the next round of star formation, the galaxy risks becoming immediately quenched.

One way to remedy this is to include magnetic supernova feedback, which can fuel the exponential magnetic field growth to observed values (Butsky et al., 2017). However, in our attempts to simulate such a field, the small supernova injection sites were not sufficiently resolved to accurately capture cosmic-ray transport. The overabundance of cosmic-ray energy in the disk suppressed star formation, which in turn suppressed additional magnetic field injection. In these test simulations, the magnetic fields never reached observable strengths, and the streaming cosmic rays never escaped the disk.

To circumvent this problem, we set the initial disk magnetic field to $B_{0,d} = 1\mu\text{G}$, similar to that in Ruszkowski et al. (2017). This initial field is strong enough for cosmic-ray streaming models to drive outflows that are comparable in their reach to outflows generated by the diffusion models with $\kappa_\epsilon = 10^{28}\text{cm}^2/\text{s}$. The initial magnetic field in the CGM, which is the focus of this chapter, was set to $B_{0,h} = 10^{-15}$ G. Therefore, the evolution of the of the magnetic field in the halo was driven by magnetized galactic winds and the turbulence they produced.

Improved implementation of the co-evolution of magnetic fields with streaming cosmic rays will require detailed resolution and parameter studies which are outside of the scope of this work.

Improved Cosmic-ray Physics

Our work makes several assumptions that are commonplace in current implementations of cosmic-ray transport. One such approximation is that of a constant diffusion coeffi-

cient, κ_ε , which avoids calculating the momentum-weighted integral of the local cosmic-ray energy density. The velocity of cosmic-ray transport in the diffusion limit is therefore very sensitive to the choice of κ_ε (see Figure 2.11). Because the value of κ_ε is poorly constrained, simulations with the same model for cosmic-ray transport can produce significantly varied results.

However, it is possible to improve upon the constant diffusion model without the computational expense of explicitly solving for the momentum-weighted value at every grid cell. For example, Farber et al. (2017) recently demonstrated that using a temperature-dependent, bimodal value for κ_ε alters galactic wind properties and spatial distribution of cosmic rays.

The underlying assumption of our cosmic-ray transport models is that cosmic rays must propagate either in the diffusion limit or the streaming limit. Realistically, both modes of transport must be taking place. In a recent advancement, Jiang and Oh (2017) describe a new numerical scheme for cosmic-ray transport that self-consistently handles both streaming and diffusion processes. This prescription is a promising new direction that may resolve the discrepancies between current implementations of cosmic-ray transport presented in this chapter.

Cosmological Context

The idealized experimental setup of isolated disk galaxies offers great control in isolating the effects of cosmic-ray-driven galactic outflows on the structure of the CGM. However, this isolation comes at the expense of simulating a realistic CGM.

For example, the CGM in our simulations is populated almost entirely by cosmic-ray-driven outflows. Neglecting inflows from the IGM leads to an unrealistically empty CGM, which is particularly apparent in our control model. The isolated disk galaxy model is an oversimplification of galactic evolution since most galaxies, including our own Milky Way, evolve in a group or cluster environment. Interactions with nearby galaxies and satellites

can have a significant effect on the host galaxy’s gas supply, which in turn affects its ability to form stars and drive outflows. These interactions can also strip gas directly from the CGM.

We focus solely on the CGM of Milky Way-type galaxies, in which purely thermal feedback is successful at reproducing galactic disk properties. However, the differences between cosmic-ray transport mechanisms presented above are may change with galaxy mass. For example, [Jacob and Pfrommer \(2017b\)](#) recently showed that the strength and mass-loading factor galactic outflows driven by isotropic cosmic-ray diffusion depends on the host galaxy’s mass. This mass-dependency is likely to be present for anisotropic diffusion and streaming transport prescriptions. However, the nature of that relationship may change for different transport mechanisms.

Future parameter studies using cosmological simulations will be necessary to develop a robust prescription of cosmic-ray transport. We judge our cosmic-ray transport models by the temperature and ionization structure of the simulated CGM. However, cosmic-ray collisions in the CGM are expected to account for up to 10% of the diffuse, isotropic gamma ray background ([Feldmann et al., 2013](#)). Therefore, observations of the diffuse gamma ray emissions, such as those taken with the Fermi-LAT telescope can be used to constrain cosmic-ray transport models ([Ackermann et al., 2012](#)).

2.6 Summary

Simulations including cosmic-ray feedback are more effective at driving galactic outflows and reproducing the observed ionization structure in the CGM than models with purely thermal feedback. However, models for simulating cosmic-ray feedback and transport are poorly constrained.

In this chapter, we demonstrate that galactic outflows and CGM structure are sensitive to the invoked cosmic-ray transport mechanism. We achieve this by simulating a suite of isolated MW-type disk galaxies with three commonly-used prescriptions for cosmic-ray transport relative to thermal gas: isotropic diffusion, anisotropic diffusion, and stream-

ing. For completeness, we also include advection-only models, in which cosmic rays are constrained to move with the bulk motion of the gas, and control models without any cosmic-ray physics. The results are summarized below.

- Models with cosmic-ray transport relative to the thermal gas (streaming or diffusion) drive strong outflows. These outflows are generated by cosmic-ray pressure support, which lifts thermal gas higher out of the gravitational potential well. Models with no cosmic-ray feedback and those with cosmic-ray advection do not launch strong galactic winds.
- Models with isotropic diffusion launch the fastest winds that last around 5 Gyr. Models with anisotropic cosmic-ray diffusion and streaming drive steady winds that persist after 13 Gyr of evolution. Models with anisotropic diffusion continue to drive outflows even after the galaxy is quenched. Models with cosmic-ray streaming support simultaneous inflows near the disk and outflows at larger radii.
- All models with cosmic-ray feedback suppress star formation by supporting thermal gas against collapse. The degree to which star formation is suppressed depends on the cosmic-ray pressure within the disk. Models with pure cosmic-ray advection quenched after the first episode of star formation. The star formation in models with isotropic diffusion closely followed that of the control. Models with anisotropic diffusion suppressed star formation more efficiently, ultimately quenching after 10 Gyr. Models with cosmic-ray streaming had a cyclical star formation history, supported by inflows from the CGM.
- cosmic-ray pressure in the CGM supports gas with cooler temperatures. However, that temperature structure is sensitive to the cosmic-ray transport model. The CGM of models with isotropic diffusion is primarily composed of warm gas that is spatially uniform. Models with anisotropic diffusion produce large quantities of cool ($T <$

$10^5 K$) gas out to radii of 100 kpc that remain even after star formation is quenched. This is an interesting example of a quenched galaxy with a reservoir of cool gas in its CGM (e.g., [Gauthier et al. \(2010\)](#); [Thom et al. \(2012\)](#)). Models with cosmic-ray streaming produce a patchy, multiphase gas distribution with cool gas existing alongside warm and hot gas at large radii.

- Cosmic-ray pressure creates a multiphase medium, allowing gas of a given temperature to span several orders of magnitude in density. At late times, models with isotropic diffusion show a relatively uniform CGM temperature, whereas anisotropic diffusion and streaming models retain varied temperature profiles. In anisotropic diffusion models, the influence of cosmic rays is strongest near the galactic center and decreases with spherical radius. In cosmic-ray streaming models, the multiphase temperature structure is patchy, with clumps of cool gas existing 200 kpc from the galactic center.
- Models with anisotropic diffusion and streaming generate higher column densities of H I, Si IV, C III, and O VI than models with isotropic diffusion. The column densities generated by models with cosmic-ray streaming have less variation in predicted column densities as a function of impact parameter and are less sensitive to changes in resolution.
- The differences between our galaxy models stem from the varied distribution of cosmic rays in the CGM. Compared to isotropic diffusion, anisotropic diffusion and cosmic-ray streaming are more effective at retaining cosmic-ray pressure near the galactic disk. Since the transport in isotropic diffusion depends only on the gradient of cosmic-ray energy density, its cosmic-ray pressure support in the CGM decreases at late simulation times.
- The distribution of cosmic-ray pressure in the CGM is sensitive to runtime param-

eters such as the amount of cosmic rays injected in supernova feedback, the velocity of cosmic-ray transport, and the resolution. We find that models with isotropic cosmic-ray diffusion are the most sensitive to changes in these parameters. This is because the velocity of cosmic-ray transport in this approximation depend only on the cosmic-ray energy gradient and the choice of constant diffusion coefficient. The cosmic-ray pressure distribution in models with anisotropic diffusion are less sensitive in comparison. We conclude that models with streaming, in which cosmic-ray transport depends on the shape, direction, and strength of the magnetic field lines, are the most robust.

We have demonstrated that cosmic-ray feedback can drive strong galactic outflows and provide the necessary pressure support to reproduce the multiphase temperature and ionization structure of the CGM. However, because the state of the simulated CGM depends strongly on the invoked cosmic-ray transport method, it is necessary to first develop a robust numerical cosmic-ray transport model before simulations with cosmic-ray feedback can hold predictive power.

2.7 Chapter Appendix: Cosmic-ray Physics in Enzo

In §2.2, we described the implementation of cosmic-ray physics into the Riemann solvers in Enzo. Here, we demonstrate the performance of our implemented cosmic-ray advection, anisotropic diffusion, and streaming. For tests of the isotropic diffusion module, refer to [Salem and Bryan \(2014\)](#).

2.7.1 *Modified Sod Shock-tube*

The Sod shock-tube, first described in [Sod \(1978\)](#) is used to test the behavior of gas in the presence of a strong shocks in numerical simulations. Because the original Sod shock-tube does not include cosmic rays, we use a modified version first described in [Pfrommer et al. \(2006\)](#). The initial conditions are described in Table 2.2 below.

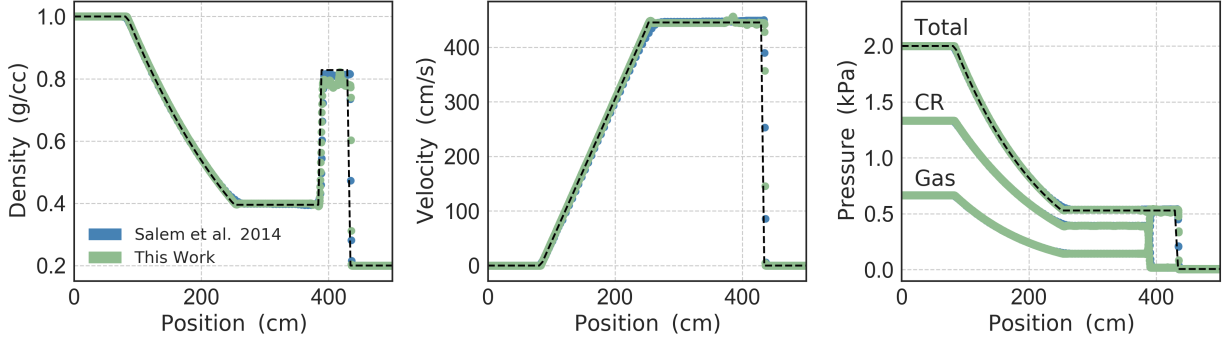


Figure 2.12 The density, velocity, and pressure (thermal, cosmic-ray, and total pressures) as a function of position in a 1D simulation of the modified Sod shock-tube. Cosmic-ray pressure compliments thermal pressure while the total pressure remained unchanged in the rarefaction wave.

In Figure 2.12 we test our implementation of the non-diffusive ($\kappa_\epsilon = 0.0$) two-fluid cosmic-ray model and compare it to the existing implementation in the ZEUS hydro scheme in ENZO (Salem and Bryan, 2014). From left to right, the panels show the density, velocity, and pressures of this shock-tube after $t = 0.31$ code units of evolution. Where applicable, the analytic solution is depicted as a black dashed line. Compared to Salem and Bryan (2014), our implementation has a sharper velocity profile at $x \simeq 250$ cm, but slightly under-predicts the density value around $x = 400$ cm. Overall, the two implementations of cosmic-ray advection agree well with each other and with the analytic solution.

	ρ	P_g	ϵ_c	v	
Left	1.0	$2/3 \times 10^5$	4.0×10^5	0.0	^a
Right	0.2	267.2	801.6	0.0	

Table 2.2 Initial conditions for the modified Sod Shock-tube

^aThe initial density, thermal pressure, cosmic-ray energy density, and velocity for the modified Sod shocktube. The left and right regions of the shocktube are defined as $(0 < x < 250 \text{ cm})$ and $(250 < x < 500 \text{ cm})$ respectively.

	ρ	P_g	ε_c	v_x	v_y	B_x	B_y
Left	1.0	0.6	1.2	0.0	0.0	1.0	1.0
Right	0.125	0.06	0.12	0.0	0.0	1.0	-1.0

Table 2.3 Modified Brio-Wu Shock-tube

^aThe initial density, thermal pressure, cosmic-ray energy density, velocity and magnetic field strengths for the modified Brio-Wu shocktube. The left and right regions of the shocktube are defined by $(-0.5 < x < 0)$ and $(0 < x < 0.5)$ respectively.

2.7.2 Brio Wu Shock-tube

The Brio-Wu shock-tube [Brio and Wu \(1988\)](#) tests the advection properties of gas interactions with magnetic fields in the presence of an extreme shock. In the modified Brio-Wu shock-tube, we include cosmic-ray pressure and evolve the system for 0.2 code units. The initial conditions of the gas are described in [Table 2.3](#).

2.7.3 Anisotropic Diffusion

In the anisotropic diffusion approximation, cosmic rays propagate down their gradient, along magnetic field lines. In [Figure 2.14](#), we test our implementation with the anisotropic ring problem initially described by [Parrish and Stone \(2005\)](#); [Sharma and Hammett \(2007\)](#) and explored in detail in [Pakmor et al. \(2016a\)](#). The experiment uses a uniform density box in with no gas (or a gas that is fixed in space such that there is no cosmic-ray advection) on a domain of $[-1, 1]^2$.

Following the setup in [Pakmor et al. \(2016a\)](#), we set initial conditions for the cosmic-ray energy density to be

$$\epsilon_c(x, y) = \begin{cases} 12 & \text{if } 0.5 < r < 0.7 \text{ and } |\phi| < \frac{\pi}{12} \\ 10 & \text{else,} \end{cases} \quad (2.18)$$

where the radial coordinate $r = \sqrt{x^2 + y^2}$, $\phi = \text{atan2}(y, x)$, and the diffusion coefficient

is set as $\kappa_c = 0.01$.

In Figure 2.14, we compare the performance of our anisotropic diffusion implementation against the analytic solution given by

$$\epsilon_c(x, y) = \begin{cases} 10 + \operatorname{erfc}\left[\left(\phi + \frac{\pi}{12}\right)\frac{r}{D}\right] - \operatorname{erfc}\left[\left(\phi - \frac{\pi}{12}\right)\frac{r}{D}\right] \\ \end{cases} \quad (2.19)$$

where $D = \sqrt{4\kappa_c t}$. $\epsilon_c(x, y) = 10$ everywhere else.

After evolving this simulation for 10 code time units, we see the initial wedge of uniform cosmic-ray energy density moving down its gradient around the magnetic fields lines. The lower resolution runs have lower peak values of cosmic-ray energy density and show signs of cosmic-ray transport perpendicular to the magnetic field direction. Both of these properties improve with increased resolution. The best-resolved simulation (800 x 800, fixed grid) matches the analytic solution well.

At a later time ($t = 100$ code units), the cosmic-ray energy density has reached the opposite side of the circle traced by the toroidal magnetic field lines. The energy density approaches a steady state and is nearly evenly distributed around the annulus. In low-resolution runs, the average final cosmic-ray energy is lower, due to conservation of cosmic-ray energy in the thicker rings.

2.7.4 Streaming

We test the behavior of our cosmic-ray streaming implementation with a 1D simulation of an initial Gaussian profile of cosmic-ray energy density (see Figure 2.15). The initial cosmic-ray energy density profile is set by

$$\varepsilon = \varepsilon_0 e^{-x^2/2D}, \quad (2.20)$$

where x is the spatial coordinate. In our example, we chose constants $\varepsilon_0 = 100$ and $D = 0.05$. We include a magnetic field in the $\hat{x}$ direction of a strength of 0.25 in code units.

We isolate the effects of cosmic-ray streaming and diffusion by fixing the gas so that no advection is taking place.

For cosmic-ray diffusion, the analytic solution for the evolution of the cosmic-ray energy density over time is given by

$$\varepsilon = \varepsilon_0 \sqrt{\frac{D}{D + 2\kappa_\varepsilon t}} \exp\left(\frac{-x^2}{2(D + 2\kappa_\varepsilon t)}\right). \quad (2.21)$$

The cosmic-ray diffusion implementation follows the analytic solution well. Although there is no analytic solution for the cosmic-ray streaming case, our results are qualitatively comparable to previous studies (e.g., [Uhlig et al. \(2012\)](#); [Wiener et al. \(2017\)](#)).

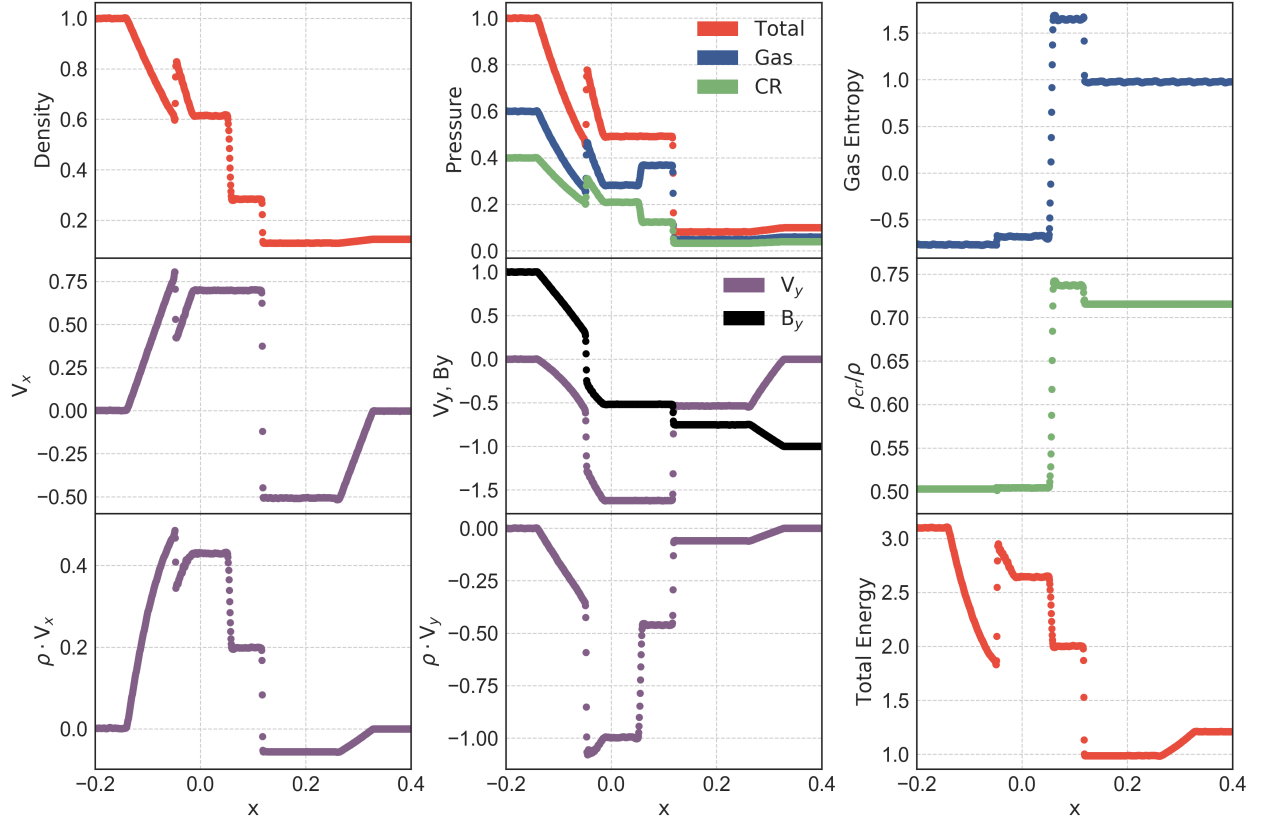


Figure 2.13 Various parameters of the modified Brio-Wu MHD shock-tube as a function of one dimensional position. (Top row) density, cosmic-ray, thermal, and total pressure, and thermal gas entropy. (Middle row) x-component of the velocity, y-component of the velocity and magnetic field, ratio of cosmic-ray density to thermal density. (Bottom row) the density-weighted x and y components of the velocity, and the total energy. Thermal gas is influenced by the pressure of both cosmic rays and magnetic field lines.

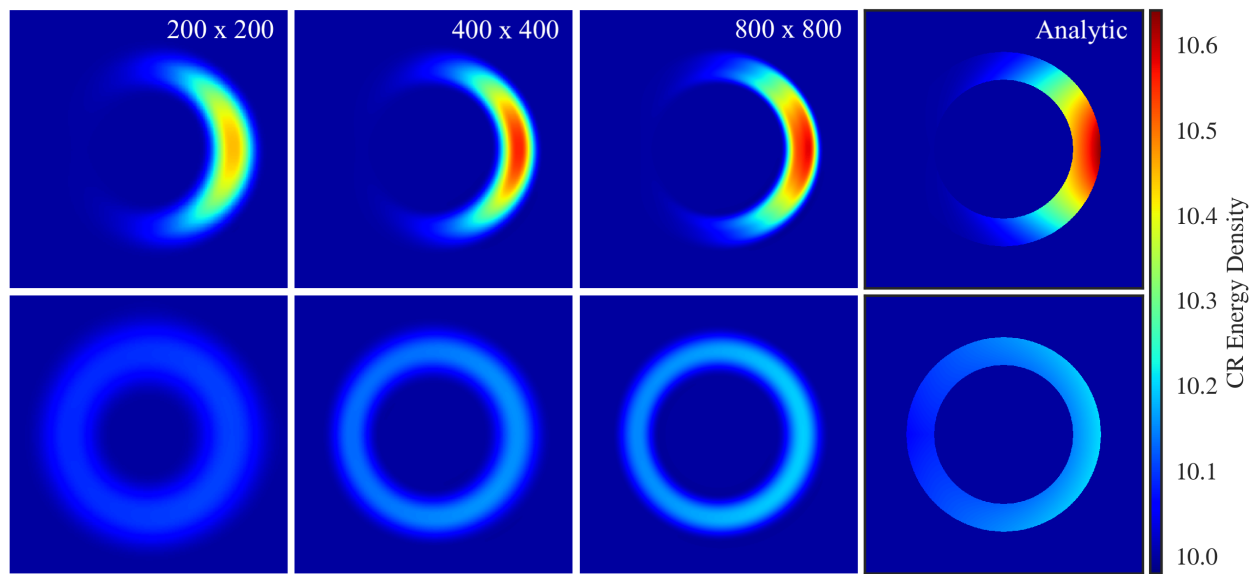


Figure 2.14 A 2D test of anisotropic diffusion of cosmic-ray energy density along circular magnetic field lines at an early time ($t = 10$; top row) and a late time ($t = 100$; bottom row). The columns are ordered from left to right by increasing resolution, ending with the analytic solution. With anisotropic diffusion, cosmic rays are confined to propagate solely along magnetic field lines. Increasing resolution decreases the amount of diffusion perpendicular to the magnetic field.

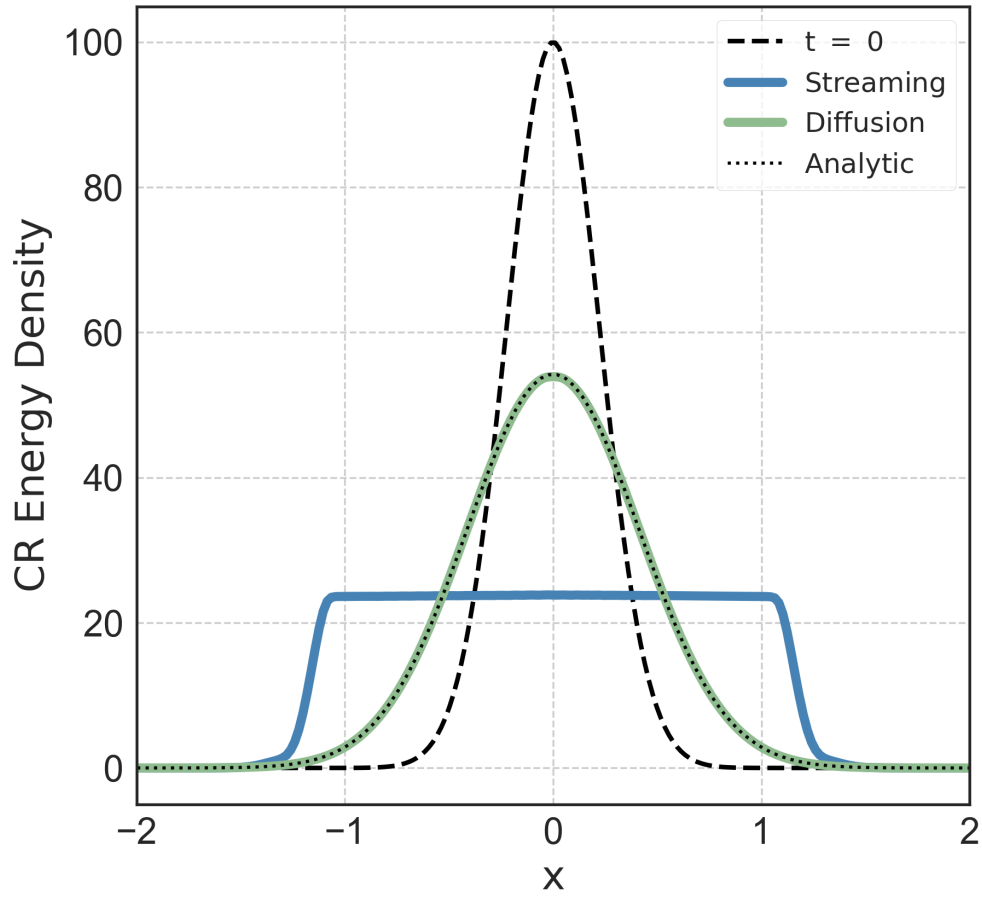


Figure 2.15 A comparison of the time evolution of a 1D Gaussian profile with cosmic-ray streaming (green) and diffusion (blue). A magnetic field of strength 0.25 code units lies in the x direction. The analytic solution for the cosmic-ray diffusion profile is overplotted as a black dotted line. Although no analytic solution exists for the cosmic-ray streaming case, our results qualitatively match previous studies.

Chapter 3

THE IMPACT OF COSMIC RAYS ON THERMAL INSTABILITY IN THE CIRCUMGALACTIC MEDIUM

Portions of this chapter were originally published in collaboration with Drummond Fielding, Christopher Hayward, Cameron Hummels, Thomas R. Quinn, and Jessica Werk in the November 2020 edition of The Astrophysical Journal (Butsky et al., 2020, ApJ, Vol. 903, 2; 2020 ©American Astronomical Society, DOI: 10.3847/1538-4357/abba2), and are reproduced below with the permission of the American Astronomical Society.

Summary

Large reservoirs of cold ($\sim 10^4$ K) gas exist out to and beyond the virial radius in the circumgalactic medium (CGM) of all types of galaxies. Photoionization modeling suggests that cold CGM gas has significantly lower densities than expected by theoretical predictions based on thermal pressure equilibrium with hot CGM gas. In this chapter, we investigate the impact of cosmic-ray physics on the formation of cold gas via thermal instability. We use idealized three-dimensional magnetohydrodynamic simulations to follow the evolution of thermally unstable gas in a gravitationally stratified medium. We find that cosmic-ray pressure lowers the density and increases the size of cold gas clouds formed through thermal instability. We develop a simple model for how the cold cloud sizes and the relative densities of cold and hot gas depend on cosmic-ray pressure. Cosmic-ray pressure can help counteract gravity to keep cold gas in the CGM for longer, thereby increasing the predicted cold mass fraction and decreasing the predicted cold gas inflow rates. Efficient cosmic-ray transport, by streaming or diffusion, redistributes cosmic-ray pressure from the cold gas to the background medium, resulting in cold gas properties that are in between those predicted by simulations with inefficient transport and simulations without cosmic rays. We show that cosmic rays can significantly reduce galactic accretion rates and resolve the tension between theoretical models and observational constraints on the properties of cold CGM gas.

3.1 Introduction

Observations of H I Lyman series and low-ion metal transitions in quasar absorption-line spectroscopy studies indicate that cold ($\sim 10^4$ K) gas exists around galaxies of all types out to ~ 300 kpc (Chen et al., 2010; Prochaska et al., 2011; Tumlinson et al., 2013; Keeney et al., 2018). Cold circumgalactic medium (CGM) gas makes up a substantial fraction (30–50%) of galactic baryons (Werk et al., 2014) and may accrete onto galaxies to fuel star formation. It is then particularly intriguing that the CGM of some quenched galaxies are observed to have massive reservoirs of cold gas (Thom et al., 2012; Berg et al., 2019). How these galaxies remain quenched despite these large cold gas reservoirs is uncertain. It is possible that they are about to resume star formation, that this gas is incapable of cooling to the right temperatures in the interstellar medium (ISM), or perhaps that there is some mechanism preventing this gas from accreting onto its host galaxy. Furthermore, careful ionization modeling based on the COS-Halos observations suggests that the densities of cold CGM gas are at least an order of magnitude too low for the cold gas to be in thermal pressure equilibrium with the theoretically predicted pressure of hot CGM gas (Werk et al., 2014). Although the density of the hot CGM gas phase is itself poorly constrained, these observations are consistent with the presence of nonthermal pressure support in the CGM. Understanding the origin and physical properties of cold CGM gas is integral to a self-consistent theory of galaxy evolution.

There are two families of explanations for the origins of cold CGM gas: the gas formed elsewhere and was transported to the CGM, or the gas was formed in situ (Hafen et al., 2019). Both of these mechanisms play a role to different degrees in different galaxies. Traditionally, transporting cold gas from the ISM to the CGM has been challenging, as the survival times of cold gas embedded in a hot medium are short (McKee and Cowie, 1975; Zhang et al., 2017). However, there is a wealth of multiwavelength observations supporting the existence of multiphase outflows (Heckman et al., 2000; Chen et al., 2010; Ashley et al., 2020; Burchett et al., 2020; Fluetsch et al., 2020) and theoretical works demonstrating

prolonged survival and growth of cold gas in a hot wind (McCourt et al., 2015; Thompson et al., 2016; Wiener et al., 2017; Schneider et al., 2018; Gronke and Oh, 2018; Fielding et al., 2020a; Li et al., 2020). It remains unclear if the amount of cold gas entrained in outflows is enough to explain the observed abundance of cold CGM gas.

Alternatively, cold gas can form directly out of a hot ($\sim 10^6$ K) medium through thermal instability (Field, 1965). When the cooling time of gravitationally stratified hot gas in thermal hydrostatic equilibrium is $\lesssim 10$ times the gravitational freefall time, small isobaric perturbations can drive runaway cooling, resulting in cold gas condensation and precipitation (McCourt et al., 2012; Sharma et al., 2012; Voit et al., 2015). Although thermal instability in gravitationally stratified gas was originally invoked to explain observations of galaxy clusters (Gaspari et al., 2012; Sharma and Nath, 2012b), thermal instability is believed to also play an integral role in producing cold CGM gas and regulating the baryon cycle (Fielding et al., 2017; Voit et al., 2017, 2019; Esmerian et al., 2020). Both cosmological and idealized simulations have explored the impact of a broad range of processes on thermal instability including thermal conduction (Sharma et al., 2010; Wagh et al., 2014), magnetic fields (Ji et al., 2018), turbulence (Voit, 2018), the shape of the gravitational potential (Meece et al., 2015; Choudhury and Sharma, 2016), and perturbation amplitude (Pizzolato and Soker, 2005; Singh and Sharma, 2015; Choudhury et al., 2019). While the impact of cosmic rays has largely been ignored in simulations of thermal instability, Sharma et al. (2010) used two-dimensional simulations to show that the presence of adiabatic cosmic rays decreases the density of cold gas that forms through thermal instability.

Cosmic rays are likely an important source of energy in the CGM. In the Milky Way ISM, cosmic-ray energy is roughly in equipartition with thermal and magnetic energies (Ginzburg and Ptuskin, 1985; Boulares and Cox, 1990), and many recent simulations have shown that cosmic rays launch far-reaching galactic outflows (Uhlig et al., 2012; Booth et al., 2013; Girichidis et al., 2016; Simpson et al., 2016; Ruszkowski et al., 2017; Bustard et al., 2020; Jana et al., 2020), altering the phase structure of the CGM (Salem et al., 2016; Butsky and Quinn, 2018; Buck et al., 2020; Ji et al., 2020a). Galaxy-scale simulations that

include cosmic rays find that cosmic-ray pressure may even be the dominant source of pressure in the CGM (Girichidis et al., 2018; Ji et al., 2020a).

There are several ways in which cosmic rays could alter the thermal instability in CGM gas. nonthermal cosmic-ray pressure supports cold gas, enabling it to cool isochorically (Sharma et al., 2010; Kempster and Quataert, 2020) and may explain the inferred low densities of cold CGM gas. Cosmic-ray pressure also counteracts gravity and may prevent cold halo gas from accreting onto the galaxy (Hopkins et al., 2020). In some transport approximations, streaming cosmic rays transfer energy to the thermal gas and provide a source of heating. In some regimes, this additional heating term can balance radiative cooling and has been shown to prevent gas from overcooling in simulations of galaxy clusters (Guo and Oh, 2008; Sharma et al., 2010; Jacob and Pfrommer, 2017a; Jacob et al., 2017). Linear thermal stability analysis predicts that CGM gas ($10^5\text{K} < T < 10^7\text{K}$) is likely thermally unstable in the presence of streaming cosmic rays, but the predicted thermal instability growth rate depends on the invoked cosmic-ray transport mechanism (Kempster and Quataert, 2020). However, linear analysis breaks down once thermal instability saturates, and there is a strong need for simulations to further understand the cold gas properties and subsequent evolution.

In this chapter, we run the first three-dimensional simulations of thermal instability in a gravitationally stratified medium that include cosmic-ray pressure with diffusion and streaming. We focus our analysis on the properties of the cold gas that forms through thermal instability and its implications for observations of cold CGM gas. The chapter is organized as follows. In Section 3.2, we describe the initial conditions, model assumptions, and the scope of the parameter study. In Section 3.3, we provide physical expectations of the impact of cosmic-ray pressure, transport, and heating on thermal instability. In Section 3.4, we present the results of our simulations with a focus on the gas density, cold mass fraction, and cold mass flux. In Section 3.5, we discuss the implications of these results on cold cloud sizes, galaxy accretion rates, and the CGM pressure problem. We summarize our findings in Section 3.6. In the Appendix, we demonstrate the impact

of resolution (Appendix 3.7.1), cold gas temperature (Appendix 3.7.2), and halo profile (Appendix 3.7.3).

3.2 Methods

We perform our simulations with the astrophysical simulation code, ENZO (Bryan et al., 2014; Brummel-Smith et al., 2019), using the magnetohydrodynamics (MHD) local Lax-Friedrichs (LLF; Kurganov and Tadmor, 2000) Riemann solver. This MHD solver uses the piecewise linear reconstruction method (PLM; van Leer, 1977) and performs divergence cleaning of the magnetic field as described in Dedner et al. (2002) and tested in Wang et al. (2008). We perform all simulations on a 3-dimensional grid with uniform resolution.

In addition to the standard Euler equations, which define the conservation of mass, momentum, and energy in hydrodynamics simulations, our simulations also conserve the magnetic flux and cosmic-ray energy. The following equations describe the evolution of the gas, magnetic field, and cosmic-ray fluids.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (3.1)$$

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla \cdot \left(\rho \mathbf{v} \mathbf{v}^T - \frac{\mathbf{B} \cdot \nabla \mathbf{B}}{4\pi} \right) + \nabla P_{\text{tot}} = -\rho \mathbf{g} \quad (3.2)$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{B} \mathbf{v}^T - \mathbf{v} \mathbf{B}^T) = \mathbf{0} \quad (3.3)$$

$$\frac{\partial \varepsilon_g}{\partial t} + \nabla \cdot (\mathbf{v} \varepsilon_g) = -P_g \nabla \cdot \mathbf{v} - \mathcal{L} + \mathcal{H} + \mathcal{H}_c \quad (3.4)$$

$$\frac{\partial \varepsilon_c}{\partial t} + \nabla \cdot \mathbf{F}_c = -P_c \nabla \cdot \mathbf{v} - \mathcal{H}_c \quad (3.5)$$

$$\mathbf{F}_c = \underbrace{\mathbf{v}\varepsilon_c}_{\text{advection}} + \underbrace{\mathbf{v}_s(\varepsilon_c + P_c)}_{\text{streaming}} - \underbrace{\kappa_c \mathbf{b}(\mathbf{b} \cdot \nabla \varepsilon_c)}_{\text{diffusion}} \quad (3.6)$$

In the equations above, ρ is the gas density, $\mathbf{v}$ is the gas velocity vector, $\mathbf{g}$ is the gravitational acceleration, and t is the time variable. $\mathbf{B}$ is the magnetic field vector and $\mathbf{b}$ is the magnetic field direction, $\mathbf{b} = \mathbf{B}/|\mathbf{B}|$. $\mathcal{L}$ and $\mathcal{H}$ are the gas cooling and heating terms defined in section 3.2.2. ε_g and ε_c are the gas and cosmic-ray energy densities (energy per volume). $P_g = (\gamma - 1)\varepsilon_g$, $P_B = B^2/8\pi$, $P_c = (\gamma_c - 1)\varepsilon_c$ are the gas, magnetic, and cosmic-ray pressures. Together, they comprise the total pressure, $P_{\text{tot}} = P_g + P_B + P_c$. The adiabatic indices are $\gamma = 5/3$, and $\gamma_c = 4/3$ respectively.

$\mathbf{F}_c$ describes the cosmic-ray flux, which encompasses advection, streaming, and diffusion. In the streaming approximation, cosmic rays move along magnetic field lines at the streaming velocity,

$$\mathbf{v}_s = -\text{sgn}(\mathbf{b} \cdot \nabla \varepsilon_c) \mathbf{v}_A, \quad (3.7)$$

and heat the gas at a rate proportional to the Alfvén velocity,

$$\mathcal{H}_c = |\mathbf{v}_A \cdot \nabla P_c|. \quad (3.8)$$

In the equations above, sgn returns the sign of the enclosed expression, and the Alfvén velocity is defined as $\mathbf{v}_A = \mathbf{B}/\sqrt{4\pi\rho}$. We note that the streaming term is always positive, so that energy is only ever transferred *from* the cosmic rays to heat the gas. When streaming is turned off, $\mathcal{H}_c = 0$. In the diffusion approximation, we assume a constant cosmic-ray diffusion coefficient, κ_c . When modeling cosmic-ray transport, we either invoke diffusion *or* streaming. Cosmic-ray advection is always turned on. For an in-depth description of the implementation and tests of the anisotropic cosmic-ray physics in ENZO, see chapter 2.

3.2.1 Initial Conditions

The initial conditions model the behavior of a column of gas extending off the disk of a galaxy into the CGM. The physical domain is comprised of a gravitationally stratified medium in hydrostatic equilibrium, similar to the simulations described in [McCourt et al. \(2012\)](#) and [Ji et al. \(2018\)](#). The gravitational acceleration is given by the following expression:

$$\mathbf{g} = g_0 \frac{z/a}{[1 + (z/a)^2]^{1/2}} \hat{z}. \quad (3.9)$$

Here, z is the vertical distance from the midplane, g_0 is a constant acceleration factor, and a is the gravitational smoothing length scale. This definition ensures that the gravitational acceleration goes smoothly to zero at the midplane but is nearly constant for $|z| > a$. The corresponding gas freefall time from a position, z , above the disk midplane is:

$$t_{\text{ff}} = \sqrt{\frac{2z}{g_0}}. \quad (3.10)$$

Using the criterion for hydrostatic equilibrium, $dP_{\text{tot}}/dz = -\rho(z)\mathbf{g}(z)$, we derive the total pressure profile, $P_{\text{tot}}(z)$, from the gravitational acceleration profile. We initialize magnetic and cosmic-ray pressures to be constant fractions of the gas pressure throughout, $\beta = P_g/P_B$ and $\eta = P_c/P_g$. Therefore, the the total pressure can be expressed as a multiple of the thermal pressure: $P_{\text{tot}} = (1 + \beta^{-1} + \eta)P_g$.

Given the derived vertical pressure profile, we can choose a variety of gas density and temperature profiles $(\rho(z), T(z))$ – so long as they obey the ideal gas law: $P = nk_B T$. We consider two such halo profiles: isothermal (constant temperature) and “iso-cooling” (constant cooling time).

In the isothermal halo, the density and temperature profiles are described by

$$\rho(z) = \rho_0 \exp \left[-\frac{a}{H} (1 + \beta^{-1} + \eta) \left([1 + (z/a)^2]^{1/2} \right) \right] \quad (3.11)$$

$$T(z) = T_0. \quad (3.12)$$

We define the scale height, $H = g_0/c_s^2$, and choose a gravitational smoothing length scale, $a = 0.1H$. In the purely hydrostatic case ($\beta = \infty, \eta = 0$), the temperature and density profiles described above are identical to those described in [McCourt et al. \(2012\)](#) and [Ji et al. \(2018\)](#). In simulations with $\beta < \infty$, the magnetic field is initialized to have a constant β everywhere so that magnetic pressure contributes to hydrostatic equilibrium. This is different from the initial conditions described in [Ji et al. \(2018\)](#), in which the magnetic fields do not contribute to hydrostatic equilibrium and are initialized with a constant magnetic field strength throughout.¹

When the cosmic-ray and magnetic pressures contribute to hydrostatic equilibrium, the thermal gas contributes less to balancing gravity. Therefore, in the isothermal halo profile, nonthermal pressure changes the steepness of the vertical gas density profile (Eq. 3.11). Since gas cooling times are proportional to the square of the density, simulations with an isothermal halo profile initialized with different amounts of nonthermal pressure will have different cooling time profiles, $t_{\text{cool}}(z)$. The differences in cooling times as a function of height makes it difficult to discern the impact of nonthermal pressure support from the impact of different cooling times on the onset of thermal instability. For this reason, we consider a new hydrostatic gas profile, in which the density and temperature of the gas are calibrated such that cooling time is constant everywhere (“iso-cooling”; [Meece et al., 2015](#)). Using this new constraint, the temperature and density profiles in the “iso-cooling” setup are given by

$$T(z) = T_0 \left[1 - \frac{1}{2 - \alpha} \frac{a}{H} (1 + \beta^{-1} + \eta) \left([1 + (z/a)^2]^{1/2} - 1 \right) \right], \quad (3.13)$$

$$\rho(z) = \rho_0 \left(\frac{T}{T_0} \right)^{1-\alpha}, \quad (3.14)$$

where α is the power-law index of the cooling function (see Section 3.2.2).

Both the isothermal and “iso-cooling” profiles describe gas distributions that are ho-

¹The choice of initial magnetic field configuration does not qualitatively impact the results.

homogeneous at a every height, z . However, thermal instability needs local inhomogeneity in order to grow. We seed the instability by introducing small isobaric perturbations with wavenumbers, k , such that $4 \leq (kL/2\pi) \leq 32$, and a root-mean-square perturbation amplitude of 0.02.

We choose the constants $g_0 = 5 \times 10^{-10} \text{ cm s}^{-2}$ (so that the gravitational freefall time at the scale height is $7.37 \times 10^8 \text{ yr}$), $\rho_0 = 10^{-27} \text{ g cm}^{-3}$, and $T_0 = 10^6 \text{ K}$. In physical units, the scale height, H , is 43.85 kpc. Although these constants are chosen to represent typical gas properties in the CGM of an L^* galaxy, the simulations are scale-free and insensitive to the choice of physical parameter values.

Our fiducial simulations are performed in tall, skinny boxes with resolution of $64 \times 64 \times 256$. The vertical axis spans $4 H$ in the “iso-cooling” profile and $6 H$ in the isothermal profile. The horizontal axes span $1 H$ in both profiles. We have confirmed that the choice of geometry does not affect the properties of the resulting thermal instability. The $\hat{x}$ and $\hat{y}$ boundaries have periodic boundary conditions, and the $\hat{z}$ boundary has “hydrostatic” boundary conditions. At the hydrostatic boundary, fluid values are interpolated quadratically from the horizontally averaged values in the preceding cells, with a couple of notable exceptions: (1) the vertical velocity is set to zero and (2) the magnetic field is set to its value in the nearest vertical layer.

3.2.2 Cooling and Heating

Both cooling and heating are crucial to developing local thermal instability in a globally stable atmosphere. Without a heating mechanism, simulations suffer from a cooling catastrophe. We assume that the gas is optically thin and cools radiatively following a simple power-law function described below.

$$\mathcal{L} = n^2 \Lambda(T), \quad (3.15)$$

$$\Lambda(T) = \Lambda_0 T^\alpha \text{ erg cm}^3 \text{ s}^{-1}, \quad (3.16)$$

for $T_{\min} < T < T_{\max}$. For our fiducial runs, we use $\alpha = -2/3$, which is a reasonable approximation of the real cooling curve in the CGM. The truncated cooling term, $T_{\min}$, regulates the minimum temperature in our simulation which is $\sim T_0/20$. We use a tanh function to let the cooling rate go smoothly to zero near $T = T_{\min}$ and $T = T_{\max}$. Truncating the cooling curve at $T_{\min}$ allows us to control the characteristic temperature of the cold gas. Since the size of cold gas clouds is proportional to the cooling time, the choice of $T_{\min}$ also prevents the simulation from prohibitively short time steps or severely underresolved cold gas clouds. The truncation at $T_{\max}$ does not impact the simulation, as the cooling times in the hot phase are much longer than the duration of the simulation. The constant Λ_0 is a free parameter that is used to change the ratio of the cooling time to freefall time in the simulations. The cooling time of gas is given by:

$$t_{\text{cool}} = \frac{k_B T}{(\gamma - 1)n\Lambda(T)}, \quad (3.17)$$

where k_B is the Boltzmann constant.

Observations of high column densities imply that the CGM is likely long-lived and globally stable (Tumlinson et al., 2011; Stocke et al., 2013; Werk et al., 2014). We model this global stability by balancing the total cooling with a mass-weighted heating in each vertical layer, so that the heating in a given cell is

$$\mathcal{H}_i = \rho_i \frac{\langle \mathcal{L} \rangle}{\langle \rho \rangle}, \quad (3.18)$$

where the angled brackets represent the volume average of the enclosed quantity in a vertical layer. Since ENZO explicitly tracks the specific energy ($e = \varepsilon_g/\rho$), we modify the above equations so that the cooling and heating in each cell becomes

$$\Delta e_{i,\text{cool}} = \Delta t \frac{\mathcal{L}_i}{\rho_i} \quad (3.19)$$

$$\Delta e_{i,\text{heat}} = \Delta t \frac{\langle \mathcal{L}_i \rangle}{\langle \rho_i \rangle}. \quad (3.20)$$

In the equations above, $\mathcal{H}_i$ and $\mathcal{L}_i$ are the volumetric heating and cooling in a given cell, i , and Δt is the current simulation time step. Ultimately, we model global thermal equilibrium by ensuring that the total cooling in each vertical layer is exactly balanced by the total heating. The fiducial simulations with cosmic-ray streaming have an additional perturbative heating term, $\mathcal{H}_c$, that is not accounted for in $\mathcal{H}$ above.

We turn off all cooling and heating within $0.1H$ of the midplane to prevent unphysical runaway cooling. Similarly, we turn off all cooling and heating within $0.05H$ of the vertical domain boundaries to prevent any unphysical precipitation seeded by the boundary conditions.

3.2.3 Parameter Survey Description

We systematically vary the parameters described below.

Cooling time: We keep the gravitational freefall time fixed and vary Λ_0 to achieve the following ratios of cooling time to freefall time (measured at $z = H$): $t_{\text{cool}}/t_{\text{ff}} \in [0.1, 0.3, 1, 3, 10]$. All simulations are evolved for $t = 10t_{\text{cool}}$.

Magnetic field strength: For every cooling time above, we run simulations with $\beta \in [\infty, 100, 10, 3]$. Our fiducial runs have $\beta = 100$.

Cosmic-ray pressure: For every combination of initial cooling time and magnetic field strength, we vary the initial ratio of cosmic-ray pressure to gas pressure, $\eta = P_c/P_g \in [0, 0.01, 0.1, 1, 10]$. Additionally, we run a small subset of the parameter space with an initial $P_c/P_g = 3.0$.

Cosmic-ray transport:

Advection: The simulations with cosmic-ray pressure described above all include cosmic-ray advection. Simulations with additional cosmic-ray transport are run for $t_{\text{cool}}/t_{\text{ff}} = 0.1 - 3$.

Diffusion: For every simulation with $\beta = 100$, we run simulations with three different diffusion coefficients, $\kappa_{\text{c}} \in [7.9 \times 10^{28}, 2.6 \times 10^{29}, 7.9 \times 10^{29}] \text{ cm}^2 \text{ s}^{-1}$, corresponding to diffusion time scale ratios of $t_{\text{diff}}/t_{\text{ff}} \in [10, 3, 1]$. We define the diffusion time scale as $t_{\text{diff}} = H^2/\kappa_{\text{c}}$. In the diffusion transport prescription, the transport velocity only depends on the direction of the magnetic field and not its strength. Therefore, our choice of $\beta = 100$ allows us to better isolate the effects of cosmic-ray transport from those of magnetic fields. Simulations with cosmic-ray diffusion have no cosmic-ray streaming and no cosmic-ray heating.

Streaming: For every initial cosmic-ray pressure, we turn on cosmic-ray streaming in runs with $\beta \in [100, 10, 3]$. Since the cosmic-ray streaming velocity depends on the magnetic field strength (Eq. 3.7), this effectively models cosmic-ray streaming at three different transport rates, $t_{\text{stream}}/t_{\text{ff}} \in [6, 1.8, 1]$, where $t_{\text{stream}} = H/\mathbf{v}_{\text{A}}$.

The fiducial simulations with cosmic-ray streaming have an additional heating term, $\mathcal{H}_{\text{c}}$, that is not present in cosmic-ray diffusion. To separate out the impact of cosmic-ray heating, we run each streaming simulation with and without the additional heating term. Runs with streaming but without cosmic-ray heating are marked with the label “no heating” for clarity. Simulations with cosmic-ray streaming have no cosmic-ray diffusion ($\kappa_{\text{c}} = 0$).

Miscellaneous: The parameters listed above summarize the fiducial simulation suite. However, there are a few additional parameters that we vary for a subset of the above simulations. Most of the simulations described below are discussed in Section 3.4.6 and in the Appendix.

Resolution: The fiducial resolution of our simulations is $64 \times 64 \times 256$ cells across a

simulation domain of $1 \times 1 \times 4H$. We also run a subset of the above simulations with half and double the resolution elements.

Halo profile: Our fiducial simulations have an “iso-cooling” profile. We also run a subset of simulations with an isothermal gas profile.

Cold gas temperature: The fiducial simulation suite has a $T_{\min} = 5 \times 10^4 \text{K}$. We also run a handful of simulations with $T_{\min} = 1 \times 10^4 \text{K}$.

3.3 Physical Expectations

3.3.1 Classical Thermal Instability

Classical thermal instability describes how the interplay of local cooling and heating in a globally stable gas leads to condensation and the formation of a two-phase medium. Consider an initially uniform patch of hot gas that undergoes a small density perturbation. Since heating rates are proportional to density while cooling rates are proportional to density squared, the perturbed overdense gas will cool faster than it can be heated. As the gas cools and condenses, its cooling rate continues to increase, until the cold gas reaches a new equilibrium temperature. The initially uniform single-phase medium is now transformed into a two-phase medium with cold gas cloudlets in pressure equilibrium with the volume-filling hot gas.

The growth rate of thermally unstable gas can be derived analytically, measured by the density fluctuation:

$$\frac{\delta\rho}{\rho} = \frac{\rho - \langle\rho\rangle}{\langle\rho\rangle}. \quad (3.21)$$

By perturbing Eqs. 3.1 - 3.4, we can determine the dispersion relation and solve for the characteristic growth time scale of the thermal instability under different conditions. For gas with a simple power-law cooling function and mass-weighted heating, the exponential growth rate of the thermal instability is characterized by t_{TI} (McCourt et al., 2012; Sharma

et al., 2012):

$$t_{\text{TI}} = \frac{\gamma t_{\text{cool}}}{(1 - d\ln\Lambda/d\ln T)}. \quad (3.22)$$

In the expression above, $d\ln\Lambda/d\ln T = \alpha$ is the logarithmic slope of the cooling function.

In the presence of gravity, buoyancy forces (characterized by the freefall time) become important. Assuming gas is initially in hydrostatic equilibrium, an overdense parcel of gas will begin to sink in the direction of the gravitational acceleration. As the cold gas sinks, its surroundings become progressively more dense, and the cold gas experiences compressive heating. If the cooling time is sufficiently fast, the overdense gas will form into cold cloudlets (“condensation”) and fall down the potential well towards the galaxy (“precipitation”). Alternatively, if the cooling time is slow the overdense parcel of gas will be compressively heated faster than it can cool, preventing condensation.

The balance between radiative cooling and compressive heating is often expressed as the ratio of the gas cooling time and freefall time, $t_{\text{cool}}/t_{\text{ff}}$. If $t_{\text{cool}}/t_{\text{ff}}$ is less than 1, cooling is considered efficient and cold gas is expected to form. If $t_{\text{cool}}/t_{\text{ff}}$ is greater than one but is less than $\sim 10 - 20$, cold gas may still form with the help of magnetic fields or large density perturbations (Meece et al., 2015; Voit et al., 2017; Ji et al., 2018; Prasad et al., 2018; Choudhury et al., 2019). The median ratio of $t_{\text{cool}}/t_{\text{ff}}$ in the CGM is expected to be between 5 and 20 (Esmerian et al., 2020).

Magnetic fields enhance thermal instability in gas with $t_{\text{cool}}/t_{\text{ff}} \geq 1$ in two ways. Magnetic tension can directly counteract compressive heating by supporting overdense gas against gravity so that it cools in-situ. Magnetic tension can also indirectly counteract compressive heating by confining pressurized hot gas (Ji et al., 2018).

3.3.2 Thermal Instability with Cosmic rays

The behavior of cosmic rays in galaxy-scale simulations is well modeled as that of a relativistic fluid. This cosmic-ray fluid interacts with the gas by providing nonthermal pressure support (P_c in Eqs. 3.2 and 3.4), and, in some cases, by heating the thermal gas ($\mathcal{H}_c$ in

Eqs. 3.4 and 3.5). The cosmic-ray fluid moves both with the gas (advection) and relative to the gas, along magnetic field lines. The latter motion is typically approximated by either diffusion or streaming.

The impact of cosmic rays on thermal instability depends on how cosmic-ray pressure scales with gas density, $P_c \propto \rho^{\gamma_{c,\text{eff}}}$. In the limit of inefficient cosmic-ray transport (i.e., advection only), cosmic rays are fully coupled with the gas, and $\gamma_{c,\text{eff}} = \gamma_c = 4/3$. Cosmic-ray transport redistributes cosmic-ray pressure from high-density to low-density regions, effectively lowering $\gamma_{c,\text{eff}}$. In the limit of very efficient cosmic-ray transport, cosmic-ray pressure decouples from the gas and $\gamma_{c,\text{eff}} \rightarrow 0$. The exact value of $\gamma_{c,\text{eff}}$ depends on the balance of the efficiency of cosmic-ray transport, the ratio of cosmic-ray pressure to gas pressure, the gas cooling time, and the Alfvén velocity.

In the discussion below, we provide a brief overview of the relevant cosmic-ray physics and provide some intuition for how different aspects of the cosmic-ray fluid can affect thermal instability. We first focus on the impact of cosmic-ray pressure in the limit of no cosmic-ray transport and make predictions for the gas density contrast and cold cloud sizes. We then discuss the expected qualitative impact of cosmic-ray transport.

Thermal Instability with Cosmic-ray Pressure

Cosmic-ray pressure can convert thermal instability from an isobaric to an isochoric process. Unlike regular gas, cosmic rays do not lose energy through radiative cooling. In a purely thermal gas, a cooling cloud condenses to balance its change in temperature in order to remain in pressure equilibrium with the hot medium. In the presence of cosmic rays, as a cooling cloud contracts, its nonthermal cosmic-ray pressure grows. The added pressure support lets gas cool without contracting as much, since the cooling cloud needs to be in *total* pressure equilibrium, $P_{\text{tot}} = P_g + P_B + P_c$. With sufficiently high cosmic-ray pressures, gas cools at constant density (isochorically; Sharma et al., 2010; Kempster and Quataert, 2020).

This nonthermal pressure support increases the size of cold gas clouds, ℓ_{cloudlet} , and lowers the density contrast, δ , between the cold and hot gas phases,

$$\delta = \frac{\langle \rho_{\text{cold}} \rangle}{\langle \rho_{\text{hot}} \rangle}. \quad (3.23)$$

We introduce a simple model for how these quantities depend on cosmic-ray pressure below.

Assuming that the total pressure stays constant, $(P_g + P_B + P_c)_{\text{cold}} = (P_g + P_B + P_c)_{\text{hot}}$, and that the magnetic and cosmic-ray pressures scale with gas density, we expect the density contrast to follow

$$\begin{aligned} P_{B,\text{hot}} &= \beta_{\text{cold}}^{-1} P_{g,\text{cold}} \left(\frac{\rho_{\text{hot}}}{\rho_{\text{cold}}} \right)^{\gamma_B}, \\ P_{c,\text{hot}} &= \eta_{\text{cold}} P_{g,\text{cold}} \left(\frac{\rho_{\text{hot}}}{\rho_{\text{cold}}} \right)^{\gamma_{c,\text{eff}}}, \end{aligned} \quad (3.24)$$

we expect the density contrast to follow:

$$(1 + \beta_{\text{cold}}^{-1} + \eta_{\text{cold}}) = \frac{\Theta}{\delta} + \frac{\beta_{\text{cold}}^{-1}}{\delta^{\gamma_B}} + \frac{\eta_{\text{cold}}}{\delta^{\gamma_{c,\text{eff}}}}, \quad (3.25)$$

where $\eta_{\text{cold}}, \beta_{\text{cold}}$ are evaluated in the cold gas, and $\Theta = T_{\text{hot}}/T_{\text{cold}}$ is the temperature contrast between the hot and cold gas phases. The temperature contrast is set by the details of the atomic physics that determines the cooling curve and is independent of magnetic fields and cosmic rays. The constant $\gamma_B = 4/3$ describes how magnetic pressure scales with gas density, $P_B \propto \rho^{\gamma_B}$, in the flux-freezing limit of ideal MHD. This is similar to the advection-only limit of cosmic-ray transport. We explore the application of the predicted density contrast in Section 3.4.6 and in Appendix 3.7.2.

The characteristic scale of cold gas clouds is predicted to be set by the minimum of the product of the gas sound speed and cooling time², $\ell_{\text{cloudlet}} \sim \min(c_s t_{\text{cool}})$ (McCourt

²The minimum value of $c_s t_{\text{cool}}$ is expected to happen around $T \approx 10^{4.2}\text{K}$ for a variety of gas pressures (Liang and Remming, 2020).

et al., 2018). Both the effective sound speed and the gas cooling time may be altered by nonthermal pressure support.

In the presence of magnetic fields and cosmic rays, the maximum wave speed is given by, $c_{\max}^2 = c_s^2 + v_A^2 + c_{s,c}^2$, where $c_s = \sqrt{(\gamma P_g/\rho)}$ is the thermal gas sound speed, $v_A = \sqrt{2P_B/\rho}$ is the Alfvén velocity, and $c_{s,c} = \sqrt{\gamma_{c,\text{eff}} P_c/\rho}$ is the cosmic-ray sound speed. We can rewrite the maximum wave speed as a function of the ratios of magnetic and cosmic-ray pressures to the gas pressure, β and η :

$$c_{\max} = c_s \left(1 + \frac{2}{\gamma} \beta^{-1} + \frac{\gamma_{c,\text{eff}}}{\gamma} \eta \right)^{1/2}. \quad (3.26)$$

Assuming that gas cooling follows a power law (Eq. 3.16), the gas cooling time scales as:

$$t_{\text{cool}} = \frac{\frac{3}{2} \rho k_B T}{\left(\frac{\rho^2}{\mu m_p}\right) \Lambda_0 T^\alpha} \propto \rho^{-1} T^{1-\alpha}, \quad (3.27)$$

where μ is the mean molecular weight and m_p is the proton mass. Since the temperature of cold gas is set by the cooling curve and isn't affected by nonthermal pressure, we expect nonthermal pressure to only alter the density in the cooling time scaling relation. Combining the expected expression for the cold cloud size with Eqs. 3.26 and 3.27, we predict the nonthermal pressure-supported cold gas cloud size, ℓ_{cloudlet}^* , to scale as:

$$\frac{\ell_{\text{cloudlet}}^*}{\ell_{\text{cloudlet}}} = \left(\frac{\rho_{\text{cold}}}{\rho_{\text{cold}}^*} \right) \left(1 + \frac{2}{\gamma} \beta_{\text{cold}}^{-1} + \frac{\gamma_{c,\text{eff}}}{\gamma} \eta_{\text{cold}} \right)^{1/2}, \quad (3.28)$$

where ρ_{cold}^* is the density of nonthermal pressure-supported cold gas. In the limit of high cosmic-ray pressure (Eq. 3.25), the cold gas density is the same as the hot gas density, $\rho_{\text{cold}}^* = \rho_{\text{hot}}$, so the ratio $\rho_{\text{cold}}/\rho_{\text{cold}}^* \approx \Theta$ can be expressed in terms of the temperature contrast between cold and hot phases. For a cosmic-ray-pressure-supported medium with

inefficient transport ($\gamma_{\text{c,eff}}\eta_{\text{cold}} \gg 1$), we expect:

$$\frac{\ell_{\text{cloudlet},\eta \gg 1}^*}{\ell_{\text{cloudlet}}} \approx \Theta \left(\frac{\gamma_{\text{c,eff}}}{\gamma} \eta_{\text{cold}} \right)^{1/2}. \quad (3.29)$$

Following Eq. 3.29, we expect simulations with $\Theta = 20$, $P_{g,0} = 490 \text{ K cm}^{-3}$, $\eta_{\text{cold}} = 100$ to have cold cloud sizes, $\ell_{\text{cloudlet}}^* \approx 200 \ell_{\text{cloudlet}} \approx 40 \text{ kpc}$, which is in good agreement with the results discussed below (see Section 3.4.2). In the real CGM, the temperature contrast between hot and cold phases is closer to $\Theta = 100$ and the range of gas pressures $P_g/k_B \sim 1 - 10^3 \text{ K cm}^{-3}$ gives predicted cold cloudlet sizes of $\ell_{\text{cloudlet}} \sim 1 - 1000 \text{ pc}$. Therefore, in the limit of no cosmic-ray transport in a cosmic-ray-pressure dominated halo, we expect cold cloud sizes to be to ~ 1000 times larger than predicted for cold gas in thermal pressure equilibrium. This prediction is an upper limit for cold cloud sizes in a cosmic-ray-pressure-supported halo as realistic cosmic-ray transport will reduce $\gamma_{\text{c,eff}}$, thereby reducing the predicted cold cloud increase.

In addition to altering cold gas density and cloud size, cosmic-ray pressure also contributes to hydrostatic equilibrium and changes the effective entropy profiles of the gas. This could prevent cold gas clumps from precipitating after they condense out of the hot background medium. Additionally, if the cosmic-ray scale height is sufficiently large relative to the gas scale height, $H_c/H_g \geq 5/2$, gas becomes convectively unstable (Kempski and Quataert, 2020). Our simulations are initialized with constant η , so H_c/H_g is always close to 1.

Thermal Instability with Cosmic-ray Transport

In addition to advection, the cosmic-ray fluid moves relative to the gas via some transport mechanism. Although there is no consensus as to which transport mechanism produces the most realistic results in galaxy simulations (Butsky and Quinn, 2018; Farber et al., 2018; Buck et al., 2020; Hopkins et al., 2021b), cosmic-ray transport has been historically modeled as either streaming or diffusion. Physically, both streaming and diffusion model

how perturbations in the magnetic field lines scatter the pitch-angle of the cosmic-ray orbit. The main difference lies in the assumption about what is driving the perturbations in the magnetic field, either the streaming instability (streaming) or extrinsic turbulence (diffusion).

In the fluid approximation, both cosmic-ray streaming and cosmic-ray diffusion model how cosmic rays move along magnetic field lines, down the cosmic-ray pressure gradient. In the diffusion approximation, the transport rate is set by the constant diffusion coefficient, κ_c , and in the streaming approximation, the transport rate is set by the local Alfvén velocity. Since cosmic-ray transport reduces the nonthermal pressure support in cold gas, we expect simulations with cosmic-ray transport to have smaller cold cloud sizes, higher gas densities, and higher cold mass flux rates than simulations with only cosmic-ray advection. However, the quantitative impact on thermal instability will be sensitive to the details of the cosmic-ray transport model parameters.

In the streaming approximation of cosmic-ray transport, cosmic rays heat the gas at a rate proportional to the Alfvén velocity and cosmic-ray pressure gradient ($\mathcal{H}_c$ in Eqs. 3.4 and 3.5). We expect cosmic-ray heating to be significant in gas with low β and high η (Kempski and Quataert, 2020). This heating process is also more efficient in simulations with larger $t_{\text{cool}}/t_{\text{ff}}$, which are evolved long enough for cosmic-ray transport processes to become important.

Cosmic-ray transport also alters the growth rate of the thermal instability. In the limit of no cosmic-ray pressure, the growth rate is that predicted by classical thermal instability. In the limit of high cosmic-ray pressure, the growth rate depends on the invoked cosmic-ray transport mechanisms (see Kempski and Quataert (2020) for detailed derivations).

While the discussion above provides some intuition of the isolated impacts of cosmic-ray pressure, transport, and heating, simulations are necessary to study the interplay of these effects in the nonlinear regime.

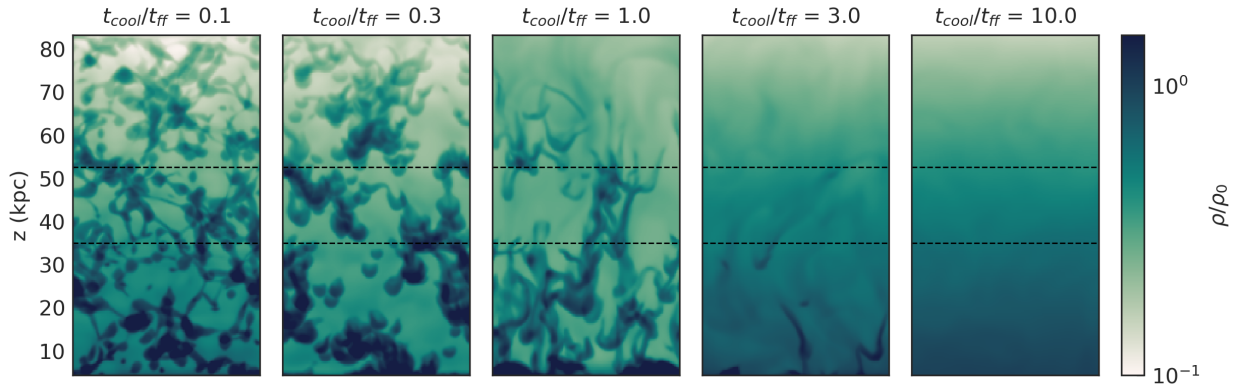


Figure 3.1 Projections of the gas density for different initial values of $t_{\text{cool}}/t_{\text{ff}}$. The dimensions of each slice are $1H \times 2H$ in the $\hat{x}$ and $\hat{z}$ directions respectively and the projection depth in $\hat{y}$ is $1H$ (43.85 kpc). The simulations showcased above were initialized with $\beta = 100$ and no cosmic rays. Since the simulations are symmetric about the midplane, we only show the top half of the domain. The snapshots are taken at $t = 4t_{\text{cool}}$, which corresponds to longer physical times for simulations with higher $t_{\text{cool}}/t_{\text{ff}}$. As expected, there is a direct relationship between the value of $t_{\text{cool}}/t_{\text{ff}}$ and the condensation of dense, cold gas. Simulations evolved for longer physical times show signs of cold gas precipitating towards the midplane. However, in simulations with $t_{\text{cool}}/t_{\text{ff}} \geq 3$, insufficient condensation occurs to form appreciable amounts of cold gas.

3.4 Results

In the following sections, we quantify the evolution of thermal instability by measuring three quantities: the density fluctuation, the cold mass fraction, and the cold mass flux. We focus our analysis around the scale height, $0.8H \leq |z| \leq 1.2H$. This region is both sufficiently thick to capture the relevant effects and sufficiently removed from the simulation center and boundaries (see Figure 3.1). We first show the growth and saturation of thermal instability without cosmic rays for a wide range of initial $t_{\text{cool}}/t_{\text{ff}}$ values. We then show the impact of cosmic-ray pressure in advection-only simulations, followed by the impact of various cosmic-ray transport models.

The density fluctuation, $\delta\rho/\rho$ (Eq. 3.21), measures the variance in density values between the cold and hot phases. In the early stages of thermal instability, the density fluctuation grows following a power law that depends on the slope of the cooling function (Eq. 3.22). At late times, the density fluctuation saturates. At very late times, the measured density fluctuation may decrease as cold gas clumps precipitate from the scale height down to the simulation midplane.

The cold mass fraction measures the total mass of cold gas as a fraction of the total gas mass ($M_{\text{cold}}/M_{\text{total}}$). The average temperature of cold gas in the simulation is set by T_{min} , which is $5 \times 10^4 \text{K}$ in our fiducial simulations. However, since the temperature distribution is highly bimodal (see Section 3.5), we define cold gas to be $T \leq 3 \times 10^5 \text{K}$ in our analysis. Like the density fluctuation, the cold mass fraction near the scale height can decrease at late times as cold gas clumps precipitate and fall towards the midplane.

The cold mass flux,

$$\frac{\dot{M}_{\text{cold}}}{\dot{M}_{\text{ff}}} = \rho_{\text{cold}} v_{\text{in}} \frac{t_{\text{ff}}}{\rho_0 H}, \quad (3.30)$$

measures the rate at which cold gas precipitates towards the midplane, normalized by the freefall mass flux.³ The quantity $v_{\text{in}} = -v_z \cdot \hat{z}$ measures the infalling velocity of cold gas

³Our initial conditions satisfy hydrostatic equilibrium and there is no initial mass flux.

clouds. Since the simulations are run for a constant number of cooling times, simulations with larger $t_{\text{cool}}/t_{\text{ff}}$ have time to accelerate to larger v_{in} velocities. Larger inflowing velocities result in an increase in the cold mass flux (assuming the simulation formed cold gas). Later, we will demonstrate how cosmic-ray pressure can suppress cold mass flux by limiting v_{in} .

3.4.1 Thermal Instability Without Cosmic rays

We first demonstrate the onset of thermal instability without cosmic-ray physics. Figure 3.1 shows density projections of simulations with $\beta = 100$, and varying initial values of $t_{\text{cool}}/t_{\text{ff}}$. These snapshots are pictured after the simulations have evolved for 4 cooling times,⁴ which is roughly when the density fluctuation saturates (see Figure 3.2). In simulations with short cooling times, cold gas condenses out of the background medium much faster than the gravitational free fall time. Therefore, after several cooling cycles, there is still plenty of cold gas high in the “atmosphere”. For larger values of $t_{\text{cool}}/t_{\text{ff}}$, the gravitational acceleration becomes more important, and condensed gas clumps start precipitating down towards the midplane. The size of the cold condensed gas clumps is also visibly larger in simulations with larger $t_{\text{cool}}/t_{\text{ff}}$, because cloud sizes are proportional to the cooling time, and because cold gas cloudlets have had more time to coagulate (Gronke and Oh, 2020). There is no sign of thermal instability in the simulation with $t_{\text{cool}}/t_{\text{ff}} = 10$.

The left panel of Figure 3.2 quantifies the time evolution of the average density fluctuation, $\langle \delta\rho/\rho \rangle$, measured at $z = 0.8\text{--}1.2H$, for the five simulations pictured in Figure 3.1. At early times, the density fluctuation for simulations with $t_{\text{cool}}/t_{\text{ff}} \leq 1$ grows at the rate predicted by linear theory (see Eq. 3.22). The thermal instability saturates after about roughly 4 cooling times. The saturated density fluctuation value is higher for simulations with lower $t_{\text{cool}}/t_{\text{ff}}$ and are generally consistent with those presented in McCourt et al. (2012) and Ji et al. (2018). For $t_{\text{cool}}/t_{\text{ff}} \geq 0.3$, the density fluctuation decreases at late times

⁴Since the projections were generated after the same number of cooling cycles, this means that simulations with longer cooling times were run for longer physical times.

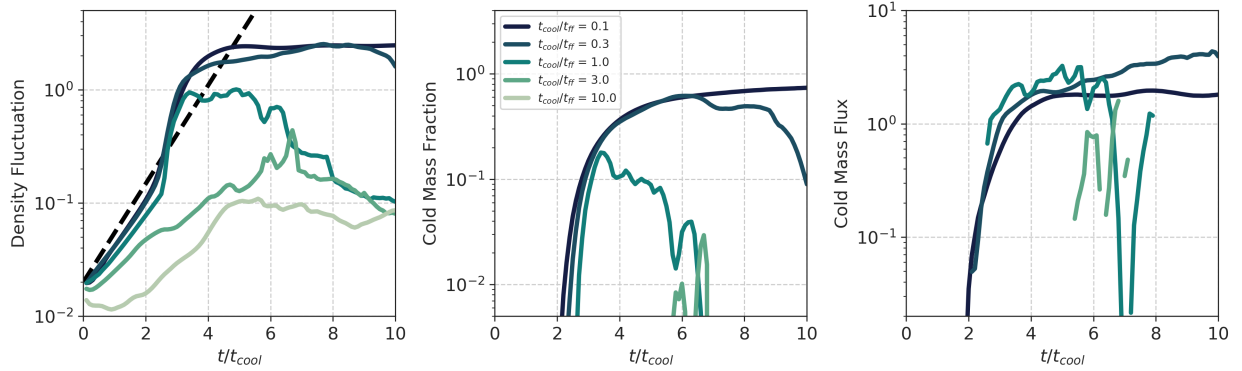


Figure 3.2 The time evolution of the density fluctuation ($\langle \delta\rho/\rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and infalling cold mass flux ($\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*). The different lines show different initial values of the ratio of cooling time to freefall time at the scale height. The black dashed line in the left panel shows the linear theory prediction for the density fluctuation growth with mass-weighted heating and a logarithmic cooling slope, $\alpha = -2/3$ (Eq. 3.16). All values are measured between 0.8 and 1.2 times the scale height. The fiducial simulations presented are initialized with $\beta = 100$. The x-axis values are scaled by the cooling time of the simulation, so that simulations with higher values of $t_{\text{cool}}/t_{\text{ff}}$ are evolved over longer physical times. This figure demonstrates thermal instability without cosmic rays: simulations with lower $t_{\text{cool}}/t_{\text{ff}}$ show higher density fluctuations and cold mass fractions. Although the cold mass fraction is significantly higher in simulations with $t_{\text{cool}}/t_{\text{ff}} = 0.1 - 0.3$ than in simulations with $t_{\text{cool}}/t_{\text{ff}} = 1$, their cold mass flux rates are comparable shortly after the saturation of the thermal instability. This is because simulations with longer $t_{\text{cool}}/t_{\text{ff}}$ have been evolved for longer physical time, and have developed a higher inflow velocity, $v_{\text{in}} = -\mathbf{v} \cdot \hat{\mathbf{z}}$.

as cold gas precipitates from the scale height towards the midplane.

The middle panel of Figure 3.2 shows the time evolution of the mass fraction, $M_{\text{cold}}/M_{\text{total}}$, of cold gas. The cold mass fraction is nearly identical for runs with $t_{\text{cool}}/t_{\text{ff}} = 0.1$ and $t_{\text{cool}}/t_{\text{ff}} = 0.3$ for the majority of the simulation. At late times ($t \gtrsim 2 t_{\text{ff}}$), the cold mass fraction decreases as cold gas clouds begin to precipitate. There is no sign of precipitation in the simulation with $t_{\text{cool}}/t_{\text{ff}} = 0.1$, since it was only evolved for $t = 10 t_{\text{cool}} = 1 t_{\text{ff}}$. The simulation with $t_{\text{cool}}/t_{\text{ff}} = 1$ only reaches a cold gas mass fraction of about 0.1 before the cold gas clumps precipitate out of the halo. Unsurprisingly, simulations with $t_{\text{cool}}/t_{\text{ff}} \geq 3$ do not form substantial amounts of cold gas.

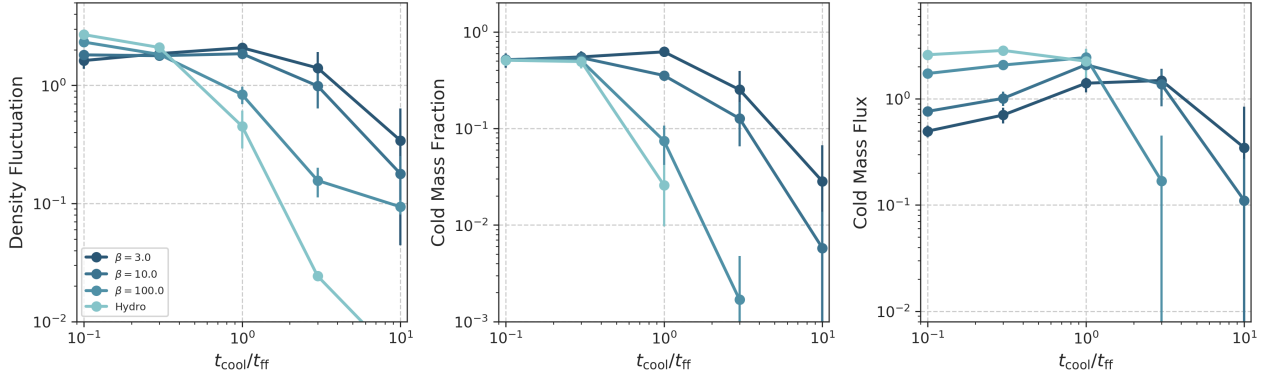


Figure 3.3 The average density fluctuation ($\langle \delta\rho/\rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*) as a function of the initial $t_{\text{cool}}/t_{\text{ff}}$ for simulations with varying initial magnetic field strengths, in the absence of cosmic rays. The measurements are taken between 0.8 and $1.2H$ and averaged over all outputs between 4 and $6 t_{\text{cool}}$, which corresponds to the saturated phase of the thermal instability (see Figure 3.2). Magnetic fields suppress buoyancy oscillations, which simultaneously enhances the formation of cold gas through thermal instability for simulations with higher $t_{\text{cool}}/t_{\text{ff}}$ and decreases the inflowing cold mass flux in simulations with lower $t_{\text{cool}}/t_{\text{ff}}$.

The right panel of Figure 3.2 shows the time evolution of the cold mass flux towards the midplane, $\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$. Although the simulation with $t_{\text{cool}}/t_{\text{ff}} = 1$ has a lower cold mass fraction near the scale height than simulations with $t_{\text{cool}}/t_{\text{ff}} = 0.1, 0.3$, it has comparable cold mass flux values due to larger values of the inflow velocity, v_{in} . Since simulations are evolved for a fixed number of cooling cycles, simulations with larger $t_{\text{cool}}/t_{\text{ff}}$ are evolved for longer physical time and develop larger infall velocities. Without thermal instability, there is no cold mass flux.

Next, we demonstrate the effects of magnetic fields on thermal instability in the absence of cosmic rays. Figure 3.3 shows the time-averaged density fluctuation, cold mass fraction, and cold mass flux as a function of the initial $t_{\text{cool}}/t_{\text{ff}}$. Each point represents the mean measurement for all simulation outputs between 4 and $6 t_{\text{cool}}$, and the error bars show one standard deviation. The colors show different initial magnetic field strengths ranging from no magnetic fields ($\beta = \infty$), to strong magnetic fields ($\beta = 3$). These initial magnetic field strengths span the range of magnetic fields considered in our cosmic-ray

simulations and serve as a useful reference to disentangle the effects of cosmic rays from the effects of magnetic fields.

When cooling times are short ($t_{\text{cool}}/t_{\text{ff}} \leq 1$), thermal instability is efficient in all simulations, independent of magnetic field strength. The density fluctuation is lower in runs with strong magnetic fields and $t_{\text{cool}}/t_{\text{ff}} = 0.1$ due to the additional nonthermal pressure support lowering cold gas densities. Although the cold mass fraction is constant between all runs with short cooling times, the cold mass flux decreases with increasing magnetic field strength due to increased nonthermal pressure support.

When cooling times are long ($t_{\text{cool}}/t_{\text{ff}} \geq 1$), magnetic fields enhance thermal instability by suppressing buoyancy oscillations (Ji et al., 2018). The density fluctuation, cold mass fraction, and cold mass flux increase with decreased β . Our density fluctuation values are consistent with those reported in Ji et al. (2018). Small differences are likely due to measurements being taken at different simulation times.

These MHD-only simulations highlight the previously demonstrated dependence of thermal instability on the gas cooling time and magnetic field strength. Simulations with short $t_{\text{cool}}/t_{\text{ff}}$ produce higher density fluctuations and cold mass fractions in less physical time. Magnetic fields enhance thermal instability when cooling times are long.

3.4.2 Thermal Instability with Cosmic-ray Pressure

In the limit that cosmic-ray transport is very slow relative to the time scale of thermal instability, cosmic-ray advection with the thermal gas becomes important. We isolate this phenomenon with a suite of simulations, varying the initial cosmic-ray pressure fraction, P_c/P_g , for which both cosmic-ray diffusion and cosmic-ray streaming are turned off.

Figure 3.4 shows the impact of cosmic-ray pressure on the density and temperature slices of thermally unstable gas. All simulations are initialized with $t_{\text{cool}}/t_{\text{ff}} = 1.0$, $\beta = 100$ and have been run for 4 cooling times. The columns differ from each other by their initial

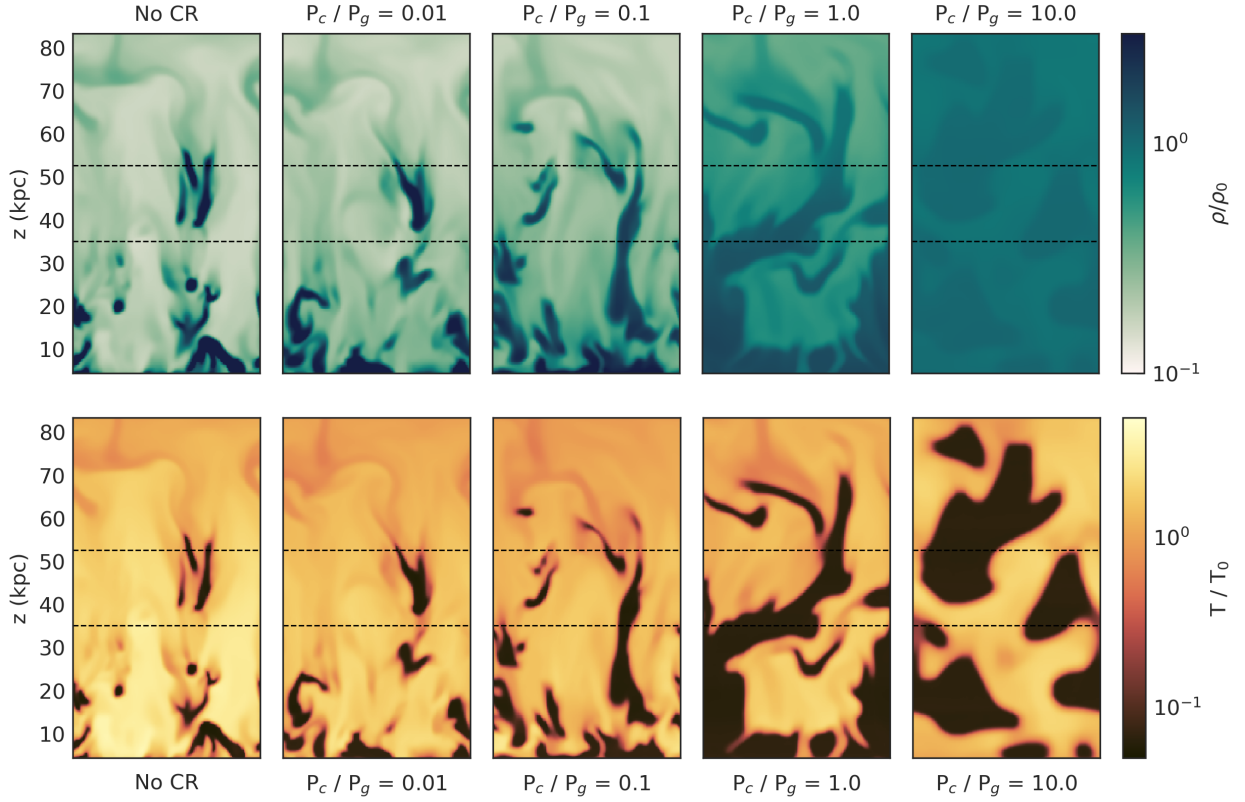


Figure 3.4 2D slices of the 3D density (top) and temperature (bottom) for simulations with varying initial ratios of cosmic-ray pressure to gas pressure, P_c/P_g . Similarly to Figure 3.1, the dimensions of each panel are $1H \times 1.8H$. All simulations are initialized with $t_{\text{cool}}/t_{\text{ff}} = 1.0$, and the slices are taken at $t = 6t_{\text{cool}}$. Simulations with cosmic rays were run with advection as the only form of cosmic-ray transport. Increased cosmic-ray pressure support creates larger cold gas clouds with lower densities. The temperature of the cold gas does not change with increased cosmic-ray pressure since the temperature is set by the cooling function and our choice of T_{min} . With sufficiently high cosmic-ray pressure, cold gas remains in the atmosphere and does not precipitate.

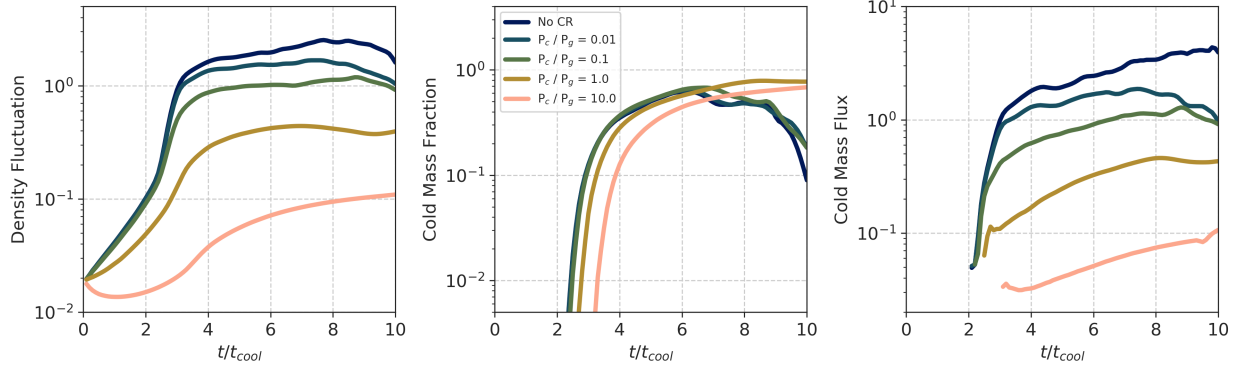


Figure 3.5 The time evolution of the density fluctuation ($\langle \delta\rho/\rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*) near the scale height ($0.8H < z < 1.2H$). All of the depicted simulations have $t_{\text{cool}}/t_{\text{ff}} = 0.3$ and $\beta = 100$ but have different initial values of P_c/P_g . Increased cosmic-ray pressure decreases density fluctuation but has a modest effect on the cold mass fraction. Nonthermal cosmic-ray pressure support counteracts gravity and lowers the cold mass flux towards the midplane. Simulations with $P_c \geq P_g$ have more cold gas near the scale height at late times.

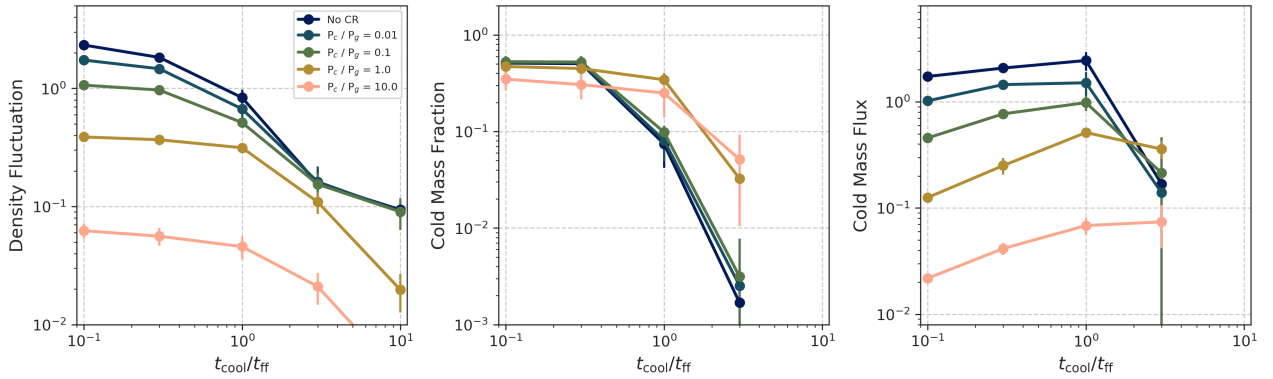


Figure 3.6 The average density fluctuation ($\langle \delta\rho/\rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*) as a function of the initial $t_{\text{cool}}/t_{\text{ff}}$ for simulations with $\beta = 100$ and varying initial ratios of P_c/P_g . The measurements are taken between 0.8 and $1.2 H$ and averaged over all outputs between 4 and $6 t_{\text{cool}}$, which corresponds to the saturated phase of the thermal instability (see Figure 3.5). Increased cosmic-ray pressure decreases the gas density fluctuation. High cosmic-ray pressures increase the cold fraction in simulations with $t_{\text{cool}}/t_{\text{ff}} \geq 1$ by preventing cold gas from precipitating towards the midplane. Cold gas does not form in simulations with $t_{\text{cool}}/t_{\text{ff}} = 10$.

value of P_c/P_g .

Increased cosmic-ray pressure alters the morphology of cold gas. Radiative gas cooling does not remove cosmic-ray energy. In the limit where the cosmic-ray pressure is high and dominates the total pressure, the loss of thermal pressure from radiative cooling leads to negligible compression. As a result the gas cools isochorically. This behavior is in contrast to traditional thermal instability, where as the gas cools, it loses thermal pressure, and collapses isobarically, with large density fluctuations (for more detail, see Section 3.4.4). Therefore, increased cosmic-ray pressure results in larger cold gas clouds that have a lower density contrast with the background medium. When cosmic-ray pressure dominates (right panel), cold cloud structures span tens of kiloparsecs, which is broadly consistent with our predictions using Eq. 3.29 in Section 3.3. Additionally, cosmic-ray pressure contributes to hydrostatic equilibrium and keeps cold gas at high altitudes for longer.

The temperature of the cold gas phase does not change with increased cosmic-ray pressure. This is because gas temperature is set by the cooling function, which is an approximation to atomic physics and is insensitive to cosmic-ray physics.

Figure 3.5 shows the time evolution of the density fluctuation, cold mass fraction, and cold mass flux for the simulations pictured in Figure 3.4. The different colored lines represent simulations with different initial values of P_c/P_g . All simulations have an initial $t_{\text{cool}}/t_{\text{ff}} = 0.3$ and $\beta = 100$.

The density fluctuation decreases monotonically with increased cosmic-ray pressure. Remarkably, the cold mass fraction remains relatively unchanged. Even in the extreme case of $P_c/P_g = 10$, the cold mass fraction only varies from the control run by a factor of 2-3, whereas the density fluctuation measurement varies by a factor of 50. At late times, runs with significant cosmic-ray pressure support have more cold gas mass near the scale height since the cosmic-ray pressure prevents it from precipitating towards the midplane. Although the cold mass fraction is relatively unchanged, the cold mass flux decreases substantially with increased cosmic-ray pressure. Even a modest initial value of $P_c/P_g =$

0.01 is enough to decrease the cold mass flux by a factor of ~ 2 . Since cosmic rays advect with the gas, cold gas clumps end up having a larger ratio of P_c/P_g . This added nonthermal pressure supports the cold gas against gravity.

Figure 3.6 compiles the average values of the density fluctuation, cold mass fraction, and cold mass flux measured between $t = 4t_{\text{cool}}$ and $t = 6t_{\text{cool}}$ as a function of the simulation's initial $t_{\text{cool}}/t_{\text{ff}}$. Increasing the cosmic-ray pressure monotonically decreases the measured density fluctuation for all initial values of $t_{\text{cool}}/t_{\text{ff}}$ (left panel). As nonthermal cosmic-ray pressure increases, the gas is better able to cool isochorically, decreasing the density contrast between the cold and hot phases. With increased cosmic-ray pressure, the average density fluctuation also becomes less sensitive to the initial $t_{\text{cool}}/t_{\text{ff}}$.

When cooling times are short, ($t_{\text{cool}}/t_{\text{ff}} \leq 1$), the average cold mass fraction (middle panel) remains relatively unchanged with increased cosmic-ray pressure. However, when cooling times are long ($t_{\text{cool}}/t_{\text{ff}} \geq 1$), the average cold mass fraction is higher for simulations with $P_c/P_g \geq 1$. *The presence of cosmic rays can, therefore, significantly increase the amount of cold gas in the CGM, particularly in the outer halo where cooling times would otherwise be too long relative to free fall times.* In part, this is due to cosmic-ray pressure counteracting compressive heating, similar to the role of strong magnetic fields in Figure 3.3 (see also Ji et al., 2018). Additionally, once the cold gas is formed, cosmic-ray pressure support prevents it from precipitating by supporting the gas against gravity. This effect is prevalent when cosmic-ray pressure is at least as strong as the gas pressure and when the cooling times are long, such that gas inflow velocities become important. This is likely a very relevant regime for low redshift galaxies.

Finally, the third panel of Figure 3.6, shows that the cold mass flux decreases with increased cosmic-ray pressure in nearly all cases. Since cosmic-ray pressure does not decrease the cold mass fraction at the midplane (see the middle panel), the decrease in cold mass flux is a result of decreased cold gas inflow velocity due to increased cosmic-ray pressure support. The increased cold mass flux at $t_{\text{cool}}/t_{\text{ff}} = 3$, $P_c/P_g = 1$ is an exception to this trend and is due to the relative increase in the average cold mass fraction.

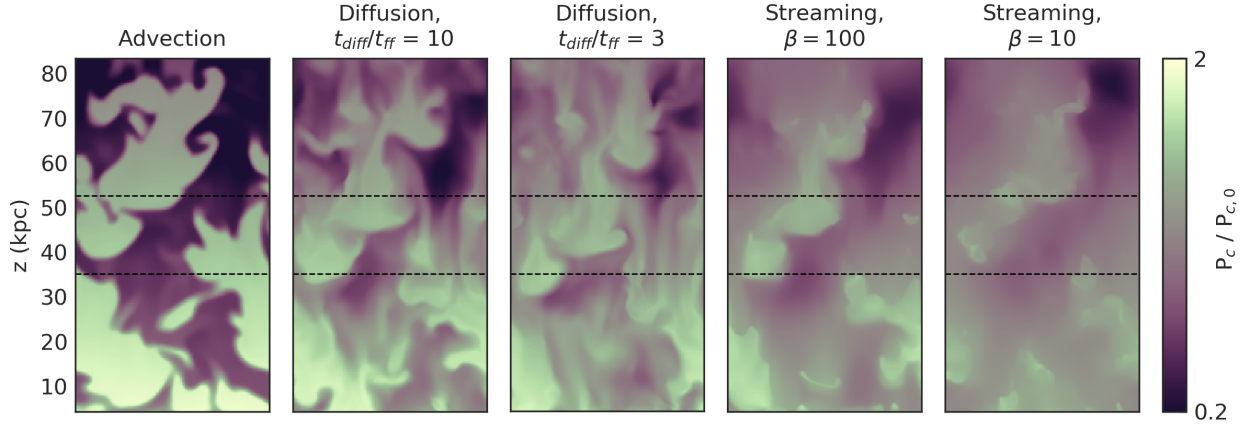


Figure 3.7 2D slices of the 3D cosmic-ray pressure for simulations with different implementations of cosmic-ray transport: advection, diffusion, and streaming. Similarly to Figures 3.1 and 3.4, the dimensions of each panel are $1H \times 1.8H$. All simulations are initialized with $t_{\text{cool}}/t_{\text{ff}} = 0.3$ and $P_c/P_g = 1$. Except for the rightmost panel, all simulations have $\beta = 100$. The slices are taken at $t = 6t_{\text{cool}}$. Cosmic-ray transport redistributes cosmic-ray pressure from regions of high density to low density. When cosmic-ray transport is more efficient (diffusion with $t_{\text{diff}}/t_{\text{ff}} = 3$ or streaming with $\beta = 10$), the cosmic-ray pressure approaches a more homogeneous distribution.

Increased cosmic-ray pressure does not inhibit the formation of cold gas through thermal instability. However, cosmic-ray pressure changes the saturation of the instability from forming small, dense cloudlets that precipitate readily to large, diffuse clouds that remain static.

3.4.3 Thermal Instability and Cosmic-ray Transport

In the previous section, we built intuition for the impact of cosmic-ray pressure on thermal instability in the limit of no cosmic-ray transport. Next, we will focus on the impact of cosmic-ray transport on the formation of cold gas and its properties.

As predicted by (Kempski and Quataert, 2020), we find that the growth rate of density fluctuations depends on the cosmic-ray transport model, so that models with cosmic-ray transport have growth rates in between those without cosmic rays and without cosmic-ray

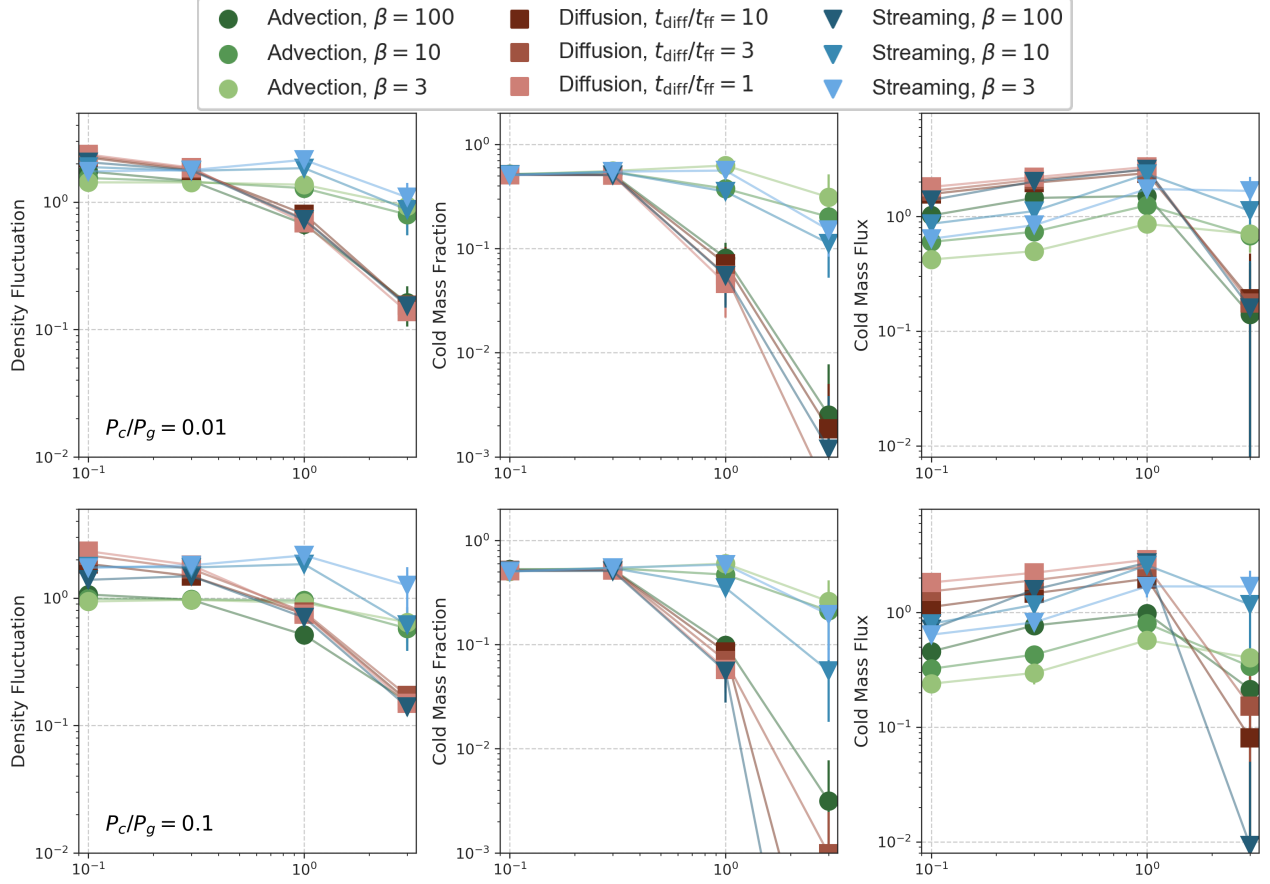


Figure 3.8 Similar to Figures 3.3 and 3.6, the panels above measure the mean density fluctuation ($\langle \delta \rho / \rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*) as a function of their initial $t_{\text{cool}}/t_{\text{ff}}$. The data points are measured between 0.8 and $1.2 H$ and averaged over all simulation outputs between $4t_{\text{cool}} \leq t \leq 6t_{\text{cool}}$. The error bars show 1 standard deviation. Starting from the top, the rows vary the initial cosmic-ray pressure ratio, $P_c/P_g = 0.01, 0.1, 1, 10$. The green lines show simulations with cosmic-ray advection for different initial values of β , the red lines show simulations with cosmic-ray diffusion for three different diffusion time scales, and the blue lines show simulations with cosmic-ray streaming for three different initial values of β . Cosmic-ray transport redistributes cosmic-ray pressure so that the resulting density fluctuation, cold mass fraction, and cold mass flux tend to lie between those of MHD-only simulations and simulations with only cosmic-ray advection. (Continued on next page.)

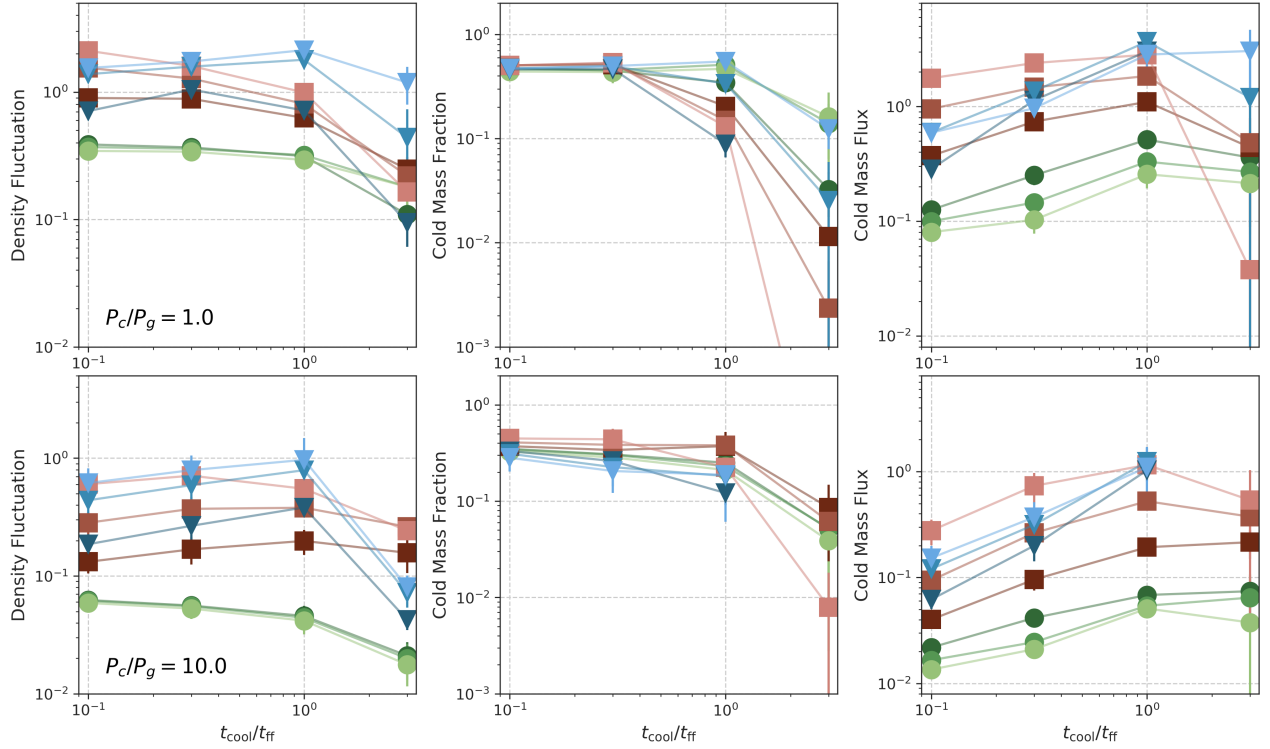


Figure 3.8 (Continued)

transport. In the limit of efficient cosmic-ray transport or low cosmic-ray pressures, the growth rates approach that of the traditional thermal instability (Eq. 3.22). However, in this chapter, we focus on the nonlinear evolution of thermal instability at late times.

As there is no consensus on the dominant cosmic-ray transport mechanisms, we investigate both cosmic-ray diffusion and cosmic-ray streaming at three different transport rates. In the case of cosmic-ray diffusion, we adopt diffusion coefficients, κ_c , such that the diffusion time, $t_{\text{diff}} = \kappa_c/H^2$, is a constant fraction of the freefall time: $t_{\text{diff}}/t_{\text{ff}} = [10, 3, 1]$. Given the freefall time in our simulations is $t_{\text{ff}} = 7.4 \times 10^8 \text{ yr}$ at the scale height, this corresponds to diffusion coefficients of $\kappa_c = [7.9 \times 10^{28}, 2.6 \times 10^{29}, 7.9 \times 10^{29}] \text{ cm}^2 \text{ s}^{-1}$.

In the case of cosmic-ray streaming, we define the streaming time, $t_{\text{stream}} = H/v_A$. Since cosmic-ray streaming is proportional to the strength of the magnetic field, we simu-

late cosmic-ray streaming for three different initial magnetic field strengths ($\beta = 100, 10, 3$) as a proxy for varying the cosmic-ray transport rate. This roughly corresponds to the following ratios of streaming time to freefall time: $t_{\text{stream}}/t_{\text{ff}} = [6, 1.8, 1]$. Simulations with cosmic-ray streaming also have a perturbative heating term, $\mathcal{H}_c$. Although this heating term is implemented in *addition* to the global heating model, $\mathcal{H}$, heating due to cosmic-ray streaming is expected to be much smaller than the global heating model.

Figure 3.7 shows the 2D slices of the cosmic-ray pressure in simulations with different models of cosmic-ray transport. All simulations have $t_{\text{cool}}/t_{\text{ff}} = 0.3$, $P_c/P_g = 1$, and are pictured after $t = 6t_{\text{cool}}$. Cosmic-ray transport redistributes cosmic-ray pressure from regions of high cosmic-ray pressure to regions of low cosmic-ray pressure. The more efficient the cosmic-ray transport (diffusion with $t_{\text{diff}}/t_{\text{ff}} = 3$ or streaming with $\beta = 10$), the more uniform the distribution of cosmic-ray pressure. Consequently simulations with more efficient cosmic-ray transport provide less nonthermal pressure support to cold gas, and form smaller cold gas structures. Simulations with cosmic-ray diffusion produce relatively large cold gas clouds with long connecting filaments. Simulations with cosmic-ray streaming have smaller, more compact cold gas clouds.

Figure 3.8 shows the average density fluctuation, cold mass fraction, and inflowing cold mass flux as a function of the initial $t_{\text{cool}}/t_{\text{ff}}$. Consistent with previous figures, each point represents the average quantity and its standard deviation measured between 0.8 and $1.2 H$, from all outputs between $t = 4 - 6t_{\text{cool}}$. The rows are organized by the initial cosmic-ray pressure ratio, ranging from $P_c/P_g = 0.01$ (top) to $P_c/P_g = 10.0$ (bottom). The different lines are colored by the cosmic-ray transport model: advection (green), diffusion (red), and streaming (blue). We remind the reader that for the majority of the lines, the corresponding MHD-only run has $\beta = 100$ (see Figure 3.3). However, two runs with cosmic-ray advection and streaming should be compared against runs with $\beta = 10$ and $\beta = 3$.

For the most part, simulations with cosmic-ray transport lie between simulations without cosmic rays and simulations with only cosmic-ray advection. Runs with relatively slow

cosmic-ray streaming and diffusion exhibit many of the same characteristics as runs with only cosmic-ray advection: cold gas has lower densities and less precipitation than predicted by purely thermal pressure support. The more efficient the cosmic-ray transport, the more closely it resembles the MHD-only thermal instability. This is because cosmic-ray transport redistributes cosmic-ray pressure from regions of high cosmic-ray density to regions of low cosmic-ray density. When cosmic-ray transport is very efficient relative to the cooling time scale, the cosmic-ray pressure profile becomes uniform (see the discussion in Section 3.4.4). As cosmic-ray pressure decreases in the cold gas clouds, the cold gas density and cold mass flux increase.

We note that when cooling times are long relative to the freefall time, the temporal variation of a single model can be larger than the variance between models. This makes it difficult to draw detailed comparisons between models with different cosmic-ray physics. Although the amount of cold gas formed is comparable, the biggest difference is that with sufficiently strong nonthermal pressure support, any cold gas that forms at the scale height remains at the scale height. For runs with cosmic-ray streaming, the perturbative heating term results in a decrease in the cold mass fraction and an increase in its flux towards the midplane. This perturbative heating destroys cold gas in simulations with high cosmic-ray pressures ($P_c/P_g \geq 1$) that are evolved for longer physical times ($t_{\text{cool}}/t_{\text{ff}} \geq 1$).

3.4.4 *Impact of Cosmic rays on Gas Phase*

Figure 3.9 shows 2D histograms of gas density and temperature, comparing simulations with $t_{\text{cool}}/t_{\text{ff}} = 0.3$ and different cosmic-ray transport. The colors show probability density, which is quantified on the top and right of each panel. The dashed lines show contours of constant thermal pressure and entropy.

Without cosmic rays (top left), the gas first cools at constant thermal pressure before dipping to lower pressures once it reaches the most rapid cooling regime, around $T \sim 10^5 \text{K}$. This pressure decrement is likely the result of insufficient spatial resolution to

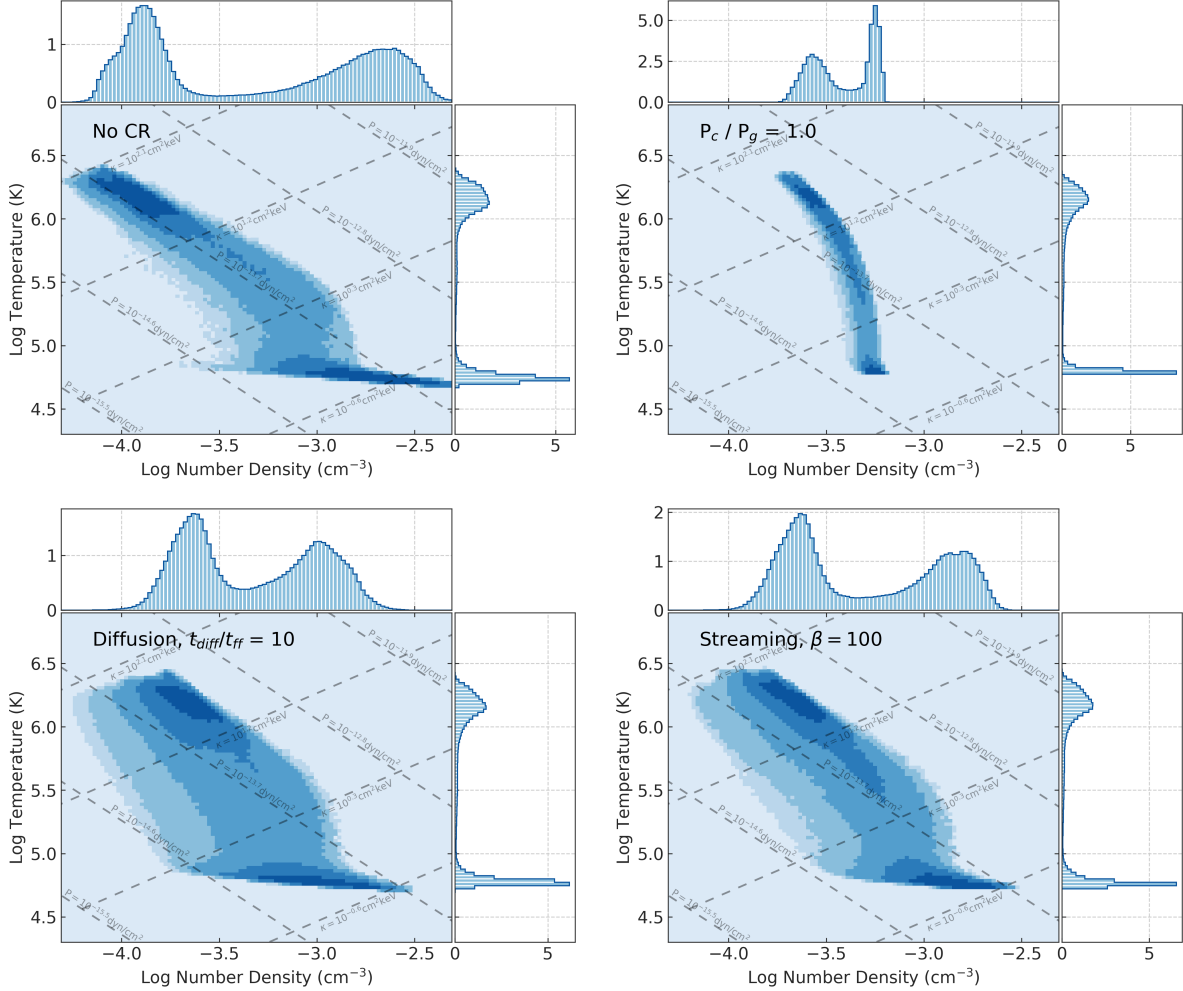


Figure 3.9 The mass-weighted 2D histograms of density and temperature for simulations with $t_{\text{cool}}/t_{\text{ff}} = 0.3$ with various cosmic-ray transport prescriptions. The data presented here are an accumulation from all outputs between $t = 4 - 6t_{\text{cool}}$, measured between 0.8 and $1.2H$ to minimize the influence of stochastic processes. The top-left panel shows the phase histogram of a simulation without cosmic rays and $\beta = 100$. The remaining panels all have an initial $P_c/P_t = 1.0$ and $\beta = 100$, but differ in their models of cosmic-ray transport: advection (top-right), diffusion (bottom-left), and streaming (bottom-right). The dashed lines show contours of constant thermal pressure and entropy. Without cosmic rays, gas cools at constant thermal pressure. With sufficient cosmic-ray pressure support, gas cools isochorically. Cosmic-ray transport widens the gas temperature-density phase space into low-density, low-temperature regimes that are not present in either simulations without cosmic rays or simulations without efficient cosmic-ray transport.

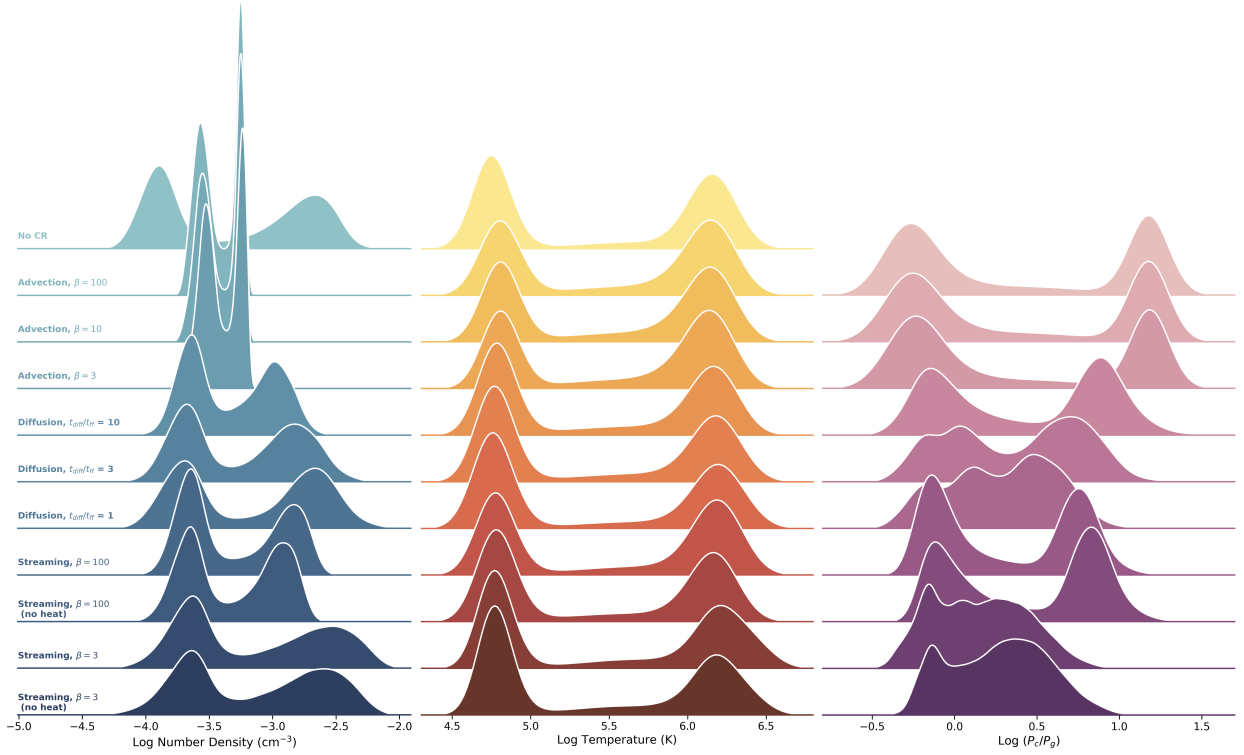


Figure 3.10 The mass-weighted probability density functions (PDFs) of the gas density, temperature, and cosmic-ray pressure ratio for simulations with $P_c/P_g = 1$ and $t_{\text{cool}}/t_{\text{ff}} = 0.3$ (above) and $t_{\text{cool}}/t_{\text{ff}} = 1.0$ (next page). The data in the PDFs is an aggregate from all simulation outputs between $t = 4 - 6t_{\text{cool}}$, measured between 0.8 and 1.2 scale heights. The PDFs are normalized so that the area under each distribution integrates to 1. Different implementations of cosmic-ray transport change the distribution of the ratio of cosmic-ray pressure to gas pressure, which in turn sets the distribution of gas densities. When cold gas has high cosmic-ray pressures, the density contrast between the cold and hot gas phases decreases. When cooling times are short ($t_{\text{cool}}/t_{\text{ff}} \leq 1$), cosmic-ray physics does not have a significant impact on the distribution of gas temperatures. However, when cooling times are long enough for the freefall time to be important ($t_{\text{cool}}/t_{\text{ff}} \gtrsim 1$), cosmic-ray pressure prevents precipitation and keeps cold gas near the scale height. This effect is strongest for simulations with cosmic-ray advection and modest in simulations with efficient cosmic-ray transport. (Continued on next page)

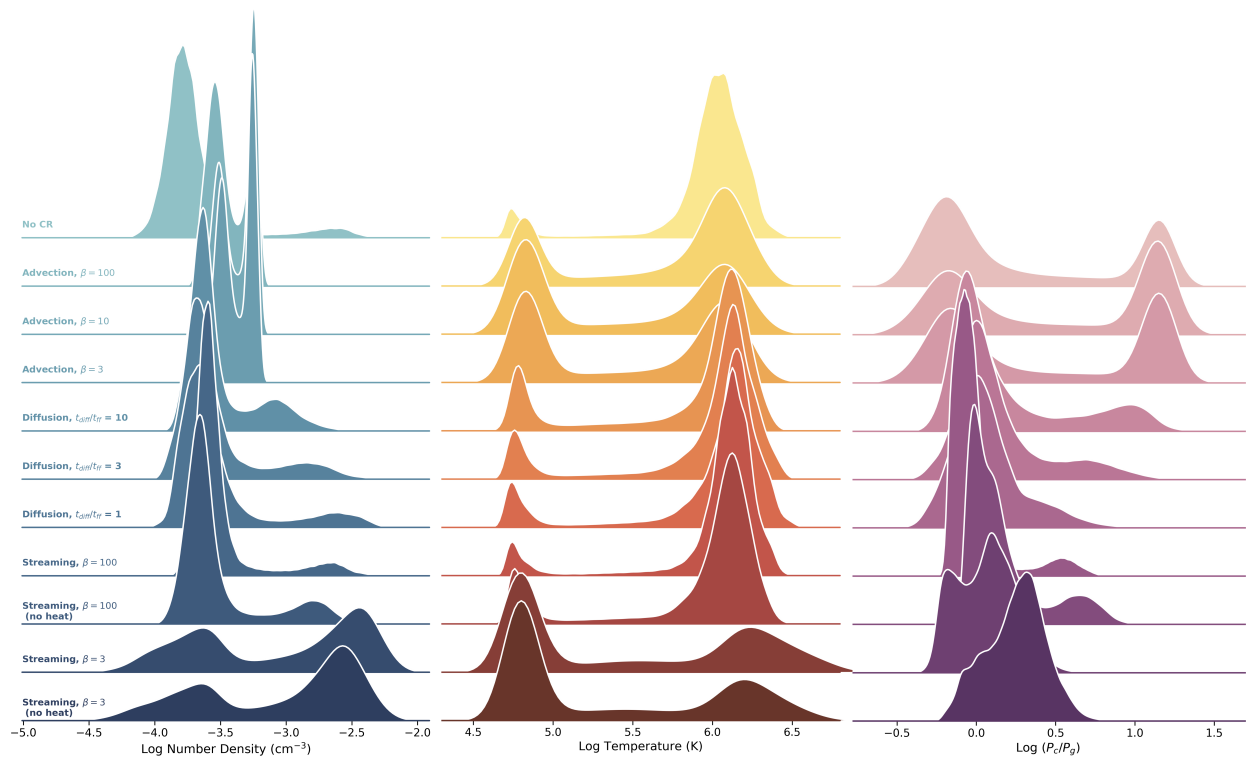


Figure 3.10 (Continued)

capture the cooling length scale $c_s t_{\text{cool}}$ (e.g., [Fielding et al., 2020a,b](#)). Although the cooling curve cuts off at $T = 5 \times 10^4 \text{K}$ in these simulations, we expect the general shape of the phase diagram to be the same if a lower cutoff temperature were adopted. The loss of thermal energy due to cooling leads to compression, which maintains pressure equilibrium (when the cooling length is resolved).

With added cosmic-ray pressure (top right), the loss of thermal energy does not lead to a significant *total* pressure gradient, so there is negligible compression and cooling proceeds at nearly constant density. In the simulation highlighted here, cosmic-ray pressure is initialized to be equal to the gas pressure, which is sufficiently strong to inhibit compression and cause the gas to cool isochorically.

Cosmic-ray transport (bottom row) redistributes cosmic-ray pressure so that the resulting gas temperatures and densities bridge the gap between simulations without cosmic rays and simulations without cosmic-ray transport. However, cosmic-ray transport also significantly broadens the temperature-density phase distribution of gas. Specifically, simulations with cosmic-ray transport have more intermediate-temperature gas at low densities, which is more likely to hold photoionized (rather than collisionally ionized) gas.

In [Figure 3.10](#), we compare the probability distribution functions (PDFs) of the gas density, temperature, and the ratio of P_c/P_g as a function of the initial cosmic-ray pressure ratio and cosmic-ray transport mechanism. The top panels show simulations with an initial $t_{\text{cool}}/t_{\text{ff}} = 0.3$ and the bottom panels show simulations with an initial $t_{\text{cool}}/t_{\text{ff}} = 1.0$. Both sets of simulations have an initial $P_c/P_g = 1$. Each row shows the properties of simulations with different cosmic-ray transport models. The data in the PDFs represents gas near the scale height ($0.8H \leq z \leq 1.2H$) and is accumulated from all outputs between 4 and 6 t_{cool} .

For simulations with $t_{\text{cool}}/t_{\text{ff}} = 0.3$, the distribution of gas temperatures is similar for a variety of cosmic-ray transport prescriptions. However, the density profiles vary substantially. Without cosmic rays, the gas forms a two-phase medium where the density profiles

complement the temperature profiles such that gas is always close to thermal pressure equilibrium. Cosmic-ray pressure support enables the cold and hot gas to have a lower density contrast. This effect is most pronounced in simulations with advection as the only form of cosmic-ray transport, which have distinctly bimodal distributions of cosmic-ray pressure between the hot and cold gas phases. Cosmic-ray diffusion and streaming move cosmic-ray pressure out of the regions where it is concentrated, thus removing the impact of nonthermal pressure support and thereby allowing the cold clouds to compress.

For simulations with high $t_{\text{cool}}/t_{\text{ff}} = 1$, the temperature distributions are affected by the choice of cosmic-ray physics. There are several factors at play. High cosmic-ray pressures not only alter the gas density, but they can also keep low-entropy gas from precipitating. This effect becomes relevant if the cooling time is equal to or greater than the dynamical time (see Figures 3.6 and 3.8). In this case, the MHD-only run has less cold gas at the scale height because that cold gas has precipitated out. Simulations with fast streaming also have strong magnetic fields which alter the amount of cold gas formed. For example, although both simulations with fast cosmic-ray diffusion ($t_{\text{diff}}/t_{\text{ff}} = 1$) and fast cosmic-ray streaming ($\beta = 3, t_{\text{stream}}/t_{\text{ff}} = 1$) have the same cosmic-ray transport time scale, simulations with stronger magnetic fields have a significantly larger fraction of cold gas.

The distribution of the cosmic-ray pressure ratio, P_c/P_g is a function of the transport mechanism. Simulations with only cosmic-ray advection have a distinctly bimodal distribution with the cold gas receiving substantially more pressure support than the hot gas. In the presence of both streaming and diffusion, the bimodality in cosmic-ray pressure ratios shrinks. The more efficient the cosmic-ray transport, the more the cosmic-ray pressure ratio distribution converges on the initial value. In simulations evolved for a longer physical time ($t_{\text{cool}}/t_{\text{ff}} \geq 1$), the convergence on a single value is more pronounced since the cosmic rays have had more time to propagate. Most notably, the bimodality distribution of cosmic-ray pressure ratios is inversely proportional to the bimodality of gas densities. Simulations in which cold gas builds up higher cosmic-ray pressure than hot

gas can cool isochorically. Conversely, simulations where the cosmic-ray pressure ratio is roughly constant have a larger density contrast between the cold and hot phases.

3.4.5 *Impact of Cosmic-ray Heating*

The transport model for cosmic-ray streaming traditionally includes a heating term through which cosmic rays transfer energy to the thermal gas. The simulations labeled “streaming” described so far all have this perturbative heating source. However, since our simulation setup and model for gas cooling and heating is very idealized, we also include simulations with cosmic-ray streaming *without* the additional cosmic-ray heating term, $\mathcal{H}_c$. This models the scenario in which cosmic-ray heating is just one of the many potential sources that contributes to the overall heating that ultimately balances cooling in the simulations.

We include simulations with cosmic-ray streaming but no perturbative heating in Figure 3.10, labeled with the appended “no heat”. Overall, we find that the inclusion of the cosmic-ray heating term has a modest impact on the gas phase. Since cosmic-ray heating is a function of both the cosmic-ray pressure gradient and the Alfvén velocity, we expect it to be important when the magnetic field is strong and the cosmic-ray pressure gradient is steep. That said, even the relatively weak magnetic fields in our fiducial simulations ($\beta = 100$) are enough to have an observable effect due to cosmic-ray heating.

Without the added cosmic-ray heating term, simulations with cosmic-ray streaming have less of a density contrast between hot and cold gas phases and a narrower distribution in the hot gas phase than simulations that do include cosmic-ray heating. Furthermore, the distribution of the cosmic-ray pressure ratio, P_c/P_g is shifted towards higher values when the cosmic-ray heating term is omitted. This is expected behavior as the cosmic-ray heating term is expected to remove cosmic-ray energy and use it to heat the gas.

Although cosmic-ray heating has modest effects on the global temperature and den-

sity profiles it is likely important for setting the local cold gas properties. The effect of cosmic-ray heating is strongest at the cold cloud edge, where the cosmic-ray pressure gradient is large. In this case, cosmic-ray heating can broaden the boundary between the cold and hot gas phases, with interesting implications for the observed ion abundances and kinematics (Wiener et al., 2017). Like (?), we find that the effects of cosmic-ray heating are spatially offset from regions with the shortest cooling times: cosmic-ray heating predominantly affects diffuse cool gas, by shifting it to higher temperatures. This effect is present in the lack of low temperature, low density gas in the bottom right panel of Figure 3.9. While the effects of cosmic-ray heating are modest in Figure 3.10, they primarily affect the temperature of the warm gas (by directly heating it) and the density of the cold gas (indirectly, by removing the available cosmic pressure that would have supported the cold gas). Changing the cloud boundary may also alter the mass and momentum transfer between the cold and hot gas phases (Fielding et al., 2020a).

3.4.6 Cold Gas Density Contrast

Ultimately, the impact of the wide range of cosmic-ray transport model parameters can be summarized by the distribution of cosmic-ray pressure between the cold and hot phases and its impact on the gas phase.

In Figure 3.11, we show the gas density contrast, $\langle \rho_{\text{cold}} \rangle / \langle \rho_{\text{hot}} \rangle$, as function of the cosmic-ray pressure ratio (P_c / P_g) in the cold gas. This figure includes all simulations with cosmic-ray physics that form cold gas, at both fiducial and high-resolution. Both the average density contrast and cosmic-ray pressure are measured in a region near the midplane, $0.8H \leq |z| \leq 1.2H$. In order to mitigate stochastic effects between outputs, the points show data averaged over 20 outputs between $t = 4t_{\text{cool}}$ and $t = 6t_{\text{cool}}$. The green circles show simulations with cosmic-ray advection for $\beta = 100$ (light green), $\beta = 10$ (medium green), and $\beta = 3$ (light green). The red squares show simulations with cosmic-ray diffusion with $t_{\text{diff}}/t_{\text{ff}} = 10$ (dark red), $t_{\text{diff}}/t_{\text{ff}} = 3$ (medium red), and $t_{\text{diff}}/t_{\text{ff}} = 1$ (light red).

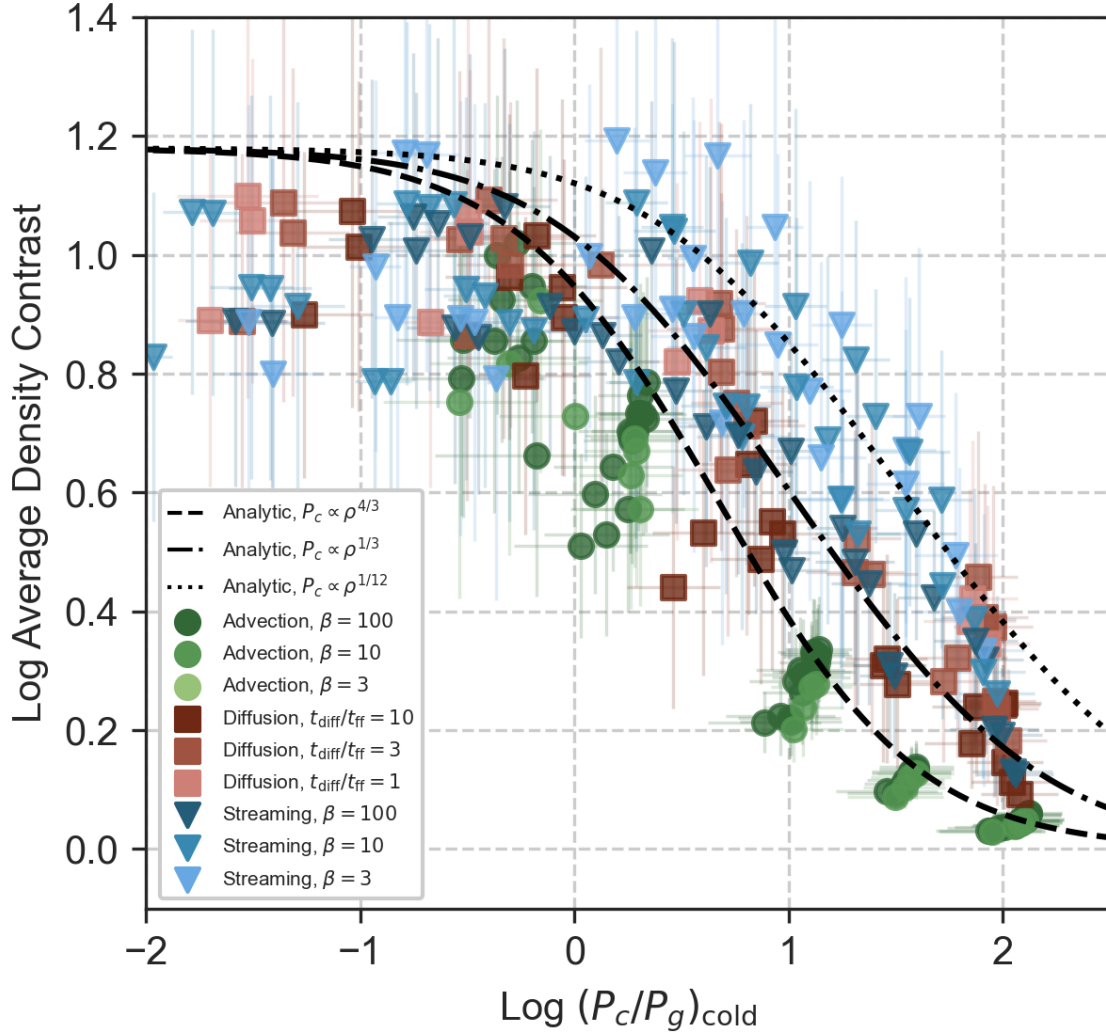


Figure 3.11 The average density contrast between the cold and hot gas phases ($\langle \rho_{\text{cold}} \rangle / \langle \rho_{\text{hot}} \rangle$) as a function of the average ratio of P_c/P_g in cold gas clumps. The points show data from all simulations described in the fiducial parameter suite (Section 3.2.3) that form cold gas, both at fiducial and high resolution. The data were measured between 0.8 and 1.2 scale heights and averaged over 20 outputs between $t = 4 - 6t_{\text{cool}}$. The different colors indicate simulations with different prescriptions of cosmic-ray transport: advection (green), diffusion (red), and streaming (blue). The black lines show predictions for the density contrast for various possible scalings of cosmic-ray pressure with gas density, assuming $\Theta = 20$ and $\beta_{\text{cold}} = 3$ (Eq. 3.25). In all cases, the density contrast between the cold and hot gas phases decreases with increased cosmic-ray pressure. However, the rate of that decrease depends on the transport model, which effectively changes the degree to which cosmic-ray pressure scales with gas density.

The blue triangles show simulations with cosmic-ray streaming with $\beta = 100$ (dark blue), $\beta = 10$ (medium blue), and $\beta = 3$ (light blue). The black lines show predictions for density contrast profiles (Eq. 3.25) as a function of how cosmic-ray pressure scales with gas density, $P_c \propto \rho^{\gamma_{c,\text{eff}}}$. In these predicted profiles, we use a temperature contrast of $\Theta = 20$, corresponding to $T_{\text{min}} = 5 \times 10^4$ K.

We assume a fixed $\beta_{\text{cold}} = 3$, which is roughly the average β in cold gas for simulations with an initial $\beta = 100$. Although the magnetic field is initialized with $\beta = 100$ everywhere in most simulations, the magnetic field strength is amplified in dense gas due to the flux-freezing assumption in ideal MHD. Furthermore, the magnetic field becomes tangled on large scales, which effectively slows cosmic-ray transport. Simulations with higher initial magnetic field strengths have more magnetic pressure support in cold clouds than accounted for in the analytic lines.

Overall, the average density contrast between the cold and hot gas phases decreases with increasing cosmic-ray pressure (Section 3.4.2). However, the slope of that decrease depends on the cosmic-ray transport prescription. In the pure advection case, we expect $\gamma_{c,\text{eff}} = \gamma_c = 4/3$, which corresponds to the dashed black line. The simulated data follow the expected density contrast relation. The scatter in the advection simulations at low cosmic-ray pressures is likely due to a combination of resolution effects, different initial values of $t_{\text{cool}}/t_{\text{ff}}$, and the relative importance of magnetic fields (which are not accounted for in the plotted analytic model). Further investigations of the effects of resolution and the choice of density contrast, are discussed in Appendices 3.7.1 and 3.7.2.

Since cosmic-ray transport redistributes cosmic-ray pressure from overdense regions, we expect simulations with cosmic-ray transport to have a weaker scaling of cosmic-ray pressure and gas density than in simulations with only cosmic-ray advection ($\gamma_{c,\text{eff}} < 4/3$). However, the exact value of $\gamma_{c,\text{eff}}$ depends on the details of cosmic-ray transport and assumptions about the impact of cosmic-ray heating. For simulations with cosmic-ray transport (diffusion with $t_{\text{diff}}/t_{\text{ff}} = 10$ and streaming with $\beta = 100$), we empirically find that $\gamma_{c,\text{eff}} \simeq 1/3$, which is modeled by the dashed-dotted line in Figure 3.11. For context,

Wiener et al. (2017) predict $\gamma_{\text{c,eff}} = 2/3$ in the case of cosmic-ray streaming where cosmic-ray heating balances gas cooling. Simulations with relatively faster cosmic-ray transport have much weaker scalings of cosmic-ray pressure with gas density. In the extreme case that cosmic-ray transport is so efficient that $\gamma_{\text{c,eff}} \rightarrow 0$, we expect the predicted density contrast to be unchanged as a function of $P_{\text{c}}/P_{\text{g}}$.

3.5 Discussion

3.5.1 The CGM Pressure Problem

Based upon the original work of Mo and Miralda-Escude (1996), numerous two-phase models of the CGM envision cold clouds condensing out of a hot medium as a result of hydrostatic instabilities. Such models have successfully reproduced many of the observed properties of high-velocity clouds in the Milky Way halo (e.g. Maller and Bullock, 2004; Putman et al., 2012).

Photoionization modeling of observed low ionization state metal-ion column densities derives cold CGM gas volume densities that are at least an order of magnitude lower than predicted by traditional two-phase models (e.g. Werk et al., 2014; Stern et al., 2016). There are two possible explanations for such low densities of cold CGM gas: (1) the cold gas is in thermal equilibrium with the hot CGM gas, which also has a much lower density than predicted by traditional two-phase models, or (2) the cold gas is out of thermal pressure equilibrium with the hot gas phase.

If cold gas is out of thermal pressure equilibrium, the lack of pressure support would imply very short lifetimes of cold clouds, in stark contrast to the ~ 100 Myr lifetimes required by simulations of the CGM that predict a cold gas origin in recycled ISM material (in which halo gas is largely in hydrostatic equilibrium; Ford et al., 2014; Anglés-Alcázar et al., 2017; Tumlinson et al., 2017a). In order to bring observations in agreement with simulations, there either needs to be some physical process capable of continually generating the observed abundance of cold gas or some additional source of nonthermal pressure.

Simulations show that the average magnetic field in the CGM can be as high as $\sim 0.1 - 0.5 \mu G$ (Pakmor et al., 2019; Nelson et al., 2020; van de Voort et al., 2020). These magnetic fields both enhance thermal instability and provide pressure support to the cold gas that forms. Due to flux freezing, the cold gas clumps are dominated by magnetic pressure ($\beta \ll 1$) even though the background halo has relatively low magnetic pressure ($\beta \geq 100$) (Nelson et al., 2020). Since there are few observational constraints of magnetic fields in galactic halos, it is unclear if such high magnetic field values are typical. However, these simulations fall well within the upper limit of magnetic field strength ($2 \mu G$) determined by (Lan and Prochaska, 2020), and provides another mechanism through which nonthermal pressure support can alleviate the pressure problem.

Galaxy simulations that include cosmic-ray physics also find that cosmic-ray pressure supports cold CGM gas at low densities (Salem et al., 2016; Butsky and Quinn, 2018; Buck et al., 2020). In a cosmic-ray-pressure-supported halo, cool, warm, and hot gas phases can exist at the same gas density (Ji et al., 2020a). Although there are few observational constraints of cosmic-ray pressures in the CGM, simulations predict that a cosmic-ray-pressure-supported halo could be consistent with existing γ -ray observations (Chan et al., 2019; Ji et al., 2020a).

In our simulations, cosmic-ray pressure (and in some cases, magnetic pressure) supplements thermal pressure to support low-density cold gas. In simulations with low initial cosmic-ray pressures, cold cloudlets are supported by cosmic-ray pressure while the background medium is dominated by thermal pressure. Simulations with high initial values of cosmic-ray pressure allow gas to cool isochorically and form large, diffuse cold gas clouds. Cosmic-ray transport complicates this behavior by redistributing cosmic-ray pressure from the cold gas to the surrounding medium. *Overall, our findings highlight that even modest cosmic-ray pressures can resolve the perceived pressure problem with two-phase halo models by providing a viable physical mechanism to maintain the cold gas while out of thermal pressure equilibrium.*

3.5.2 Cold Cloud Sizes

The sizes of cold gas clouds remains an unresolved issue within the CGM community; CGM cloud sizes (given as path lengths) derived from absorption-line spectroscopy at low and high redshift range from 1 pc – 1 Mpc (e.g. [Rauch et al., 2001](#); [Prochaska and Hennawi, 2009](#); [Stocke et al., 2013](#); [Chen et al., 2014](#); [Werk et al., 2014](#); [Crighton et al., 2015](#); [Stern et al., 2016](#); [Zahedy et al., 2019](#)). The challenge of this measurement is essentially two-fold: absorption-line probes of the CGM rely heavily on model assumptions for a length-scale estimate (e.g. strength and nature of ionization source) and most observations are limited to a single sightline per galaxy.

Nonetheless, recent studies have used additional, novel techniques to place constraints on the physical scales of structures in the CGM. [Rubin et al. \(2018b\)](#) analyzed the CGM of 27 star-forming galaxies along spatially-resolved background-galaxy lines of sight to determine that the coherence scale of Mg II absorbers is > 1.9 kpc. Specifically, cold gas clouds are either > 2 kpc in radius themselves or represent collections of much smaller clouds with similar properties. [Rudie et al. \(2019\)](#) used observations of a galaxy halo probed by a lensed background quasi-stellar object (QSO) to show that while warm (O VI bearing) gas has structures that are > 400 pc, lower-ionization cold gas exhibits significant variations on the same scales, implying that cold gas clouds have sizes < 400 pc. [Werk et al. \(2019\)](#) studied multiphase absorption at the Milky Way disk-halo interface, and showed that warm gas clouds were larger than 1 kpc, whereas cold gas was clumpy on scales down to 10 pc, possibly implying cold clouds are smaller than 10 pc (see also: [Bish et al., 2019](#)). [Zahedy et al. \(2019\)](#) find that the cold clump thickness in luminous red galaxies (LRGs) is between 10 pc and 1 kpc, with a median of 120 pc.

Theoretically, cold gas is predicted to have a characteristic cloudlet size $\ell_{\text{cloudlet}} \sim \min(c_s t_{\text{cool}})$ ([McCourt et al., 2018](#)). Using this model, a cold cloud in typical CGM conditions can have a characteristic size somewhere between $\ell_{\text{cloudlet}} \sim 1\text{pc} - 1\text{kpc}$, depending on the gas pressure, metallicity, and UV background radiation. Additionally, depending

on the conditions of the surrounding medium, the true size of cold gas clouds may be significantly larger, as clouds can coagulate to form larger structures (Gronke and Oh, 2020).

Resolving subparsec scales is currently impossible in galaxy-scale simulations and prohibitively expensive in even idealized meso-scale simulations. Recently, a number of groups have demonstrated that enhancing the spatial resolution in and beyond the galactic halo results in more cold gas due to increased accuracy in the formation and retention of cool gas structures (van de Voort et al., 2019; Hummels et al., 2019; Mandelker et al., 2019; Peebles et al., 2019b; Suresh et al., 2019). However, the size of the best-resolved CGM cells in these simulations is still hundreds of times larger than the expected cold gas cloud size. Indeed the properties of cold CGM gas in galaxy simulations have not converged with resolution, implying that current state-of-the art simulations are not resolving the true cold gas physics. Likewise, Nelson et al. (2020) find cold cloud sizes of 0.5 - 1 kpc in TNG50, but also warn that the cloud sizes do not converge, even at their highest resolution.

In our simulations, cosmic-ray pressure increases cloud sizes. The cloud size (and density) is a function of the degree of cosmic-ray pressure support in the cold cloud. By altering gas densities, cosmic-ray pressure alters the predicted cloud-size ansatz, $\ell_{\text{cloudlet}} \sim \min(c_s t_{\text{cool}})$. If cosmic-ray pressure support is modest, the resulting gas will still likely be a mist comprised of numerous tiny cloudlets, albeit with larger cloudlet sizes. However, if cosmic-ray pressure dominates over thermal pressure in halo gas, then we can expect that cold gas has similar gas densities to the hot gas phase. In the extreme case, if the cold gas has the same density as the hot gas, we can expect that cold cloud sizes would be roughly ~ 900 times larger than those predicted assuming purely thermal pressure balance (assuming a temperature contrast of 100 and $\eta = 100$ in Eq. 3.29).

With this generous boost in cloud size, we would expect the maximum cold cloud size in a cosmic-ray-pressure-supported CGM, with inefficient cosmic-ray transport to be $\ell_{\text{cloudlet}} \sim 1 - 1000$ kpc. If the characteristic cold cloud size is $\gtrsim 10$ kpc, then existing high-

resolution galaxy simulations are capable of fully resolving cold CGM gas. However, even if low-redshift galaxies have a cosmic-ray-pressure-supported CGM, this regime is an unlikely description of the high-redshift universe and simulations would still need infeasibly high resolution to model cold gas evolution at early times.

3.5.3 Cold Mass Accretion Rates

The galactic fountain, through which gas is expelled from and accreted onto the galactic disk, is an integral component of galaxy evolution. The mass accretion of cold gas in the Milky Way is measured to be somewhere between $0.0002 - 0.006 M_{\odot} \text{kpc}^{-2} \text{yr}^{-1}$ (Fox et al., 2019; Werk et al., 2019).

Throughout this chapter, we have measured the mass flux (at the scale height) in the right panel of Figures 3.2, 3.3, 3.5, 3.6, and 3.8. The values are normalized by the freefall cold mass flux, $\rho_0 H / t_{\text{ff}} = 0.00088 M_{\odot} \text{kpc}^{-2} \text{yr}^{-1}$. Fiducial MHD-only simulations with $\beta = 100$ therefore predict mass flux rates of $0.0018 - 0.0026 M_{\odot} \text{kpc}^{-2} \text{yr}^{-1}$ after $t = 4t_{\text{cool}}$. Cosmic-ray pressure counteracts gravity and reduces the mass influx rate, so that for runs with $P_c/P_g = 1$, the mass accretion rate is roughly an order of magnitude lower. This is consistent with results from Su et al. (2020), that show that cosmic rays can suppress cooling flows even with modest cosmic-ray pressures.

However, our simulations show that the predicted mass accretion rate is sensitive to both the cosmic-ray pressure and the invoked cosmic-ray transport. Differences in initial cosmic-ray pressures and cosmic-ray transport models can vary the mass accretion rate by an order of magnitude. Therefore, thermal instability with cosmic rays can simultaneously explain both high mass accretion rates and the inferred low mass accretion rates of quenched galaxies with large reservoirs of cold CGM gas.

3.5.4 *Limitations of Idealized Setup*

The highly idealized nature of our simulations is helpful for isolating the impact of cosmic-ray pressure and transport on thermal instability. However, the simulations are missing a physically realistic context that may impact the formation and survival of cold gas.

The cooling and heating models in our simulations crudely approximate an isolated, globally stable, long-lived CGM by explicitly balancing the total cooling and total heating at each vertical layer. A more realistic simulation would explicitly model the local processes (e.g. gas accretion, stellar formation and feedback, mergers) that contribute to this global equilibrium. These processes would be particularly important in simulations with long cooling times which are evolved for at least 500 million years. On those time scales, the assumption of an isolated CGM breaks down, as the CGM is likely to be perturbed by either feedback from its host galaxy or accretion from the surrounding medium.

Additionally, the isolated nature of the simulations means that once cold gas has precipitated out of the hot gas, the cooling time of the remaining gas is too long to create any more cold gas. In a realistic galaxy halo, we expect outflows or inflows to replenish thermally unstable gas. These processes interfere with the prediction for the long term state of cold gas, especially for simulations with high $t_{\text{cool}}/t_{\text{ff}}$ in the “isolated” thermal instability studied here.

The cosmic-ray transport models considered in this chapter are simplified approximations of two different regimes: pure streaming or pure diffusion. Realistically, both streaming and diffusion should happen, to different degrees, simultaneously and there are recent algorithms that can handle the two self-consistently (Jiang and Oh, 2017; Chan et al., 2019; Thomas and Pfrommer, 2019). Furthermore, unresolved microphysics alter the local cosmic-ray diffusion coefficient (Farber et al., 2018) and the dominant scattering mechanisms that determine cosmic-ray streaming parameters (see ? and references therein for a detailed comparison). Additionally, we do not explicitly include cosmic-ray “cooling” due to hadronic and Coulomb losses. While this process is important for alle-

viating cosmic-ray pressure in the interstellar medium (ISM), the typical densities in the CGM (even within the condensed cold clouds) are too low for this process to be significant. Despite the various caveats to our model described herein, the *quantitative* details of our results may fluctuate to some degree, but we expect the *qualitative* results to be robust (Hopkins et al., 2021d).

3.6 Conclusions

Thermal instability is an important mechanism through which cold gas forms in the CGM. In this chapter, we used idealized simulations of thermal instability in a gravitationally stratified medium to study the formation and evolution of cold ($T \simeq 10^4\text{K}$) gas in the presence of cosmic-ray pressure and transport. We systematically varied several key parameters, including the ratio of the cooling time to the freefall time, initial magnetic field strength, initial cosmic-ray pressure, and cosmic-ray transport parameters (assuming either cosmic-ray diffusion or streaming). Our results are summarized below.

1. Cosmic rays change the morphology of cold gas that forms through thermal instability by providing nonthermal pressure support. Increased cosmic-ray pressure prevents cold gas from compressing, allowing it to cool while maintaining lower densities (Figures 3.5 and 3.6). When cosmic-ray pressure dominates, thermally unstable gas cools at constant density (isochorically). Our results demonstrate how the inclusion of cosmic rays as a nonthermal pressure source can explain the apparent lack of thermal pressure equilibrium between observed cold and hot gas phases in the CGM. We make predictions for the density contrast between cold and hot gas as a function of magnetic and cosmic-ray pressures in the cold gas (Eq. 3.25 and Figure 3.11).
2. Simulations that include cosmic rays form larger cold gas clouds. If cosmic-ray pressure is relatively low, cold gas can still form a “mist”, with cosmic-ray pressure-supported cloudlets that are larger than the predicted subparsec cloudlets in the absence of cosmic rays. However, in a cosmic-ray-pressure-dominated halo in the limit of inefficient

cosmic-ray transport, the characteristic size of cold gas cloudlets may be up to ~ 1000 times larger than those expected in a purely thermal medium. We make predictions for how the characteristic size of cold gas scales with magnetic and cosmic-ray pressures (Eqs. 3.28 and 3.29).

3. In some cases, cosmic-ray pressure can increase the cold mass fraction in the halo by preventing the formed cold gas from precipitating towards the galaxy (Figures 3.5 and 3.6). If cosmic-ray pressure contributes to maintaining hydrostatic equilibrium, it enables gas to have a shallower entropy profile as a function of height above the galactic midplane. Consequently, halos with substantial cosmic-ray pressure support ($P_c/P_g \gtrsim 1$) have significantly reduced cold mass flux. This effect may explain observations of quenched galaxies with an abundance of cold gas in their CGM. Cosmic-ray pressure does not change the average temperature of the cold gas phase (Figure 3.10).
4. Simulations that include realistic transport mechanisms for cosmic rays (e.g., diffusion or streaming) demonstrate behavior that bridges the gap between simulations lacking cosmic rays and simulations that only include cosmic rays as an adiabatic nonthermal pressure term (e.g., advection only). Cosmic-ray transport redistributes cosmic-ray pressure from regions of high cosmic-ray pressure in cold clouds to areas of low cosmic-ray pressure in the hot background medium (Figure 3.10). This pressure redistribution decreases cold cloud sizes and increases the cold gas density and cold mass flux compared to simulations with cosmic-ray advection but without cosmic-ray transport (Figure 3.8). Simulations with cosmic-ray transport span a larger temperature-density phase space than either simulations without cosmic rays or simulations with only cosmic-ray advection (Figure 3.9). Cosmic-ray transport is most effective when the cosmic-ray transport is short relative to gas cooling times.

Cold CGM gas plays a uniquely important role in driving galaxy evolution: cold gas that accretes onto the galaxy fuels star formation, which in turn shapes the CGM through feed-

back. In this chapter, we have demonstrated that cosmic rays have the potential to dramatically alter the CGM gas morphology, gas phase, and kinematics. However, many details about cosmic-ray physics remain poorly constrained, including expected cosmic-ray pressures and magnetic field strengths in the CGM and robust models for cosmic-ray transport in hydrodynamic simulations. More constraining models for cosmic-ray physics are therefore crucial for understanding galaxy evolution in its entirety.

3.7 Chapter Appendix: Numerical Effects and Thermal Instability

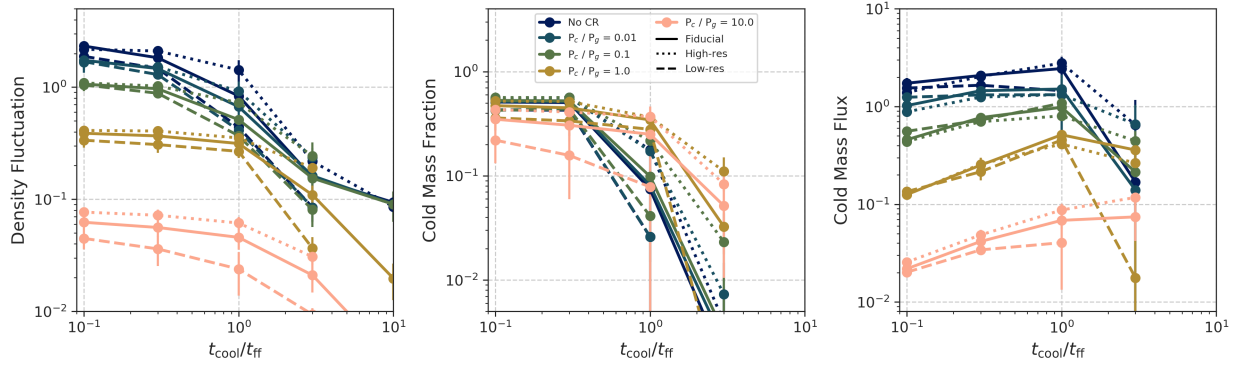


Figure 3.12 The average density fluctuation ($\langle \delta\rho/\rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*) as a function of the initial $t_{\text{cool}}/t_{\text{ff}}$ for simulations with varying ratios of P_c/P_g . The solid lines, repeated from Figure 3.6, show simulations with the fiducial resolution ($64 \times 64 \times 256$). The dashed lines show simulations with half the fiducial resolution, and the dotted lines show simulations with double the fiducial resolution. The points show each quantity averaged between $t = 4 - 6t_{\text{cool}}$ and measured between 0.8 and 1.2 scale heights. All simulations have an initial $\beta = 100$. The properties of thermal instability are reasonably well converged in our fiducial simulations.

3.7.1 Impact of Resolution

The fiducial simulation suite presented in this chapter resolved the simulation domain of $1 \times 1 \times 4H$ with $64 \times 64 \times 256$ cells, which corresponds to $\Delta x = 685.2$ pc. Additionally, we have run a subset of the simulations with half and double the resolution. Figure 3.12

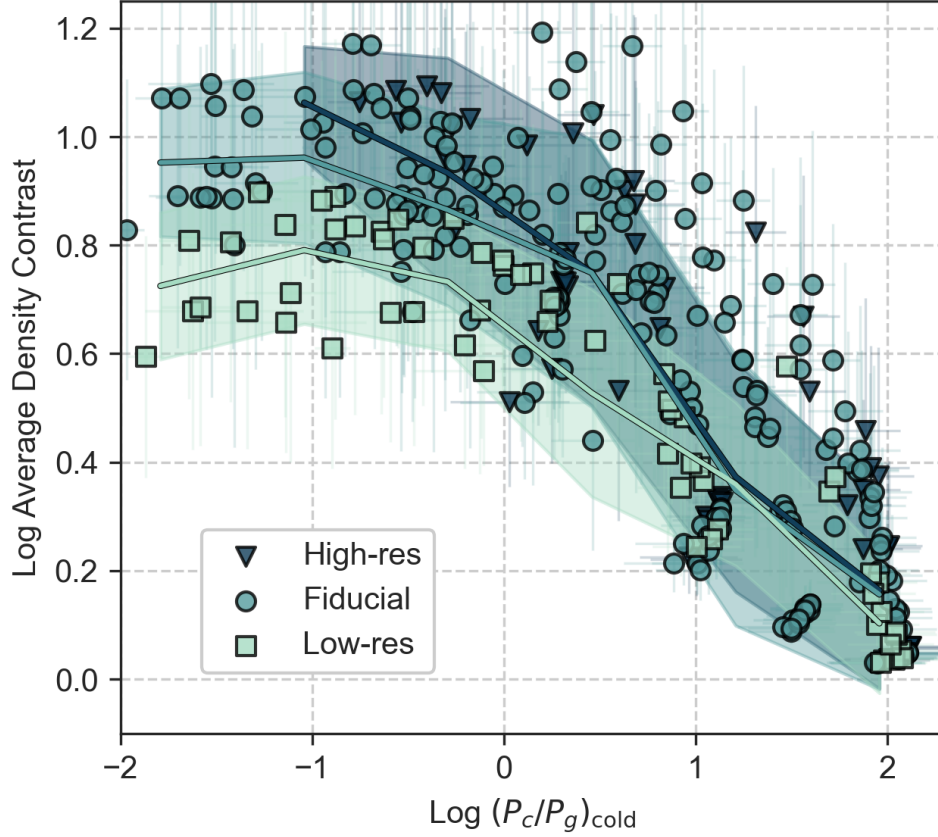


Figure 3.13 The average density contrast ($\langle \rho_{\text{cold}} \rangle / \langle \rho_{\text{hot}} \rangle$) as a function of the ratio of cosmic-ray pressure to gas pressure in cold gas. The scattered points show all simulations with cosmic-ray physics (advection, diffusion, and streaming) run with different resolutions: high resolution (triangles), fiducial resolution (circles) and low resolution (squares). The lines and shaded regions show the corresponding median and one standard deviation. When cosmic-ray pressure dominates, cold cloud structure is sufficiently resolved, even with our lowest resolution simulations.

shows the density contrast, cold mass fraction, and cold mass flux as a function of the initial $t_{\text{cool}}/t_{\text{ff}}$ for simulations with different initial cosmic-ray pressures. The solid lines show the quantities from simulations with fiducial resolutions (as seen in Figure 3.6), the dashed lines show the same simulations with low resolution, and the dotted lines show simulations with higher resolution. Simulations with our fiducial resolution are reasonably well converged.

Figure 3.13 shows the density contrast as a function of the cosmic-ray pressure ratio P_c/P_g in the cold gas for three different resolutions. At low cosmic-ray pressures, the density contrast does not converge with resolution. This is expected as cold gas scales ($\ell_{\text{cloudlet}} \sim \min(c_s t_{\text{cool}})$) are below our resolution, even with a modified minimum temperature, $T_{\text{min}} = 5 \times 10^4 \text{K}$. The differences in the median profiles between the fiducial and high-resolution simulations are smaller than those between the fiducial and low-resolution simulations and become negligible when cosmic-ray pressure is equal to or greater than the gas pressure. When cosmic-ray pressure is ten times the gas pressure, all three resolutions converge. In this case, the low density contrasts correspond to large cloud sizes which are sufficiently resolved, even in our lowest resolution simulation, which has a cell resolution of 1.3 kpc. This result suggests that current galaxy-scale simulations may be able to resolve cold CGM gas in a cosmic-ray-pressure-supported halo.

3.7.2 Impact of T_{min}

The density contrast between cold and hot gas phases depends on the details of the gas cooling curve. Without cosmic rays or magnetic fields, the density contrast between the cold and hot gas phases in an ideal gas will be set by the temperature contrast, $\Theta = T_{\text{hot}}/T_{\text{cold}}$. In our fiducial simulations, we set the minimum temperature of the gas to be $T_{\text{min}} = 5 \times 10^4 \text{K}$ which roughly corresponds to $\Theta = 20$. Artificially setting the minimum temperature of cold gas allowed us to keep our simulations at a modest resolution, which is necessary for a large-scale parameter study. However, we do expect that a different

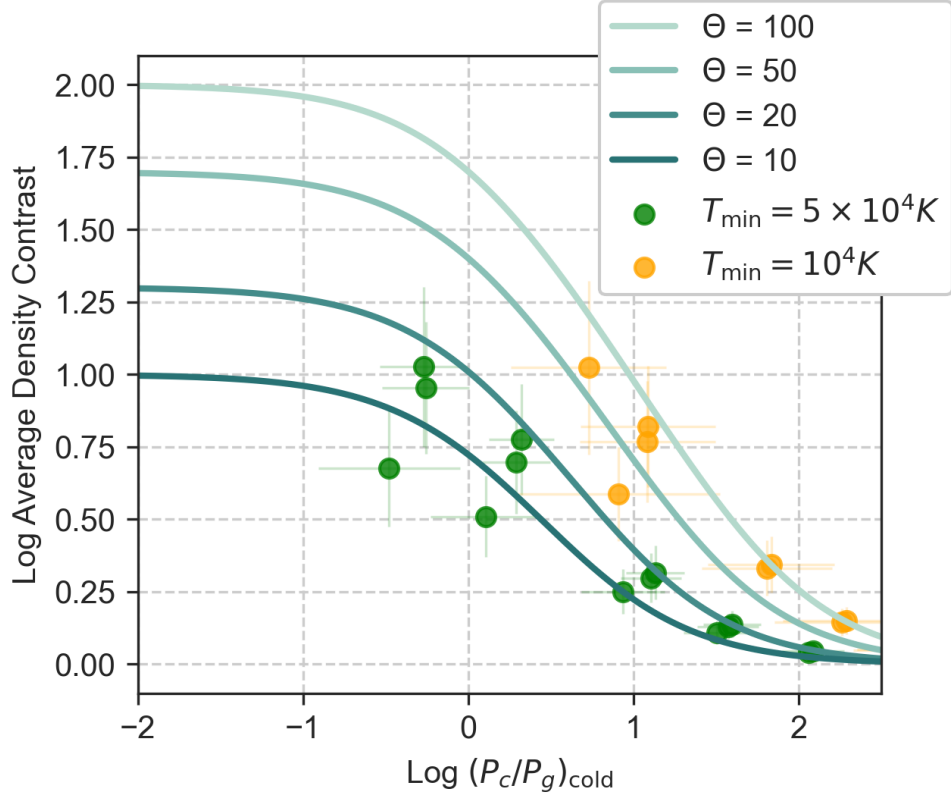


Figure 3.14 The average density contrast between the cold and hot gas phases ($\langle \rho_{\text{cold}} \rangle / \langle \rho_{\text{hot}} \rangle$) as a function of the average ratio of P_c/P_g in cold gas clumps. The points show data averaged from 20 outputs between $t = 4 - 6t_{\text{cool}}$, measured between 0.8 and 1.2 scale heights. The different colors indicate simulations with different minimum temperatures allowed by the idealized cooling curve: $T_{\min} = 5 \times 10^4 \text{ K}$ (green), and $T_{\min} = 10^4 \text{ K}$ (orange), corresponding to expected temperature contrasts of $\Theta = T_{\text{cold}}/T_0$ of 20 and 50 respectively. The different curves show predictions for the density contrast using Eq. 3.25, assuming $P_c \propto \rho^{4/3}$, for different possible values of the temperature contrast, Θ . Our simulations exactly match the predicted density contrast profiles at high cosmic-ray pressures but underpredict the high density contrast needed for purely thermal pressure equilibrium.

choice of $T_{\min}$ would change predictions for the density contrast as a function of cosmic-ray pressure presented in Figure 3.11. We explore the impact of $T_{\min}$ on the predicted density contrast in this section.

Figure 3.14 shows the density contrast as a function of the cosmic-ray pressure ratio, P_c/P_g in cold gas. The green lines show the predicted density contrast for a variety of different temperature contrasts, Θ , assuming $P_c \propto \rho^{4/3}$ (i.e., inefficient cosmic-ray transport; see Eq. 3.25). The scattered points show simulation data for runs with cosmic-ray advection, averaged between $4-6t_{\text{cool}}$, measured between 0.8 and 1.2 scale heights. Green points show simulations with our fiducial choice of $T_{\min} = 5 \times 10^4 \text{K}$ and orange points show simulations with $T_{\min} = 10^4 \text{K}$, corresponding to $\Theta \simeq 100$. These simulations were run with no magnetic fields.

At high cosmic-ray pressures, the simulation data points follow their theoretically predicted tracks well. However, the simulation points underpredict the density contrast with decreasing cosmic-ray pressure, especially the orange points which require significantly higher resolution.

In all cases, the relevant trend is that cosmic rays only have a significant effect on the density contrast when cosmic-ray pressure dominates over thermal pressure in the cold gas, $(P_c/P_g)_{\text{cold}} \gtrsim 1$. The density contrast approaches zero when $P_c/P_g \gtrsim 100$. In the intermediate regime, the density contrast decreases following a power law with a slope between -1/3 and -1. Higher temperature contrast between the cold and hot phases necessitates higher cosmic-ray pressures to achieve the same decrease in density contrast.

3.7.3 Impact of halo profile

Our fiducial suite of simulations all had an “iso-cooling” profile: the gas density and temperature as a function of height above the midplane follow Eq. 3.13 to ensure that gas cooling time is constant throughout. Although keeping the cooling time constant is advantageous in the context of an idealized parameter study, we by no means expect that

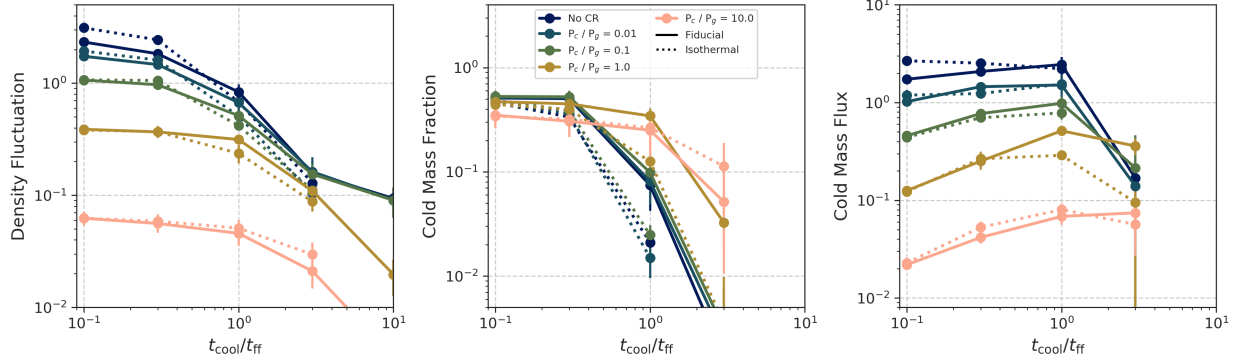


Figure 3.15 The average density fluctuation ($\langle \delta\rho/\rho \rangle$; *left*), cold mass fraction ($M_{\text{cold}}/M_{\text{total}}$; *middle*), and cold mass flux ($\dot{M}_{\text{cold}}/\dot{M}_{\text{ff}}$; *right*) as a function of the initial $t_{\text{cool}}/t_{\text{ff}}$ for simulations with varying ratios of P_c/P_g . The solid lines are repeated from Figure 3.6 and the dotted lines show the same simulations run with an isothermal gas density and temperature profile. The points show each quantity averaged between $t = 4 - 6t_{\text{cool}}$ and measured between 0.8 and 1.2 scale heights. All simulations have an initial $\beta = 100$. The choice of halo profile does not qualitatively impact our results.

all halos follow this narrow range of densities and temperatures.

To test the effect of the choice of gas profile, we run a subset of the simulations with isothermal initial conditions and compare them against the fiducial simulations in Figure 3.15. Overall, we find that the choice of profile has little effect on the qualitative density fluctuation, cold mass fraction, or cold mass flux. The largest quantitative deviation from the fiducial simulations is in the cold mass fractions for simulations with $t_{\text{cool}}/t_{\text{ff}} \geq 1$. This is likely because the gas cooling times in the isothermal profile are shortest near the midplane and cooling happens from the inside-out. Therefore, at late times, we can expect less gas near the midplane of simulations with an isothermal profile.

Chapter 4

THE IMPACT OF COSMIC RAYS ON THE KINEMATICS OF THE CIRCUMGALACTIC MEDIUM

The work presented in this chapter was conducted in collaboration with Jessica Werk, Kirill Tchernenyshyov, Drummond Fielding, Joseph Breneman, Daniel Piacitelli, Thomas Quinn, Nicole Sanchez, Akaxia Cruz, Joseph Burchett, Cameron Hummels, and Michael Tremmel.

Summary

We use hydrodynamical simulations of two Milky-Way-mass galaxies to demonstrate the impact of cosmic-ray pressure on the kinematics of cool and warm circumgalactic gas. Consistent with previous studies, we find that cosmic-ray pressure can dominate over thermal pressure in the inner 50 kpc of the circumgalactic medium (CGM), creating an overall cooler CGM than that of similar galaxy simulations run without cosmic rays. We generate synthetic sightlines of the simulated galaxies' CGM and use Voigt profile fitting methods to extract ion column densities, Doppler- b parameters, and velocity centroids of individual absorbers. We directly compare these synthetic spectral line fits with HST/COS CGM absorption-line data analyses, which tend to show that metallic species with a wide range of ionization potential energies are often kinematically aligned. Compared to the Milky-Way simulation run without cosmic rays, the presence of cosmic-ray pressure in the inner CGM creates narrower O VI absorption features and broader Si III absorption features, a quality which is more consistent with observational data. Additionally, because the cool gas is buoyant due to non-thermal cosmic-ray pressure support, the velocity centroids of both cool and warm gas tend to align in the simulated Milky Way with feedback from cosmic rays. Our study demonstrates that detailed, direct comparisons between simulations and observations focused on gas kinematics have the potential to reveal the feedback physics that shapes the CGM.

4.1 Introduction

Galaxies evolve embedded within a vast, gaseous halo that dwarfs the mass and spatial extent of the galactic disk. This circumgalactic medium (CGM) has a rich multiphase

structure with gas temperatures, densities, and metallicities spanning several orders of magnitude (Tumlinson et al., 2017a). The CGM drives galaxy evolution by controlling gas accretion, which is necessary for continued star formation, and is in turn shaped by galactic outflows, which expel the byproducts of stellar evolution. Constraints on the structure of the CGM and the origin of its multiple phases are therefore crucial for understanding the dominant physical mechanisms driving galaxy evolution.

Because the CGM is so diffuse, much of what we know about its composition and kinematics derives from absorption line studies, in which the sightline to a bright background source (typically a quasar) intersects a galaxy’s CGM. The atoms in the CGM interact with the light from the quasar, creating absorption line features in the resulting spectra from which we can measure properties like the ionic column density and line-of-sight velocity of the absorbing gas. Most sightlines intersecting the CGM detect absorption from high-, intermediate-, and low-ionization species at rest-frame Ultraviolet (UV) wavelengths, spanning over an order of magnitude in ionization potential energies, both at low redshift (e.g. $z \lesssim 1$: Prochaska et al., 2011; Tripp et al., 2011a; Tumlinson et al., 2013; Werk et al., 2013; Nielsen et al., 2013; Bordoloi et al., 2014; Liang and Chen, 2014; Borthakur et al., 2015; Burchett et al., 2019) and high redshift (e.g. $2 < z < 3$: Steidel et al., 2010; Rudie et al., 2012; Turner et al., 2015; Zahedy et al., 2019). Absorption from low-ions (e.g., Mg II, Si III), assumed to trace cool 10^{4-5} K gas, is prevalent in the inner ~ 100 kpc of the CGM while absorption from high-ions (e.g., O VI), assumed to trace warm $10^{5.5}$ K gas, is detected out to, and sometimes beyond the galaxy virial radius (Johnson et al., 2015; Keeney et al., 2018). Kinematic studies reveal that high ions and low ions often have similar line-of-sight velocity centroids, suggesting a common (or related) physical distribution of the warm and cool absorbers (Werk et al., 2016).

Ionization modeling of the measured quantities has yielded a rich set of constraints on the gas-phase metallicity of the CGM (e.g. Lehner et al., 2013; Prochaska et al., 2017; Lehner et al., 2019), its total baryonic content (e.g. Werk et al., 2014; Stern et al., 2016), and its pressure profile (Stocke et al., 2013; Werk et al., 2016; Voit et al., 2019). In particular,

around low-redshift L^* galaxies, cool CGM gas appears to have significantly lower densities than required for it to be in thermal pressure equilibrium with the hot phase (Werk et al., 2014; Stern et al., 2016).

One promising interpretation of the low densities of cool gas is that the CGM is supported by non-thermal cosmic-ray pressure. In recent years, cosmic rays have been invoked in galaxy simulations to launch winds (Ipavich, 1975; Uhlig et al., 2012; Booth et al., 2013; Pakmor et al., 2016c; Simpson et al., 2016; Ruszkowski et al., 2017; Farber et al., 2018; Hopkins et al., 2021a), and thereby altering the ionization structure of the CGM (Salem et al., 2016; Butsky and Quinn, 2018; Ji et al., 2020a; Buck et al., 2020). Although the quantitative details of the predicted CGM structure depend on the invoked model of cosmic-ray transport (Hopkins et al., 2021b,d), which is still poorly constrained, many of these simulations predict a cosmic-ray pressure-dominated CGM around low-redshift L^* galaxies. In these models, the cosmic-ray pressure can exceed the gas pressure by up to two orders of magnitude in the inner CGM. Significant cosmic-ray pressure support allows low-density cool gas to fill the CGM, naturally producing high column densities of low-ions. Significant cosmic-ray pressure can also qualitatively alter the kinematics of the CGM by changing the morphology of outflows (e.g. Girichidis et al., 2016; Jana et al., 2020) and preventing a virial shock Ji et al. (2020b).

In this chapter, we explore the implications of a cosmic-ray pressure dominated halo on the observed kinematic alignment between multiphase ions. We start with a Milky Way mass galaxy which has successfully reproduced O VI column densities with the help of supermassive black hole (SMBH) feedback (Sanchez et al., 2019). We then re-simulate that same galaxy, adding supernova cosmic-ray feedback. By redshift $z = 0.25$, this galaxy develops a cosmic-ray-pressure-supported halo, qualitatively similar to those described in the recent literature.

To compare the simulations with observations, we generate 100 synthetic spectra that pierce the inner-CGM of each simulated halo. We then analyze absorption features in these spectra with Voigt-profile fitting tools used by observers. This approach allows us

to make a detailed comparison of individual synthetic absorption-line components’ properties (e.g. Doppler- b parameters, line-of-sight velocity offsets) with the same properties derived from observations in such a way that is inaccessible to traditional simulation analysis techniques.

This paper is organized as follows. In [section 4.2](#), we describe our methods, including the simulation initial conditions, our choices of run-time physics, and the process for generating and analyzing synthetic spectra. In [section 4.3](#), we present our results. We first present a simulation-oriented view of the CGM properties and then shift the focus to properties derived from the Voigt-profile fits with an emphasis on the Doppler- b parameters and velocity offsets. In [section 4.4](#), we discuss the implications of our work in the context of recent work and future directions. In [section 4.5](#), we present a summary of this chapter and its conclusions. Lastly, we demonstrate the implementation of cosmic-ray physics in the CHANGA simulation code in [section 4.6](#).

4.2 Methods

4.2.1 *Description of Galaxy Simulations*

In this chapter, we analyze cosmological zoom-in simulations of two Milky Way-sized galaxies evolved with and without cosmic-ray feedback. The base model, “Patient 0” (P0) has been studied in great detail in [Sanchez et al. \(2019\)](#) and [Sanchez et al. \(2020\)](#). “Patient 0 with cosmic rays” (P0+CR) uses the same initial conditions and physics as P0 except that it also includes cosmic-ray feedback. We present a basic description of the simulation here for context, but encourage the reader to see the referenced works for more detail. The description of the cosmic-ray physics implementation is detailed in [section 4.6](#).

The simulations were run with ChaNGa, a smoothed-particle hydrodynamics (SPH) astrophysical simulation library ([Menon et al., 2015](#)) with a recently updated formalism that includes a geometric density approach in the force expression ([Wadsley et al., 2017](#)). We assume a Λ CDM cosmology with parameters $\Omega_m = 0.3086$, $\Omega_\Lambda = 0.6914$, $h = 0.67$, $\sigma_8 =$

0.77 and an extragalactic UV background described by [Haardt and Madau \(2012\)](#). The mass of dark matter particles and gas particles are $2.1 \times 10^5 M_\odot$ and $1.4 \times 10^5 M_\odot$ respectively.

We do not include metal line cooling for temperatures above 10^4 K. Although this is a limitation of the simulation, these effects are mitigated by the fact that the balance between heating and cooling at warm CGM temperatures is dominated by the extragalactic UV background. In this case, excluding metal line cooling overestimates the cooling time by a factor of $\sim 3 - 5$ ([Shen et al., 2010](#)). Additionally, the cooling times in $10^{4-4.5}$ K gas are well estimated by primordial cooling ([Hopkins et al., 2018](#)).

Both simulations model star formation assuming a Kroupa IMF ([Kroupa, 2001](#)) and ‘blastwave’ supernova feedback ([Stinson et al., 2006](#)). We also include SMBH feedback as described in [Tremmel et al. \(2017\)](#).

cosmic-ray energy is injected into the simulation during supernova feedback events. The total injected supernova energy remains constant, but 10% is injected in the form of cosmic-ray energy. We do not inject additional cosmic-ray energy during SMBH feedback events. Cosmic-ray transport is modeled as isotropic diffusion with a constant diffusion coefficient of $\kappa = 10^{29} \text{ cm}^2 \text{ s}^{-2}$.

4.2.2 *Generating synthetic spectra*

We explicitly track the evolution of hydrogen, oxygen, and iron at runtime. In the analysis phase, we use ([Hummels et al., 2017](#)), an extension of the widely-used simulation analysis tool, YT ([Turk et al., 2012](#)), to estimate the abundance of other chemical species as well as their ionization states. We also use to generate synthetic spectra that mimic the specifications of the HST COS-G130M and COS-G160M instruments.

We generate 100 randomly-oriented sightlines coordinates that sample the inner CGM with impact parameters between 10 and 50 kpc. To generate the coordinates of a random sightline, we first define the position of the impact parameter – the closest point between the sightline and the galactic center – as a point on the surface of a sphere centered on

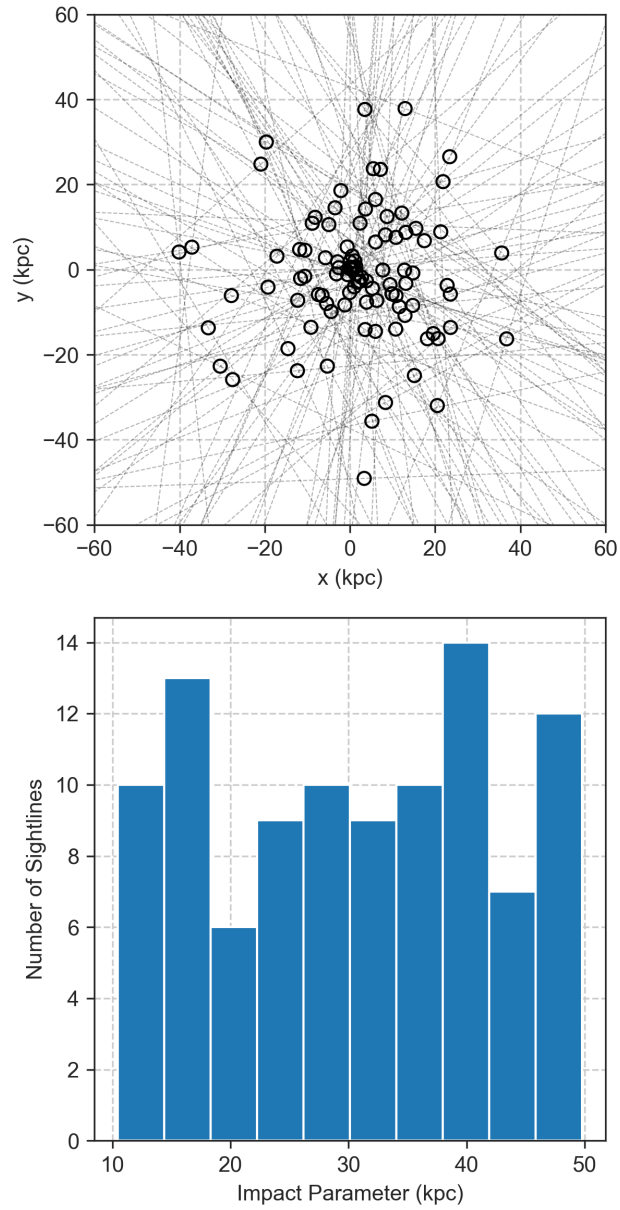


Figure 4.1 (Top) The projected paths of the 100 synthetic spectra in the x-y plane, centered on the galaxy center. The open circles show the projected position of the impact parameter – the closest point between the sightline and the galactic center. (Bottom) The random distribution of impact parameters between 10 and 50 kpc. Note that the minimum impact parameter is 10 kpc, and the appearance of impact parameters < 10 kpc in the top panel is due to projection effects.

the galaxy: $p(r, \theta, \phi)$. In this expression, r is the impact parameter, θ is the polar angle, and ϕ is the azimuthal angle. All three values are selected using a random, unweighted number generator. Once we choose the coordinates of the impact parameter, we set the orientation of the sightline to be at a random angle, ψ , in the plane tangent to the sphere. All sightlines are 500 kpc long and centered at their impact parameter.

We use the same set of galactocentric sightline coordinates to generate synthetic spectra for both, P0 and P0+CR. [Figure 4.1](#) provides a visual depiction of the randomly distributed sightlines and the distribution of impact parameters (the circles).

For each sightline in each galaxy, we generate a synthetic spectrum at $z = 0.25$, including all transitions of the H I, Mg II, C II, C III, C IV, Si II, Si III, Si IV, N V, and O VI ions. then deposits Voigt absorption profiles that explicitly include thermal broadening and implicitly include nonthermal broadening due to gas motions. We subtract out the bulk velocity of the 500 kpc sphere centered on the galaxy relative to the simulation frame. To make these synthetic spectra resemble real HST/COS data, we add noise with a signal-to-noise ratio of 10 per resolution element and convolve it with the line spread functions of the G130M and G160M spectrographs. The resulting normalized synthetic spectra are characterized by a FWHM $\approx 18 \text{ km s}^{-1}$ when they are binned by three native spectral pixels to a dispersion of $\Delta\lambda \approx 0.0367 \text{ \AA}$.

4.2.3 *Analyzing synthetic spectra*

Our spectral analysis incorporates common observational techniques for analysing high-resolution HST/COS data (e.g. [Tumlinson et al., 2011](#); [Werk et al., 2013](#)). Specifically, we extract information from the synthetic spectra by decomposing the absorption features into Voigt profiles. We do so without any regard to the parameters that are used by Trident to generate the synthetic spectra.

The decomposition involves five steps: (1) automated identification of distinct absorption components; (2) an initial Voigt profile fit; (3) manual refinement of component def-

initions; (4) a final Voigt profile fit; and (5) calculation of column density upper limits for ions with no detected components. For each ion and sightline, this procedure produces either a column density upper limit or a collection of: component column densities, N ; velocity centroids relative to the halo rest frame, v ; and linewidths expressed as as Doppler- b parameters.

To identify absorption components for an ion along a sightline, we first estimate the column density as a function of velocity, $N(v)$, using the apparent optical depth method (AOD; [Savage and Sembach, 1991](#)). We then segment $N(v)$ by computing a dendrogram ([Rosolowsky et al., 2008](#)), and take the leaves of the dendrogram to be candidate components. Finally, we remove candidate components whose integrated column densities are less than two times their integrated column density uncertainties.

Each candidate component has a centroid velocity, an allowed velocity range, and rough estimates of the component column density and linewidth. These values are used as initial conditions for the Voigt profile fit. We use optimization to find the likelihood-maximizing component parameter set and estimate uncertainties by inverting the Fisher information matrix at the maximum likelihood solution.

The automated component identification procedure is imperfect. It makes two main kinds of mistake: (1) identifying a single component where multiple components would be more appropriate and (2) identifying a single absorption feature as arising from different ions. We resolve the first kind of mistake by inspecting the initial Voigt profile fits and defining new components as needed. The second mistake happens when ions have transitions with similar rest wavelengths, such as the C II 1036Å and O VI 1037Å lines. In all such cases, at least one of the ions has more than one line, so the maximum likelihood solution for the fictitious component has a very low column density. This allows us to find and remove these incorrect components using a velocity and column density cut. A second round of Voigt profile fits done with the revised component structures provides our adopted set of component parameters.

If an ion has no components along a sightline, we calculate an upper limit on the ion's

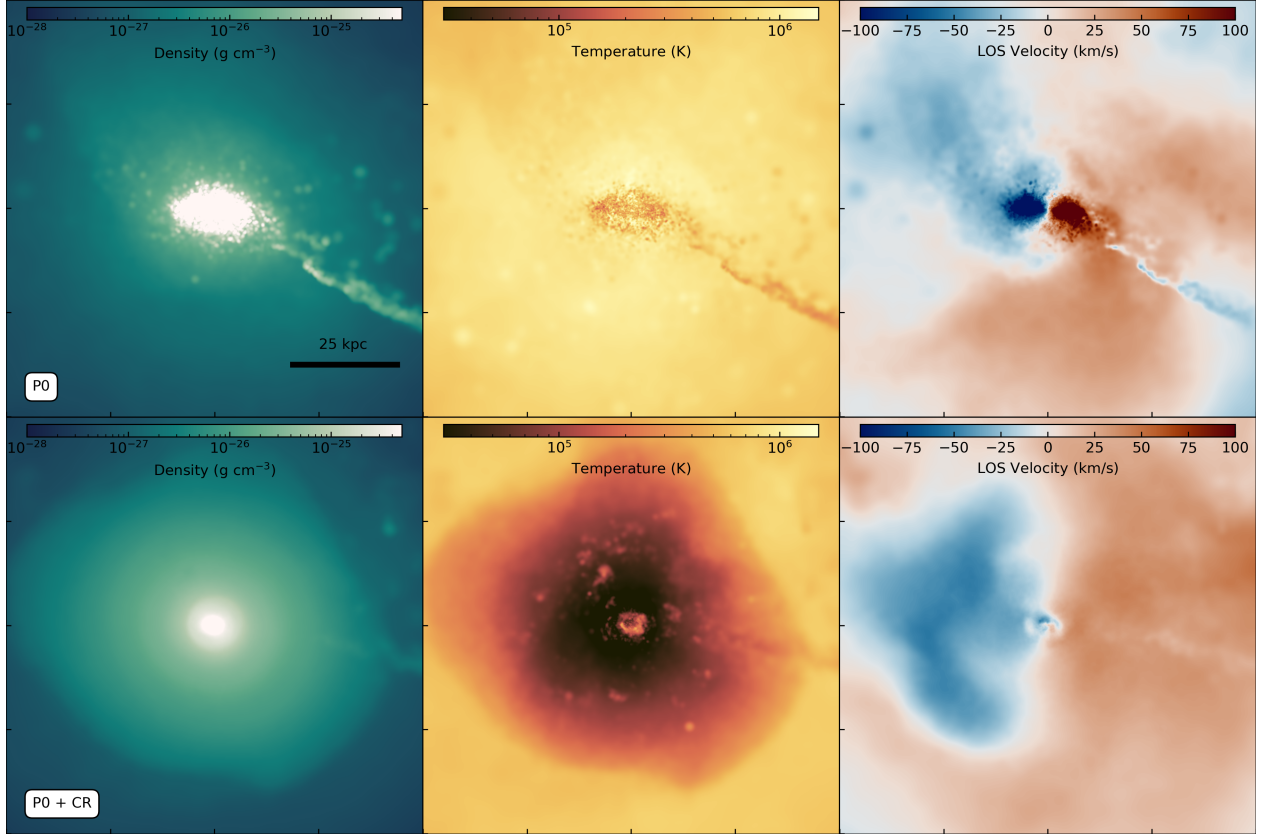


Figure 4.2 The mass-weighted projections of density, temperature and line-of-sight velocity for P0 (top) and P0+CR (bottom) at $z = 0.25$. The width and depth of the projection are 100 kpc. Relative to P0, the simulation with cosmic rays has a cooler CGM in the inner ~ 40 kpc and a larger rotating extended disk.

column density. We use AOD to calculate $N(v)$ and integrate the result over a 100 km s^{-1} interval. We then convert the total column density and column density uncertainty over this interval to a $2\text{-}\sigma$ equivalent upper limit using the formalism of [Bowen et al. \(2008\)](#).

4.3 Results

4.3.1 The physical state of the CGM

Despite starting from the same initial conditions, by a redshift of 0.25, the two galaxies have distinctly different CGM properties. While some differences are naturally to be ex-

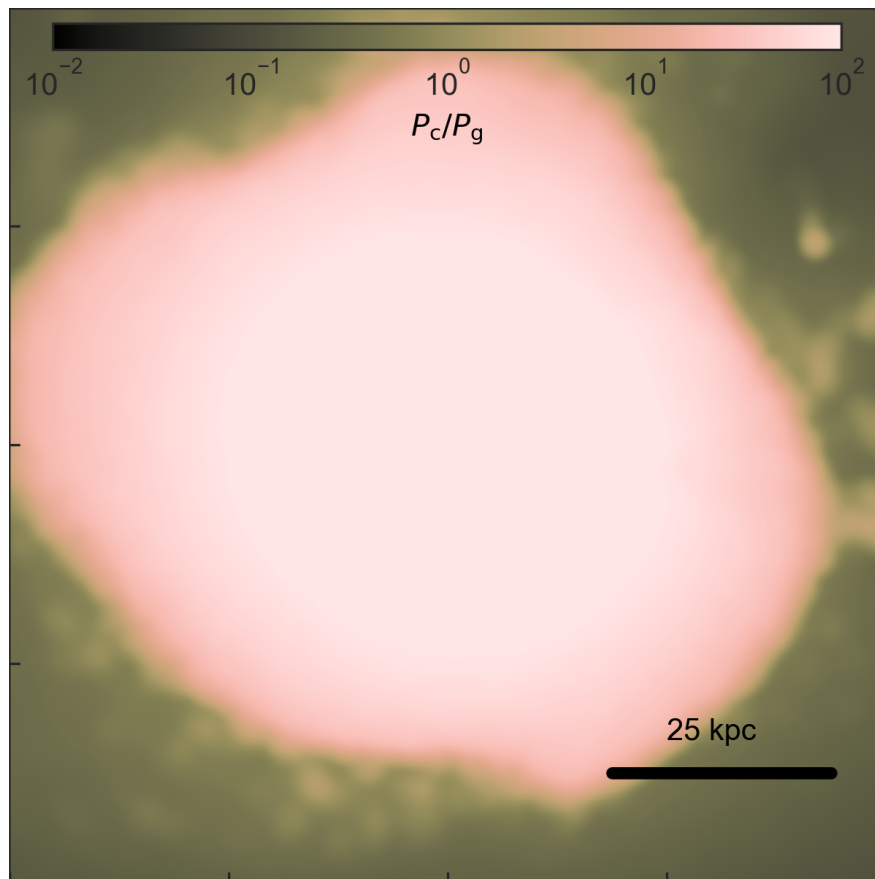


Figure 4.3 The mass-weighted projection of the ratio of cosmic-ray pressure to gas pressure in P0+CR. Cosmic-ray pressure is significantly larger than thermal pressure in the inner CGM. The cosmic-ray pressure gradient counteracts gravity to maintain hydrostatic equilibrium, allowing cool, low-entropy gas to fill the inner CGM.

pected (even for theoretically identical cosmological simulations) due to low-level non-linear effects (Genel et al., 2019), the buildup of cosmic-ray pressure in P0+CR produces a *qualitatively* different CGM, significantly exceeding the differences expected from chaotic processes of galaxy formation.

Figure 4.2 shows the mass-weighted projections of gas density, temperature, and line-of-sight velocity. The CGM of P0 is notably hotter, with temperatures in excess of 10^6 K, in part due to a recent burst of supernova feedback, and in part due to the thermal gas pressures required to maintain hydrostatic equilibrium. The cool, dense filament of inflowing gas traces the remnants of a recent merger with a satellite galaxy.

By contrast, the inner CGM of P0+CR is full of cool gas, supported against gravity and condensation by significant cosmic-ray pressure. This cool inner CGM extends roughly 40 kpc and has higher gas densities than the inner CGM of P0. The cool gas is pierced by pockets of hot bubbles from supernova feedback. There is a sharp transition between the cool, inner CGM and the outer CGM, marking the edge of the cosmic-ray-pressure-supported halo. The temperatures and densities in the outer CGM of P0+CR resemble those in the outer CGM of P0. The line-of-sight velocity distribution is smoother in P0+CR than in P0. The inflowing filament from the recent merger is also present in P0+CR, but is significantly diminished relative to the fast-moving filament in P0.

Figure 4.3 shows the projected ratio of cosmic-ray pressure to gas pressure around P0+CR. The inner ~ 40 kpc of the CGM are supported by cosmic-ray pressure while the outer regions are supported by thermal pressure. The shape of the cosmic-ray-pressure-supported region traces the shape of the cool gas. The details of the cosmic-ray pressure profile and the extent of the cosmic-ray-pressure-supported region are sensitive to the choice of cosmic-ray hydrodynamics models, which are currently unconstrained. However, this simulation is qualitatively similar to the cosmic-ray-pressure-supported CGM seen in other hydrodynamics simulations with cosmic-ray diffusion (e.g., Salem et al., 2016; Butsky and Quinn, 2018; Ji et al., 2020a; Buck et al., 2020).

These differences in the gas phase between the two galaxies translate into differences

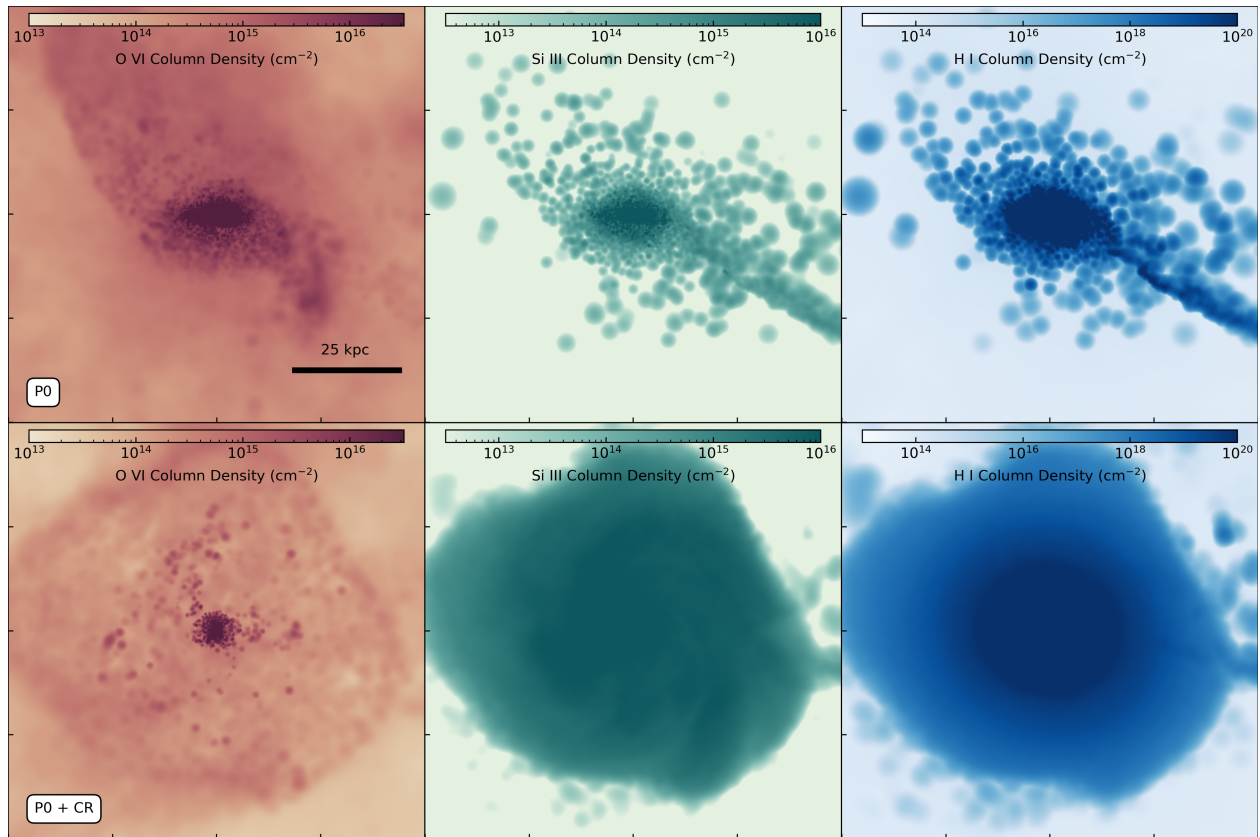


Figure 4.4 The O VI, Si III, and column densities at $z = 0.25$ for P0 (top) and P0+CR (bottom). The width (and depth) of the projection is 100 kpc. Compared to P0, the CGM of P0+CR has lower overall O VI column densities and higher column densities of Si III and in the inner 50 kpc.

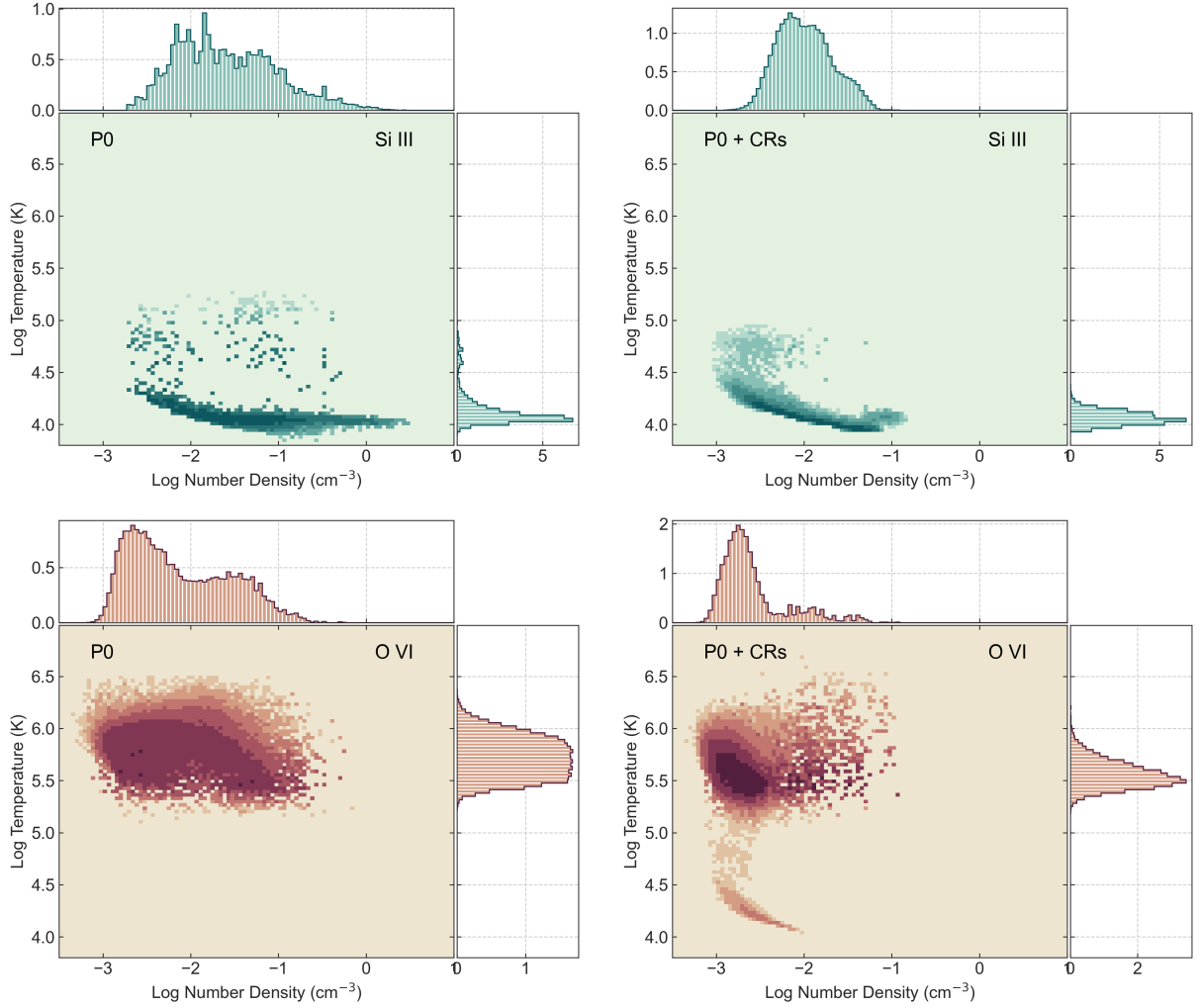


Figure 4.5 The ion-mass weighted 2D histograms of gas temperature and number density for P0 (left) and P0+CR (right). The data for these plots is generated from a spherical shell between 10 and 50 kpc from the galactic center. The additional pressure support from cosmic rays moves the gas to lower densities. P0 has a substantial amount of O VI absorption at temperatures above the collisional ionization equilibrium temperature of $T \sim 10^{5.5}$ K.

in their ion column densities. Figure 4.4 shows the column densities of O VI, Si III, and H I for the two simulated galaxies. P0 has high O VI column densities throughout, with its hot inner region exceeding column densities of 10^{15}cm^{-2} . While the O VI-bearing gas creates structures that span the extent of the inner CGM, the Si III and H I column density maps trace small-scale structures near the galactic disk and in the cold accretion stream. The cloudlets that trace Si III and H I absorbers are likely

Relative to P0, P0+CR has lower O VI column densities with a profile that traces the shape of the cosmic-ray-pressure-supported region. The inner CGM has significant Si III and H I column densities throughout.

In Figure 4.5, we take a look at the differences in the gas properties of O VI and Si III absorbers between the two simulations. The images show the 2D histograms of simulated temperature and number density, colored by the ion mass probability density of O VI and Si III. The data for these plots was generated from spherical shells centered on the galaxy with radii between 10 and 50 kpc, corresponding to the region sampled with our synthetic spectra and in the previous figures.

In both galaxies, the vast majority of Si III comes from gas around $10^{4.2}$ K, as is expected for photoionized gas. Relative to P0, the Si III in P0+CR comes from lower density gas due to nonthermal cosmic-ray pressure support. In P0, O VI traces gas with temperatures of $T = 10^{5.3-6.2}$ K — hotter than the peak O VI ionization temperature of $\sim 10^{5.5}$ K. In P0+CR, the majority of O VI absorption traces gas with temperatures with a peak at $T = 10^{5.5}$ K and has a negligible fraction of photoionized O VI at low temperatures and low gas densities. Like with Si III, O VI-bearing gas in P0+CR tends to have lower densities than in P0.

4.3.2 *Physical insights from synthetic spectra*

Next, we present the physical state of the two galaxies as seen through their synthetic spectra. Unlike real observations, with synthetic spectra we have the added benefit of actually knowing the gas properties along the sightline that lead to the absorption fea-

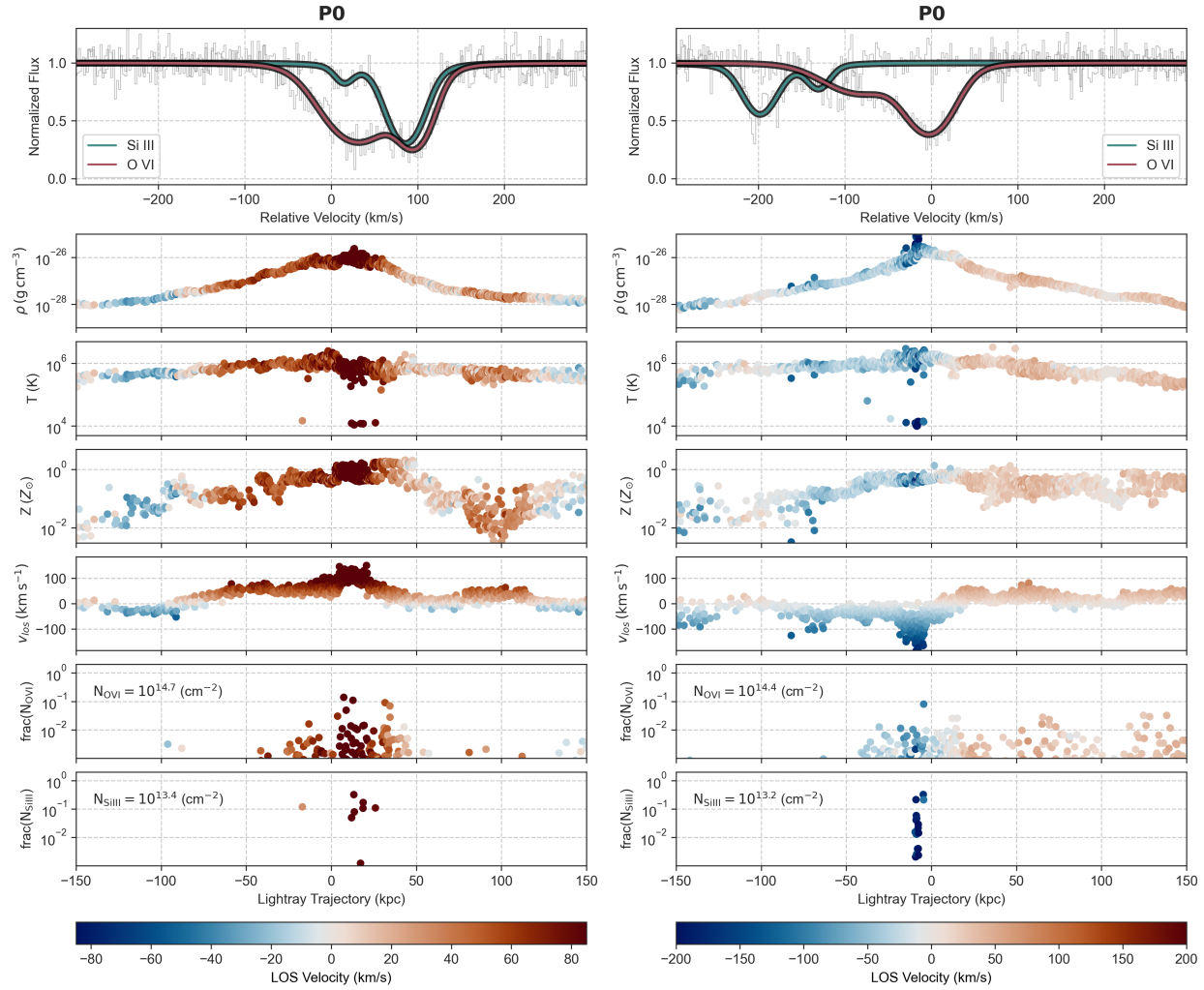


Figure 4.6 Example synthetic spectra from P0 and the gas properties along their line of sight. (Top row) The normalized flux corresponding to Si III and O VI absorbers in velocity space. The gray lines show the raw synthetic spectra and the green and red lines show the Voigt profile fits for Si III and O VI respectively. (Remaining rows) The gas density, temperature, metallicity, line-of-sight velocity, and fractional ion column densities as a function of position along the line of sight. The points are colored by their LOS velocity, which helps discern which absorber they contribute to. The fractional ion column densities in the bottom row are divided by the total ion column density, to help discern which particles contributed the most to the absorbers in the top row. In the light ray trajectory, 0 always represents the impact parameter (point of closest approach to the galaxy center). While O VI-bearing gas tends to form large, resolved structures, Si III-bearing gas tends to form dense, resolution-limited structures. By matching fractional column densities of Si III and O VI to the absorbers in the spectra, we can see that kinematic alignment does not necessarily imply physical alignment (left). Conversely, the right panel shows an example of Si III and O VI absorbers that are spatially aligned but kinematically misaligned.

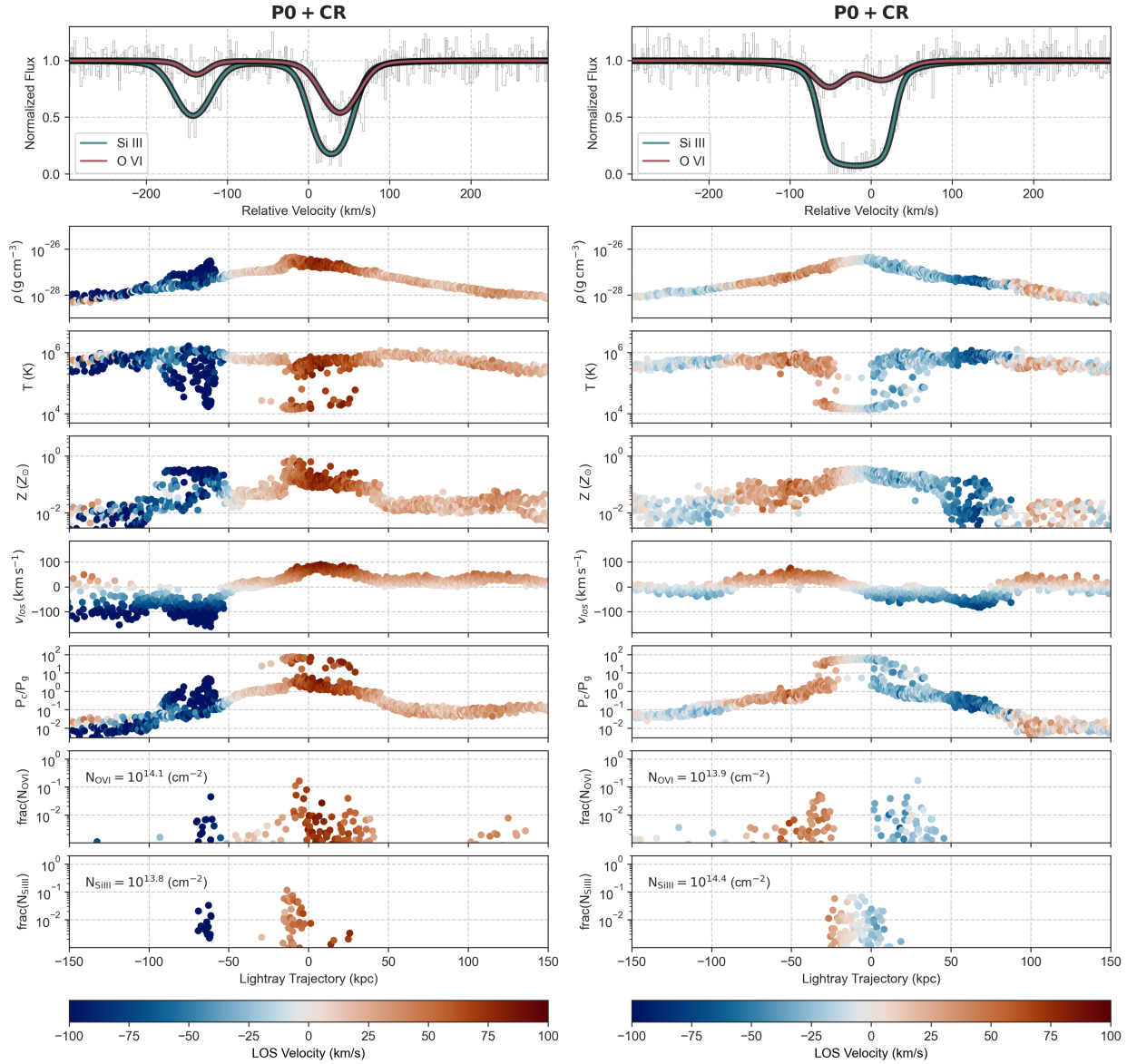


Figure 4.7 Similar to Figure 4.6, the figure above shows example synthetic spectra from P0+CR and the gas properties along their line of sight. There is an additional panel to show the ratio of cosmic-ray pressure to gas pressure, P_c/P_g , along the line of sight. (Right) An example of kinematic alignment in P0+CR in which both Si III and O VI absorbers come from the same physical structures. In all P0+CR spectra that have both O VI and Si III absorbers, there is at least one O VI component that is kinematically aligned with Si III. P0+CR has higher incidences of kinematic alignment between Si III and O VI. In most cases in P0+CR, Si III absorption comes from large, ~ 50 kpc, clouds that are enveloped by O VI absorbers. Unlike in P0, low-density Si III-bearing gas in P0+CR is resolved by many gas particles.

tures we observe. [Figure 4.6](#) and [Figure 4.7](#) each show two example spectra with both Si III and O VI absorption. The top panel shows the ion absorption as a function of its velocity offset from the galaxy rest frame. The panels below show the gas particles along the one-dimensional sightline used to generate the synthetic spectra. The x-axis shows the trajectory along the light ray, with zero corresponding to the impact parameter. The points are colored by their line of sight velocity, which corresponds to the relative velocity offset in the top panel.

The first P0 spectrum on the left-hand side of [Figure 4.6](#) is an example of two O VI absorbers, both kinematically aligned with Si III absorbers, yet with different spatial origins. From the bottom two panels, we can see that the O VI and Si III absorbers at 80 km/s (deep red) come from the same physical region as they appear at the same point along the light ray trajectory. This is consistent with cold clumps being entrained in a hot background medium. By contrast, the O VI and Si III absorbers at 20 km/s offset come from completely different regions, separated by roughly 50 kpc in space, yet happen to have a similar-line of sight velocity. Additionally, the 20 km/s Si III absorber comes from one extrapolated data point along the sightline, indicating that the cool cloud is not resolved and resulting in a narrow absorption feature. The second P0 spectrum, in the right panel of [Figure 4.6](#), is an example of a spectrum that has significant absorption of both O VI and Si III without kinematic alignment. Even though one absorber for each, O VI and Si III, comes from the same physical cloud at $x \simeq 10$ kpc along the lightray, those absorbers are moving with different velocities.

The P0+CR spectra in [Figure 4.7](#) show a very different relationship between the kinematic and physical alignment of O VI and Si III. In both cases, the O VI and Si III absorbers are kinematically aligned. In the first example, in the left panel of [Figure 4.7](#), the cool and warm gas comes from physically distinct, yet related clouds. Although O VI and Si III absorption is spatially offset, with the O VI absorption bordering the Si III absorption on either side, the velocity structure of the scatter points clearly shows that together, the O VI and Si III form a coherent physical region. The O VI and the Si III absorbers are co-

rotating. The Si III absorption is very wide and has a large Doppler- b parameter because it comes from a large Si III-bearing cloud that spans a wide range of velocity space. The two O VI absorption features, which trace the velocity at either edge of the cool cloud are nestled within the broad Si III absorber. In the second example spectrum, there are two distinct absorbers of each, Si III and O VI, both of which come from the same physical cloud. In both cases, they are kinematically aligned.

These four examples were chosen to highlight the observed trends in and differences between the P0 and P0+CR synthetic spectra. P0 tends to have broader O VI and narrow Si III absorbers, with a large fraction of them kinematically misaligned. O VI absorbers come from hot ($T > 10^6$ K) gas that spans tens of kpc while Si III absorbers come from small (and likely resolution-limited) clouds of ~ 1 kpc scales. The O VI and Si III bearing gas sometimes comes from the same physical cloud, but is often physically unrelated.

In P0+CR, Si III absorbers tend to be broader and come from large, low-density clouds spanning 10 – 50 kpc. O VI absorbers tend to come from slightly cooler gas ($T \lesssim 10^6$ K) and slightly smaller clouds (10 – 50 kpc) than in P0. O VI and Si III absorbers are often kinematically aligned and often come from either the same physical cloud or from physically related clouds.

Note that in an attempt to highlight the relationship between the kinematic and physical relationships between O VI and Si III, we omit spectra that have no measurable Si III absorption from this figure. While these true “no-lows” (see: [Werk et al., 2016](#)) are present in both simulations, they are very common in P0 and very rare in P0+CR.

4.3.3 The Doppler- b Parameter

The Doppler- b parameter is a combination of thermal and non-thermal line broadening mechanisms, $b = \sqrt{b_{th}^2 + b_{nt}^2}$. The Voigt profile of the synthetic spectra generated with TRIDENT is a convolution of Doppler line broadening (thermal), described by a Gaussian function and pressure broadening (non-thermal) modeled as a Lorentzian function.

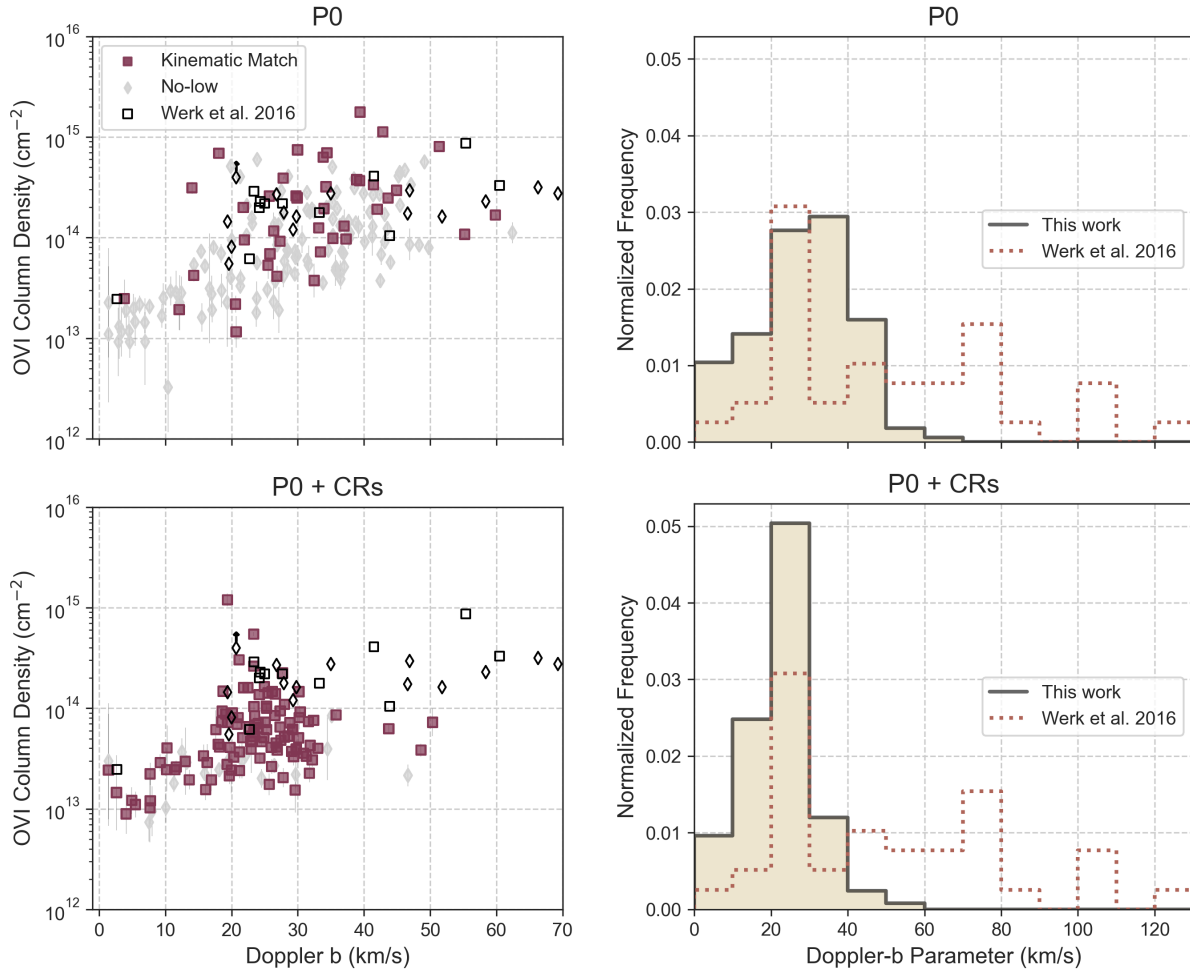


Figure 4.8 (Left) The column density of O VI absorbers as a function of Doppler- b parameter for P0 (top) and P0+CR (bottom). Purple squares indicate O VI absorbers that are matched with a Si III absorber within 35 km/s in line-of-sight velocity space. Gray diamonds indicate O VI absorbers that have no corresponding Si III absorber within 35 km/s. We include data from [Werk et al. \(2016\)](#) for comparison in black. Upward arrows indicate upper limits on the measured column density. (Right) The histograms of the Doppler- b parameters of O VI absorbers in P0 (top) and P0+CR (bottom) compared against observations. All histograms are normalized to have an area of 1. Both simulations have a distinct lack of very broad ($b > 60$ km/s) O VI absorbers.

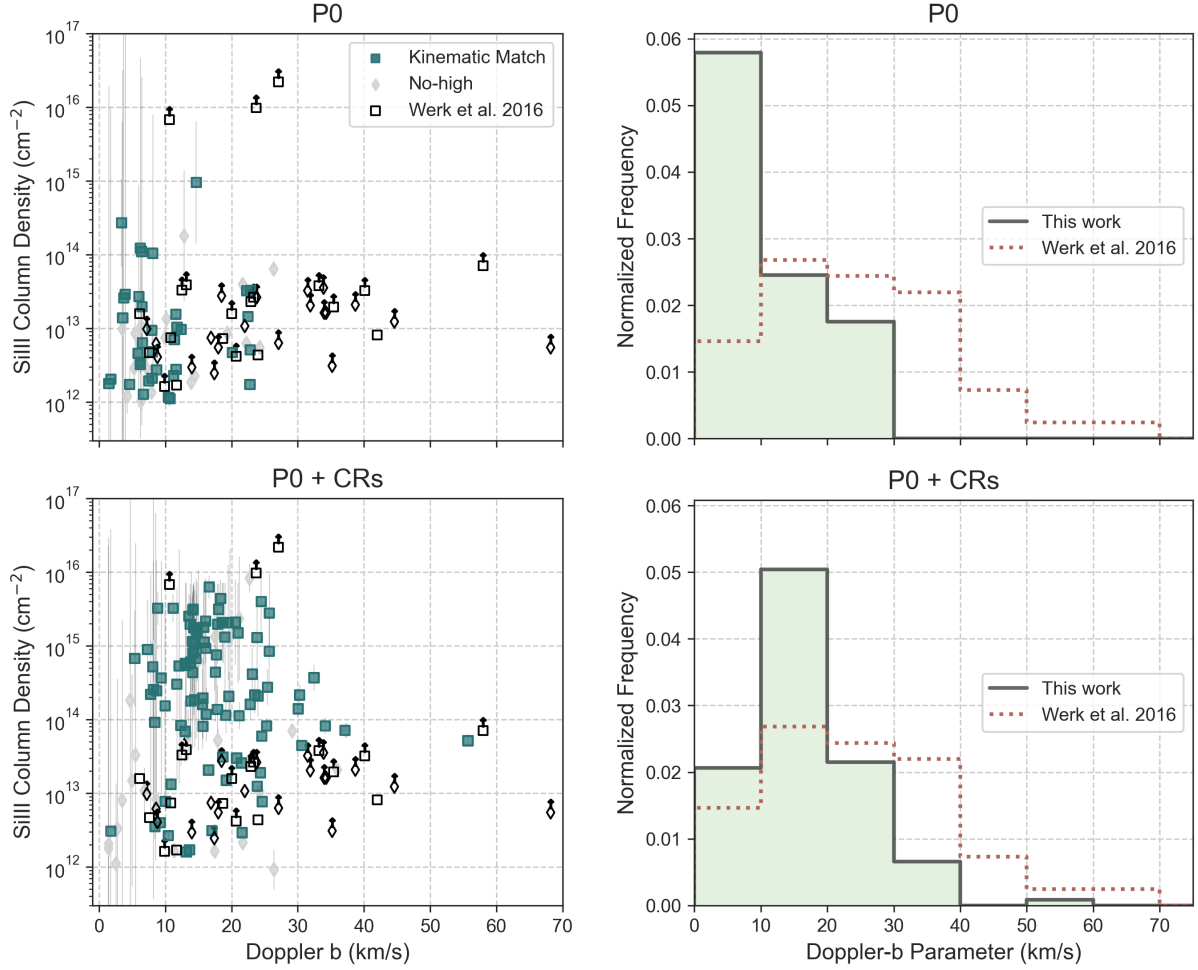


Figure 4.9 (Left) The column density of Si III absorbers as a function of Doppler- b parameter for P0 (top) and P0+CR (bottom). Green squares indicate Si III absorbers that are matched with a O VI absorber within 35 km/s in line-of-sight velocity space. Gray diamonds indicate Si III absorbers that have no corresponding O VI absorber within 35 km/s. We include data from [Werk et al. \(2016\)](#) for comparison in black. Upward arrows indicate upper limits on the measured column density. (Right) The histograms of the Doppler- b parameters of Si III absorbers in P0 (top) and P0+CR (bottom) compared against observations. All histograms are normalized to have an area of 1. P0+CR better reproduces the observed broad Si III absorbers but over-predicts the abundance of narrow, high-column Si III absorbers.

Therefore, a broad absorption feature may be due to high gas temperatures, densities, or velocity dispersions. We note that although cosmic rays are a source of nonthermal pressure support they do not explicitly affect the Doppler- b parameter value. Instead, they indirectly influence the Doppler- b parameter by altering the density, temperature, velocity profiles, or spatial extent of the gas.

The left panel of [Figure 4.8](#) shows the O VI column density as a function of Doppler- b parameter for P0 and P0+CR. Each scattered point represents a single O VI absorption feature and is colored by whether or not that absorber has a matched Si III absorber within 35 km/s in line-of-sight velocity space. P0 has significantly more “No-lows” than either P0+CR or the observations. This is in part due to the fact that P0 has both more sightlines that have no detected Si III and more sightlines with detected Si III that is kinematically unrelated to O VI.

In the cosmic-ray-pressure-supported CGM, the distribution of O VI Doppler- b values is narrower, likely because O VI comes from cooler gas ([Figure 4.5](#)). P0+CR also reproduces the observed abundance of O VI Doppler- b parameters that are 20 – 30 km/s and predicts a relative gap in O VI Doppler- b parameters around 40 km/s. In comparison, P0 has broader O VI features, with the most abundant O VI Doppler- b parameter in the 30 – 40 km/s range. Neither simulated distribution reproduces the very broad O VI features seen in [Werk et al. \(2016\)](#)¹. The lack of very broad O VI absorbers is likely influenced by the lack of O VI in the outskirts of the simulated CGM and the resolution, which narrows the velocity distribution within an O VI cloud ([Peeples et al., 2019b](#)).

[Figure 4.9](#) repeats the format of [Figure 4.8](#) for Si III absorbers. In the left panel, each scatter point represents individual Si III absorbers, colored by whether they have a corresponding O VI absorber within 35 km/s in line-of-sight velocity space. The CGM of P0+CR produces higher column densities of Si III, which appear consistent with the range of observed column densities. However, it is difficult to compare precisely as many of the ob-

¹There is one additional O VI absorber with $b = 174.7$ km/s in the [Werk et al. \(2016\)](#) data that isn’t pictured in [Figure 4.8](#).

served Si III absorbers are saturated. P0+CR also produces distinctly higher Si III Doppler- b parameters that better agree with the observed distribution. However, as with O VI absorbers, neither simulation reproduces the broad tail of Si III Doppler- b parameters.

4.3.4 *The kinematics of cool and warm gas*

Next, we consider the impact of cosmic rays on the kinematics of O VI and Si III. Using synthetic spectra, we compare the velocity offsets of individual absorbers of O VI and Si III and compare them directly against the properties of the velocity offsets of the absorbers in [Werk et al. \(2016\)](#).

In [Figure 4.10](#), we plot the histograms of minimum difference in velocity centroids between O VI and Si III for all sightlines that have detections of both ions. P0 has significantly more spectra that have Si III absorbers that are kinematically offset from the O VI absorbers. This is because the cool, Si III absorbing, gas in P0 is often physically unrelated to the warm, O VI absorbing, gas.

[Figure 4.11](#) highlights the radial velocity differences between cool and warm gas in both simulations. In P0, the majority of cool gas is radially infalling. Even if we were to exclude the fast inflowing cool gas that originates from the accreting stream, the remaining cool gas radial velocity histogram is still offset from the warm gas radial velocity histogram. Meanwhile, the cosmic-ray pressure support in P0+CR helps support cool gas against gravity, giving it a very similar radial velocity distribution as that of the warm gas.

In this way, significant cosmic-ray pressure support naturally leads to kinematic alignment between the cool and warm gas phases.

4.3.5 *Relating Kinematic Alignment to Physical Absorbers*

With synthetic spectra, we have the unique opportunity to relate the kinematic alignment between O VI and Si III to the spatial relationship of the absorbing gas along the line of sight. To do this, we turn back to the simulated properties of each 1D sightline from which

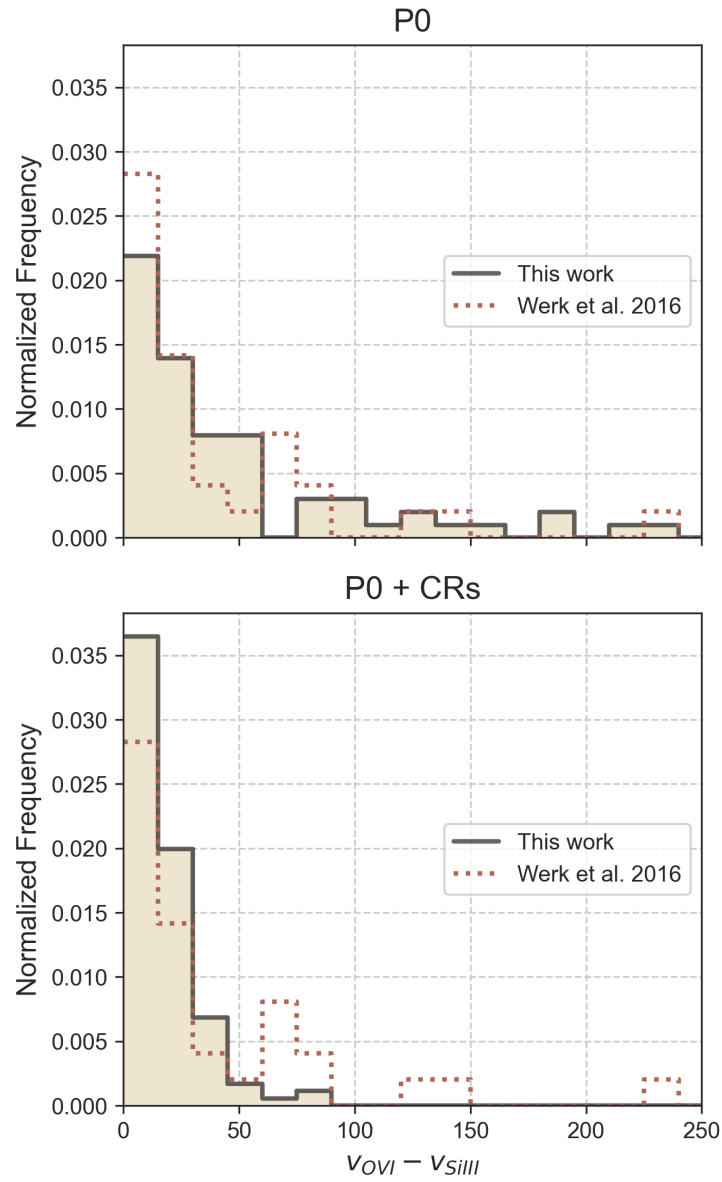


Figure 4.10 The histograms of the minimum velocity differences between O VI and Si III absorbers for P0 (top) and P0+CR (bottom). This excludes sightlines that have O VI but no Si III absorbers. All histograms are normalized to have an area of 1. P0+CR better reproduces the observed kinematic link between O VI and Si III absorbers.

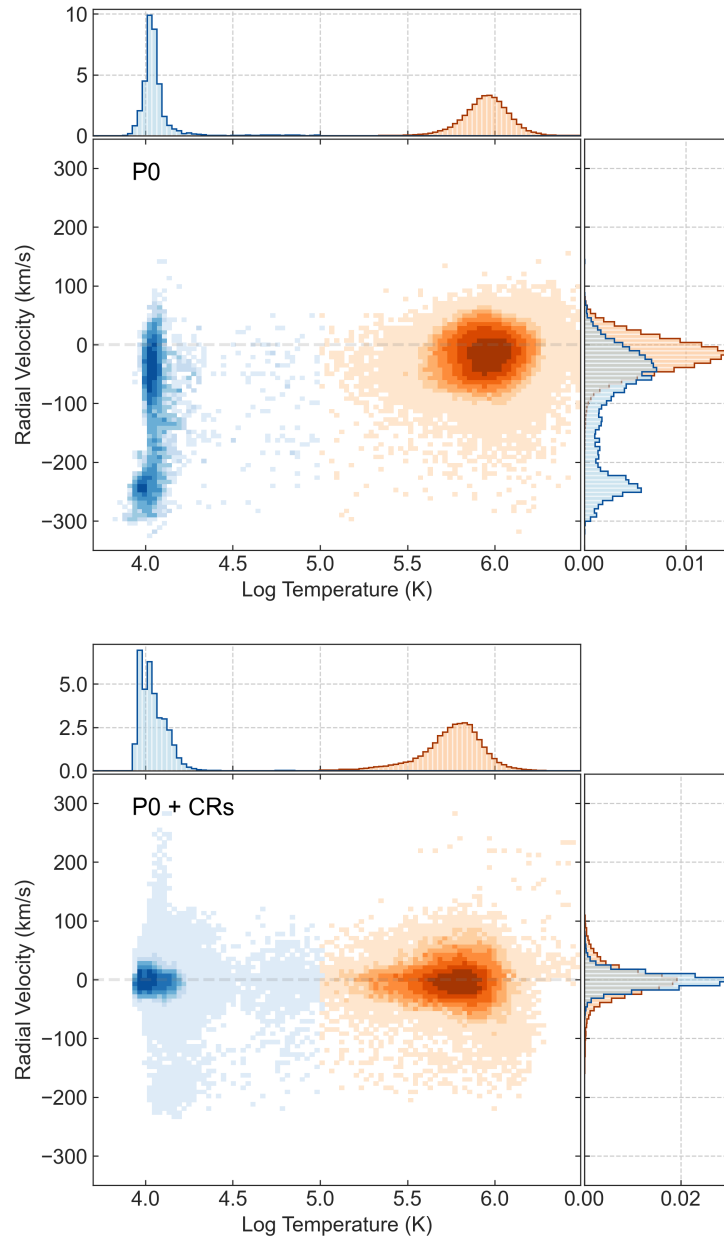


Figure 4.11 The mass-weighted 2D histogram of radial velocity as a function of temperature for cool (blue) and warm (orange) CGM gas for P0 (left) and P0+CR (right). The data is taken from gas that is between 10 and 50 kpc from the galactic center. Without cosmic rays, cool gas in the inner CGM tends to be on a radially inward trajectory. With substantial cosmic-ray pressure support, low entropy cool gas is supported against gravity and has a very similar velocity distribution to that of the warm gas, leading to kinematic alignment of multiphase absorbers.

the synthetic spectra are generated. For each sightline that contains a detectable amount of both O VI and Si III absorption, we calculate the Wasserstein distance (also known as the earth mover’s distance) between the line-of-sight distributions of the O VI and Si III particles in velocity and in position along the sightline. We use SCIPY to calculate the Wasserstein distance, $W_p(u, v)$, which measures the amount of “work” it takes to transform one 1D probability distribution (u) into another (v). We consider all particles whose column density is at least 10^{-2} of the total column density of the sightline.

Considering a single sightline, if the two ions are co-located and co-moving, both distances will be small. If they are co-located but not co-moving (or vice versa), one of the distances will be large while the other is small. Finally, if the ions are in different places and moving with different velocities, both distances will be large. Considering an ensemble of sightlines, the degree to which the distances are correlated provides information on how tightly and uniquely connected position and velocity are. The dispersion of the position distances provides information on how variable the abundance ratios of the two ions are.

Figure 4.12 shows the relationship between the Wasserstein distances for the velocity and position distributions of O VI and Si III. In the cosmic-ray-pressure-supported halo, there is a clear relationship between the kinematic and spatial alignment of cool and warm gas. By contrast, there are fewer sightlines in P0 that have both a kinematic and spatial alignment, and there is no clear relationship between the two properties. This may be due to a lack of resolution of the cool gas structures in P0, many of which are comprised of only a few particles along the line of sight (Peeples et al., 2019b).

4.4 Discussion

4.4.1 Implications for CGM Kinematics

In a thermal-pressure-supported CGM, like the one present in P0, cool gas is not buoyant. In order to maintain thermal pressure equilibrium, cool gas must have higher densi-

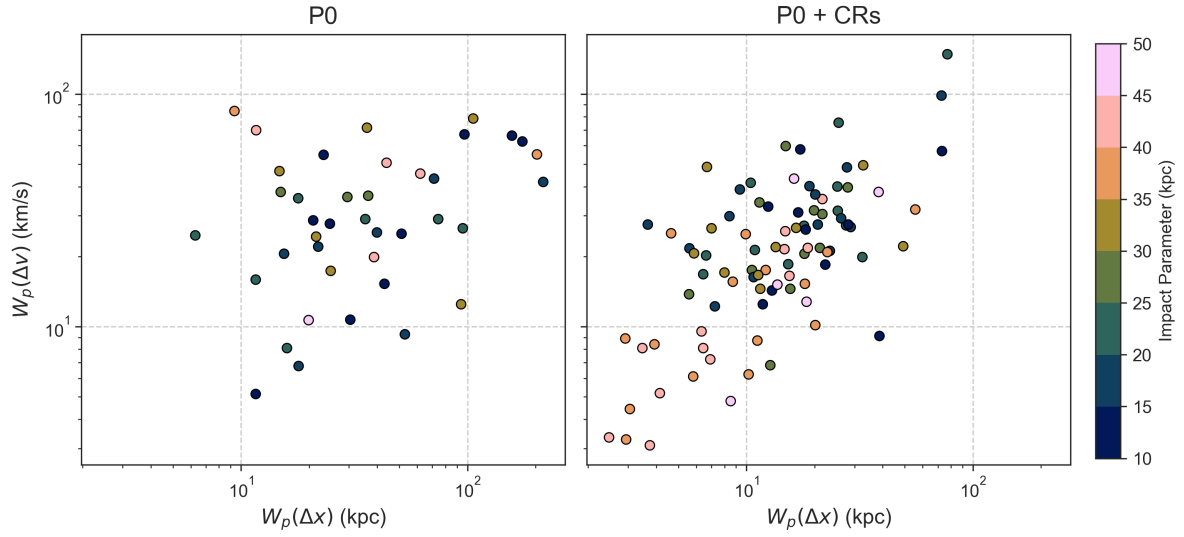


Figure 4.12 The Wasserstein distance between O VI and Si III line-of-sight velocities and positions along the sightline. The color of the points indicates the impact parameter of the sightline. P0+CR has a clear relationship between the kinematic and spatial alignment of O VI and Si III absorbing gas. In contrast, O VI and Si III gas in P0 are less likely to be kinematically or spatially aligned.

ties than the warm phase, inversely proportional to the temperature contrast, $\rho_{\text{cold}}/\rho_{\text{hot}} = T_{\text{hot}}/T_{\text{cold}}$. As a natural consequence, cool gas forms small cloudlets. In this case, the majority of cool CGM gas will be accelerating towards the galaxy. Even if cool gas condenses from the hot phase, initially sharing its velocity, the common velocity phase will be short-lived as cool droplets will accelerate towards the galaxy with a characteristic timescale set by the gravitational freefall time, t_{ff} . For a MW-sized galaxy, this timescale is roughly 700 Myr. Therefore, in a thermal-pressure-supported CGM, one would expect a large fraction of cool gas absorbers to have very large velocity offsets from warm absorbers.

In a cosmic-ray-pressure-supported CGM, the cool gas phase has significantly lower densities and is supported against gravity by the cosmic-ray pressure gradient. Rather than fragmenting into many dense cloudlets, cool gas forms a large (tens of kpc), low density cloud with a velocity distribution similar to that of the warm phase. This naturally leads to a kinematic alignment between the cool and warm phases.

4.4.2 *Uncertainty in Modeling cosmic rays*

Despite significant recent theoretical and computational advances in cosmic-ray hydrodynamics (e.g. [Jiang and Oh, 2017](#); [Thomas and Pfrommer, 2019](#); [Hopkins et al., 2021c](#)), there is no consensus as to which existing cosmic-ray transport models (if any) realistically model the true behavior of cosmic rays. Several recent studies have demonstrated that different cosmic-ray hydrodynamics models can change the predicted properties of the galactic disk, galactic outflows, and CGM structure (e.g., [Ruszkowski et al., 2017](#); [Butsky and Quinn, 2018](#); [Buck et al., 2020](#); [Hopkins et al., 2021b](#)). Therefore, we expect that many of the quantitative details in this chapter, for example the exact ion column densities, the radial extent of the cosmic-ray pressure dominated region, or the details of the gas phase distribution of our simulation will likely change with improved models for cosmic-ray transport. However, the *qualitative* predictions in this chapter, in particular the predictions for the kinematic link between cool and warm gas phases, are robust for

any CGM model that contains significant non-thermal pressure support.

4.4.3 *The Relationship Between Kinematic and Spatial Alignment*

With synthetic spectroscopy, we have access to both realistic absorption spectra and the exact state of the gas from which the absorption features are generated. Using this approach allows us to demonstrate that kinematic alignment between cool and warm gas absorbers does not necessarily reflect physically associated gas clouds.

In our spectra, we see three physical explanations of kinematic alignment. 1) Some kinematic alignment is happenstance and comes from physically unrelated gas clouds. This physically unrelated kinematic alignment accounts for 37.5% of O VI-Si III absorbers in P0 and only 5% of O VI-Si III aligned absorbers in P0+CR. 2) Some kinematic alignment traces multiphase gas clouds – either a cool cloud embedded in a warm cloud, or an intermediate temperature cloud that produces sufficient cool and warm components. These types of clouds tend to produce small kinematic offsets and comprise 62.5% of aligned O VI-Si III absorbers in P0 and 38% percent of aligned O VI-Si III absorbers in P0+CR. It is worth mentioning that we also see instances of O VI and Si III absorbers that come from the same physical cloud but that are kinematically misaligned. 3) The last physical explanation for kinematic alignment is when both cool and warm gas are tracing the large scale rotation of the CGM (for example, see the right panel of [Figure 4.7](#)). In this case, the warm gas envelops the inner cool gas, and This type of physical alignment produces slightly larger velocity offsets than clouds that are both kinematically and physically aligned. Roughly 67% of kinematic alignment in P0+CR falls into this category but is not present in P0.

4.5 Summary

In this chapter, we use synthetic spectroscopy to investigate the role of cosmic-ray pressure in setting the observed kinematics relationship between cool and warm gas in the

CGM of low-redshift L^* galaxies. We simulate two Milky Way-sized galaxies, one without cosmic rays (P0), and one with cosmic-ray supernova feedback (P0+CR). By a redshift of $z = 0.25$, these two galaxies, which started from the same initial conditions, have evolved fundamentally different CGM properties.

P0 has a hot, thermal-pressure-supported CGM that is pierced by cool cloudlets in the inner CGM as well as an accreting stream from a recent merger event. By contrast, the inner CGM of P0+CR is supported against gravity by cosmic-ray pressure and filled with cool, low density gas.

We systematically probe the inner CGM of both galaxies with synthetic spectra and compare the extracted column densities, Doppler- b parameters, and velocity centroids directly against COS-Halos data. We focus our analysis on two ions: O VI, which traces warm $\sim 10^{5.5}$ K gas, and Si III, which traces cool $\sim 10^{4.2}$ K gas.

Our results are summarized below.

1. **O VI Doppler- b parameters.** The cosmic-ray-pressure-supported CGM results in more narrow (20-30 km/s) O VI Doppler- b parameters than the thermal-pressure-supported CGM. This is due to the relatively cooler temperatures of O VI-bearing gas in the P0+CR simulation. In P0+CR, O VI absorption peaks at $10^{5.5}$ K, while in P0, O VI traces both warm and hot gas with temperatures of $10^{5.5-5.9}$ K (Figure 4.5). While P0+CR can explain the observed overabundance of O VI Doppler- b parameters between 20-30 km/s, neither simulation offers a statistically good fit to the observed data. Notably, neither simulation reproduced the observed large O VI Doppler- b parameters > 60 km/s (Figure 4.8).
2. **Si III Doppler- b parameters.** In both simulations, Si III traces gas peaked at $10^{4.2}$ K (Figure 4.5). In P0, cool gas tends to form small cloudlets with narrow Doppler- b parameters (Figure 4.9). In contrast, the lower density cool gas in P0+CR fills the inner CGM, resulting in large column densities and broader absorption features of Si III. While the distribution of Si III Doppler- b parameters in P0+CR is in better agreement with

observations, it still underpredicts the observed abundance broad Si III features.

3. **Kinematic alignment of low and high ions.** There is significantly more kinematic alignment between O VI and Si III ($|v_{\text{O VI}} - v_{\text{Si III}}| < 35\text{km/s}$) in P0+CR (Figure 4.10). Out of 125 O VI absorbers in P0+CR, 94% are from a sightline that also detects Si III absorption. Of these sightlines, we find that 90% of O VI absorbers are kinematically aligned with a Si III absorber. In contrast, only 41% of the 163 O VI absorbers from P0 come from sightlines that also detect Si III. Of all sightlines that contain both, O VI and Si III absorbers in P0, we find that 60% of O VI absorbers are kinematically aligned with a Si III absorber. We demonstrate that in a cosmic-ray-pressure-supported halo, in which low-entropy cool gas is supported against gravity, the velocity distribution of cool and warm gas is similar, leading to a natural alignment between multiphase ions. This contrasts the kinematics of the thermally supported CGM of P0, in which cool gas is denser and is more likely to have an inward radial velocity than the warm gas (Figure 4.11).
4. **Relationship between kinematic and physical alignment.** We demonstrate that kinematic alignment does not necessarily imply that the absorbers trace physically related clouds. Our simulations predict that in a cosmic-ray-pressure-supported CGM, there is a relationship between the kinematic offset between O VI and Si III absorbers and their physical separation along the line-of-sight (Figure 4.12).

4.6 Chapter Appendix: Cosmic Rays in ChaNGa

4.6.1 Equations of Motion

In the Lagrangian approximation, a fluid is discretized by some number of massive particles. Traditionally, each particle has a mass, velocity, and specific energy, and these quantities are evolved from their initial conditions following conservation equations. We model cosmic rays as an additional “fluid” such that each particle also contains a specific

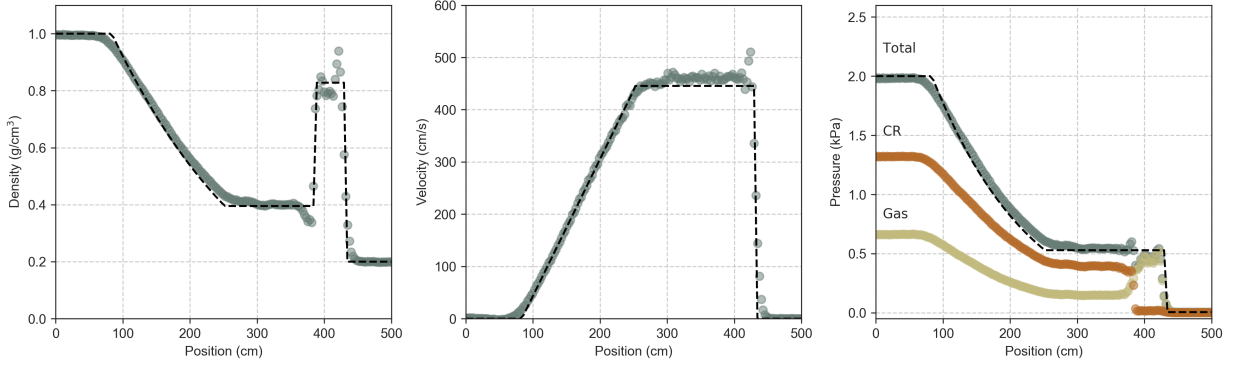


Figure 4.13 The SOD shocktube. The state of the gas density (left), velocity (middle), and pressure (right) at $t = 0.31$ seconds. The dashed line shows the analytic solution for the gas density, velocity, and total pressure, which is a sum of gas and cosmic-ray pressures. The shocktube was initialized with a contact discontinuity at $x = 250$ cm at $t = 0$. To the left of the discontinuity, the gas density, pressure, and cosmic-ray pressure are initialized to $\rho = 1\text{g/cm}^3$, $P_g = 2/3$ kPa, $P_c = 4/3$ kPa. To the right of the discontinuity, the gas density, pressure, and cosmic-ray pressure are initialized to $\rho = 0.2\text{g/cm}^3$, $P_g = 267.2$ Pa, $P_c = 267.2$ Pa. The velocity is initialized to zero everywhere.

cosmic-ray energy. The evolution of these particles is governed by the equations for the conservation of mass, momentum, thermal energy, and cosmic-ray energy below.

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{v} \quad (4.1)$$

$$\frac{\rho D\mathbf{v}}{Dt} + \nabla(P_{tot}) = \mathbf{g} \quad (4.2)$$

$$\frac{\rho Du_g}{Dt} + P_g \nabla \cdot \mathbf{v} = \Lambda_g - \Gamma_g \quad (4.3)$$

$$\frac{\rho Du_c}{Dt} + P_c \nabla \cdot \mathbf{v} = \nabla \cdot (\kappa_c \nabla u_c) + \Lambda_c. \quad (4.4)$$

We define $\rho, \mathbf{v}, u_g$ to be the gas density, velocity, and specific internal energy (energy per mass). Similarly, u_c is the cosmic-ray specific internal energy. The gas and cosmic-ray

pressures are related to the internal energy by the adiabatic index, $P_g = (\gamma - 1)\rho u_g$ and $P_c = (\gamma_c - 1)\rho u_c$, where $\gamma = 5/3$ and $\gamma_c = 4/3$. The total pressure of the system given by the sum of thermal and cosmic-ray pressures, $P_{tot} = P_g + P_c$. $\mathbf{g}$ is the gravitational force. Λ and Γ are shorthand representations of the total source and sink terms of gas and CR energy. κ_c is the constant cosmic-ray diffusion coefficient. Lastly, t represents time, and $D/Dt = \partial/\partial t + \mathbf{v} \cdot \nabla$ denotes the convective derivative.

In the SPH approach, the above equations become ordinary differential equations for the motion, internal energy, and cosmic-ray energy of each particle as follows:

$$\frac{d\mathbf{v}_i}{dt} = - \sum_j m_j \left(\frac{P_{tot,i} + P_{tot,j}}{\rho_i \rho_j} + \Pi_{ij} \right) \nabla_i \bar{W}_{ij} \quad (4.5)$$

$$\frac{du_{g,i}}{dt} = - \sum_j m_j \left(\frac{P_{g,i} + P_{g,j}}{\rho_i \rho_j} + \Pi_{ij} \right) \nabla_i \bar{W}_{ij} \quad (4.6)$$

$$\frac{du_{c,i}}{dt} = - \sum_j m_j \left(\frac{P_{c,i} + P_{c,j}}{\rho_i \rho_j} + \Pi_{ij} \right) \nabla_i \bar{W}_{ij}. \quad (4.7)$$

In the equations above, m is the mass of an individual particle, Π is an artificial viscosity term and W is the general SPH kernel function. The subscript i indicates a single particle, and $\sum_j$ is the sum of properties over that particle's nearest neighbors. Lastly, we model the diffusion of cosmic-ray energy as

$$\frac{du_{c,i}}{dt} \Big|_{\text{Diff}} = - \sum_j m_j \frac{\kappa_c (u_{c,i} - u_{c,j}) (\mathbf{r}_{ij} \cdot \nabla_i \bar{W}_{ij})}{\frac{1}{2}(\rho_i + \rho_j) \mathbf{r}_{ij}^2}, \quad (4.8)$$

where $\mathbf{r}_{ij}$ is the distance between neighboring particles. In the following section, we test the performance of advection and diffusion of the newly added cosmic-ray fluid against analytic solutions.

4.6.2 Tests of CR performance

We demonstrate the advection of the thermal and cosmic-ray fluids using a modified SOD shocktube test (Sod, 1978; Pfrommer et al., 2006). In the initial conditions, 24,000 particles are arranged in a long, narrow three-dimensional glass (Backus, 2017) with dimensions $100 \times 100 \times 1000$ cm and periodic boundary conditions. Smoothing is done with an M_4 cubic spline kernel using 64 neighboring particles. The initial discontinuity is placed at $z = 250$ cm. To the left of the discontinuity, the gas density, pressure, and cosmic-ray pressure are initialized to $\rho = 1 \text{ g/cm}^3$, $P_g = 2/3 \text{ kPa}$, $P_c = 4/3 \text{ kPa}$. To the right of the discontinuity, the gas density, pressure, and cosmic-ray pressure are initialized to $\rho = 0.2 \text{ g/cm}^3$, $P_g = 267.2 \text{ Pa}$, $P_c = 267.2 \text{ Pa}$. The velocity is initialized to zero everywhere.

Figure 4.13 shows the evolved state of the modified SOD shocktube after $t = 0.31$ seconds. The scattered points show the gas properties, averaged in spatial bins with $\delta x = 5$ cm. The black dashed shows the analytic solution for the gas density, velocity, and total pressure. The simulated shocktube follows the analytic predictions well. The slight noise to the right of the contact discontinuity (~ 400 cm), is likely due to resolution-related particle noise.

In this chapter, we model cosmic-ray transport as isotropic diffusion with a constant diffusion coefficient, κ_c . We test the implementation of cosmic-ray diffusion by measuring the evolution of an initial overdensity of cosmic-ray energy. We initialize 20,000 particles as an SPH glass with dimensions $0.2 \times 0.2 \times 1$ kpc. The distribution of cosmic-ray energy density is initialized as:

$$u_c = u_{c,0} e^{-r^2/2D}, \quad (4.9)$$

where $r = x^2 + y^2$ is the distance from the center. We choose constants $u_{c,0} = 0.9$, $D = 0.002$ and a diffusion coefficient of $\kappa_c = 0.05 \text{ kpc}^2/\text{Myr}$. In order to only test cosmic-ray diffusion in the absence of advection, we turn off gas particle motions.

Figure 4.14 shows the evolution of an initial Gaussian overdensity of cosmic-ray energy assuming diffusion as the only form of cosmic-ray transport (neglecting any advection due

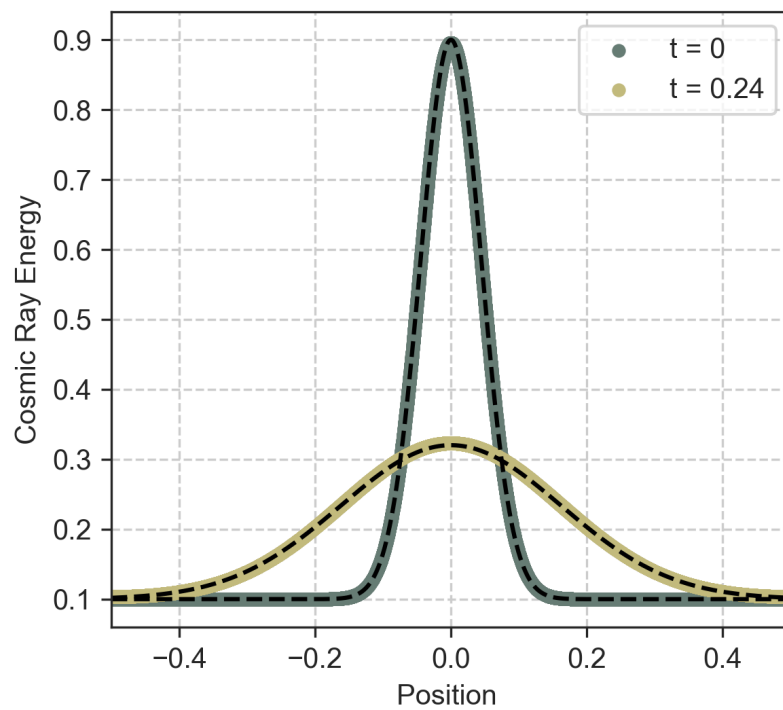


Figure 4.14 Demonstration of cosmic-ray diffusion. An initial Gaussian overdensity of cosmic-ray energy decays overtime as cosmic rays diffuse down their energy gradient with a constant diffusion coefficient. The y-axis shows radially-averaged values of the cosmic-ray energy as a function of position, $r = x^2 + y^2$. The black dashed lines show analytic solutions for $t = 0$ and $t = 0.24$ Myr.

to gas motion). Our implementation follows the expected analytic solution after $t = 0.24$ Myr.

Chapter 5

ULTRAVIOLET SIGNATURES OF THE MULTIPHASE INTRACLUSTER AND CIRCUMGALACTIC MEDIA IN THE ROMULUSC SIMULATION

Portions of this chapter were originally published in collaboration with Joseph Burchett, Daisuke Nagai, Michael Tremmel, Thomas R. Quinn, and Jessica Werk in the December 2019 edition of The Monthly Notices of the Royal Astronomical Society (Butsky et al., 2019, MNRAS, Vol. 490, 3; 2019 ©Monthly Notices of the Royal Astronomical Society, DOI: 10.1093/mnras/stz2859), and are reproduced below with the permission of the Royal Astronomical Society.

Summary

Quasar absorption-line studies in the ultraviolet (UV) can uniquely probe the nature of the multiphase cool-warm ($10^4 < T < 10^6 \text{K}$) gas in and around galaxy clusters, promising to provide unprecedented insights into 1) interactions between the circumgalactic medium (CGM) associated with infalling galaxies and the hot ($T > 10^6 \text{K}$) X-ray emitting intracluster medium (ICM), 2) the stripping of metal-rich gas from the CGM, and 3) a multiphase structure of the ICM with a wide range of temperatures and metallicities. In this chapter, we present results from a high-resolution simulation of a $\sim 10^{14} M_{\odot}$ galaxy cluster to study the physical properties and observable signatures of this cool-warm gas in galaxy clusters. We show that the ICM becomes increasingly multiphased at large radii, with the cool-warm gas becoming dominant in cluster outskirts. The diffuse cool-warm gas also exhibits a wider range of metallicity than the hot X-ray emitting gas. We make predictions for the covering fractions of key absorption-line tracers, both in the ICM and in the CGM of cluster galaxies, typically observed with the Cosmic Origins Spectrograph aboard the Hubble Space Telescope (HST). We further extract synthetic spectra to demonstrate the feasibility of detecting and characterizing the thermal, kinematic, and chemical composition of the cool-warm gas using H I, O VI, and C IV lines, and we predict an enhanced population of broad Ly α absorbers tracing the warm gas. Lastly, we discuss future prospects of probing the multiphase structure of the ICM beyond HST.

5.1 Introduction

Galaxy clusters form ecosystems on the largest mass and spatial scales and serve as unparalleled laboratories for galaxy evolution and extreme magnetohydrodynamic phenomena. Clusters are marked by hot, X-ray emitting, intracluster media (ICM) that serve as records of cluster dynamics and chemical enrichment history. All infalling galaxies are subject to the punishing conditions of the ICM throughout their journey, while individual galaxies are embedded in diffuse, multiphase circumgalactic media (CGM) that mediate the ‘baryon cycle’, consisting of galactic outflows and accretions of gas that ultimately dictate star formation activity and the transport of heavy elements (Tumlinson et al., 2017b). Thus, it is the interplay between the ICM and CGM that manifests in many aspects of cluster gas physics, and understanding the complex thermodynamic and chemical structures of the ICM is critical to understanding the evolution of cluster galaxies (see Kravtsov and Borgani, 2012; Walker et al., 2019, for reviews).

Galaxy clusters are also sites of extraordinary galaxy transformation. On average, cluster galaxies are more likely to be quenched and to have less gas in their interstellar medium (ISM) (Davies and Lewis, 1973; Dressler, 1980; Sandage et al., 1985) than isolated field galaxies. There are several ways in which the cluster environment may contribute to this gas shortage, although the dominant mechanisms are still debated (Fraser-McKelvie et al., 2018): a combination of tidal stripping by the massive center galaxy (Moore et al., 1996; Lake et al., 1998; Wang et al., 2004), high-speed fly-bys, and mergers with other galaxies (Toomre and Toomre, 1972; White and Rees, 1978; Roediger et al., 2015) or ram-pressure stripping from the ICM (Gunn and Gott, 1972; Fumagalli et al., 2014). This cool, metal-rich, stripped gas contributes to the clumpy morphology in cluster outskirts before ultimately mixing with the ICM (Tonnesen et al., 2007; Jáchym et al., 2014). Recent studies have also shown that the CGM of cluster galaxies is quite deficient relative their more isolated counterparts (Yoon and Putman, 2013; Burchett et al., 2018), although the samples remain small and it is less clear where this transformation occurs. If galaxies’ CGM are

stripped early upon infall, this may lead to a much slower quenching process than rapid stripping of the interstellar medium (ISM) (Zinger et al., 2018).

To date, X-ray and microwave measurements of the thermodynamic and metallicity profiles of the ICM have been critical towards determining the physics governing structure formation (Walker et al., 2019; Mroczkowski et al., 2019, for reviews), chemical enrichment of the ICM (Werner et al., 2013; Urban et al., 2017; Mernier et al., 2018, for a review), and cosmological models (Allen et al., 2011; Pratt et al., 2019, for reviews). Modern cosmological simulations of galaxy cluster formation predict that the outskirts of galaxy clusters is a cosmic-melting pot, where the structure formation processes, such as mergers and gas accretion (Lau et al., 2015; Zinger et al., 2016), generate clumpy (Nagai and Lau, 2011; Zhuravleva et al., 2013; Vazza et al., 2013; Rasia et al., 2014) and turbulent (Lau et al., 2009; Nagai et al., 2013; Nelson et al., 2014) hot X-ray emitting ICM in the outskirts of galaxy clusters. In this chapter, we explore an alternative approach to studying the ICM and cluster galaxy CGM: probing the diffuse, cool-warm, gas that is virtually invisible to the observational techniques described above, using using ultraviolet (UV) absorption-line spectroscopy.

Rest-frame UV absorption-line spectroscopy studies have revolutionized our understanding of how the CGM influences and, conversely, is influenced by relatively isolated galaxies (e.g. Tumlinson et al., 2011; Tripp et al., 2011b; Stocke et al., 2013; Werk et al., 2013; Bordoloi et al., 2014). Our picture of the CGM has transformed from that of a quiescent remnant of galaxy formation, to one of a turbulent, multiphase medium with a rich ionization and kinematic structure that plays a key role in galaxy evolution (Tumlinson et al., 2017b). Similarly, UV observations of the cool-warm ICM have the potential to provide unprecedented insights to the thermodynamic, kinematic, and chemical properties of galaxy clusters. Directly observing the stripping of the CGM of infalling galaxies will place stringent constraints on 1) the dominant quenching mechanisms in high density environments, 2) the conditions and timescales that govern CGM stripping through interactions with the ICM, 3) the distribution of metals across all phases of the ICM, and

4) the role of feedback on the thermodynamic and chemical properties of the CGM. Additionally, UV-derived column density measurements and photoionization modeling can constrain the baryon fraction in the hot ($T \sim 10^6\text{K}$) X-ray emitting ICM to complement those estimates made using X-ray and microwave observations (Burchett et al., 2018; Ge et al., 2016; Wang and Walker, 2014).

Several groups have successfully pioneered UV observations of the cool-warm gas in galaxy groups and clusters using *HST*/COS (e.g., Yoon et al., 2012; Johnson et al., 2015; Muzahid et al., 2017; Pointon et al., 2017; Yoon and Putman, 2017; Burchett et al., 2018; Nielsen et al., 2018; Stocke et al., 2019), although the large samples of UV sightlines that exist for CGM samples have not yet been obtained systematically probing cluster environments. Next-generation UV telescopes (e.g., *LUVOIR*; Bolcar et al., 2017) have the potential to increase both the number of observable background sources (e.g., quasars, or QSOs, and galaxies) and the sensitivity to lower column densities of cool-warm gas by orders of magnitude. We return to compare current and future capabilities later in Section 5.6.

In this chapter, we characterize the multiphase ICM using a high resolution simulation of a $\sim 10^{14}M_{\odot}$ cluster and make testable predictions for its observable properties, both with *HST*-COS and with future instruments. This chapter is organized as follows. In §5.2, we describe our methods, the ROMULUSC simulation of a galaxy cluster, and the tools integral to our analysis. In §5.3, we present evidence for a multiphase, metal-enriched ICM. In §5.4, we discuss the properties of the CGM of cluster galaxies. In §5.5, we demonstrate how observable signatures trace the physical conditions of the gas using synthetic spectra. In §5.6, we discuss the current and future prospects of observing the cool-warm gas in galaxy clusters. We summarize our results in §5.7.

Throughout this chapter, we divide the gas into four distinct phases: *cold* ($T < 10^4\text{K}$), *cool* ($10^4 < T < 10^5\text{K}$), *warm* ($10^5 < T < 10^6\text{K}$) and *hot* ($T > 10^6\text{K}$). This convention differs somewhat from that adopted elsewhere in the literature (e.g., Cen and Ostriker, 1999), as we simply refer to the $10^5 < T < 10^6\text{K}$ phase as ‘warm’ rather than ‘warm-hot’. In the context of galaxy clusters, which contain an abundance of $T > 10^6\text{K}$ gas that is often sim-

ply deemed ‘hot’ in the literature, we feel that our nomenclature avoids ambiguity when discussing relationships between the phases. Thus, in this chapter, we focus primarily on gas at cool-warm temperatures.

5.2 Methods

5.2.1 *The RomulusC Simulation*

ROMULUSC (Tremmel et al., 2019) is a hydrodynamic cosmological zoom-in simulation of a $10^{14} M_{\odot}$ galaxy cluster run with the new Tree+Smoothed Particle Hydrodynamics (SPH) code, CHANGA (Menon et al., 2015). The zoom-in region is a Lagrangian region derived from the highest mass halo selected from a 50 Mpc uniform volume, dark matter-only simulation. ROMULUSC is among the highest resolution hydrodynamic cosmological simulations of a galaxy cluster run to date, with a Plummer equivalent gravitational force resolution of 250 pc (a 350 pc spline kernel is used), a maximum SPH resolution of 70 pc, and gas and dark matter mass resolutions of 2.12×10^5 and $3.39 \times 10^5 M_{\odot}$ respectively. At this resolution, ROMULUSC is one of only two cluster cosmological simulations currently in production that is capable of resolving the multiphase structure of gas in the ICM (see also Nelson et al. (2019); Pillepich et al. (2019)). Lower mass halos and galaxies, including their interaction with the ICM, are also followed with greater detail than ever before. ROMULUSC resolves halos as small as $3 \times 10^9 M_{\odot}$ with at least 10^4 particles (spatial resolution sufficient for resolving ram-pressure stripping (Roediger et al., 2015)). As the CGM and ISM of infalling galaxies also contributes to the temperature, density, and metallicity distribution of gas within the ICM, ROMULUSC is able to provide a more complete picture of the ICM structure than other cluster simulations with more typical resolutions (often lower by factors of 10 or more in both mass and spatial resolution, see Table 1 in Tremmel et al. (2019)).

CHANGA uses sub-grid physics modules for star formation, stellar feedback, the UV background with self-shielding (Haardt and Madau, 2012), and low temperature metal

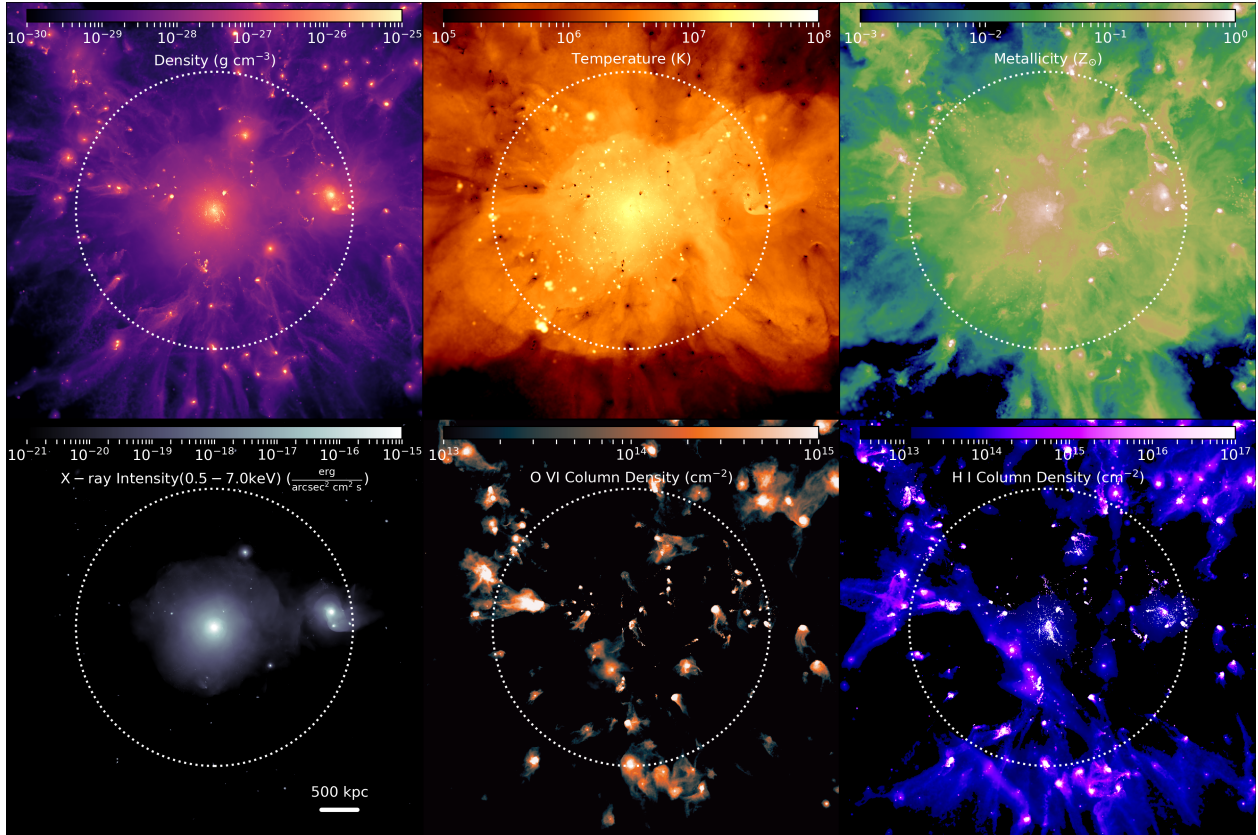


Figure 5.1 A 5 x 5 Mpc snapshot (in physical units) of the ROMULUSC simulation at $z = 0.31$. The dashed circles show the extent of $2 R_{200}$. *Top row:* The density-weighted projections of gas density, temperature, and metallicity. *Bottom row:* The integrated X-ray intensity, O VI column density, and H I column density. The color scaling of the images in the bottom row is roughly consistent with the sensitivity of existing instruments. Compared to X-ray emission, the structure probed by UV absorption studies (O VI and H I column densities) better traces cluster outskirts and small-scale structure within R_{200} .

cooling that have been previously implemented and tested in GASOLINE (Wadsley et al., 2004, 2008, 2017). Supermassive black hole (SMBH) formation, dynamics, growth, and feedback are also included (Tremmel et al., 2015, 2017). Importantly, the simulation includes an updated implementation of turbulent diffusion (Wadsley et al., 2017), shown to be important for producing realistic entropy profiles in galaxy cluster cores (Wadsley et al., 2008) and metal distributions in galaxies (Shen et al., 2010). The combination of a gradient-based shock detector, time-dependent artificial viscosity, and an on-the-fly time-step adjustment system allows for a more realistic treatment of both weak and strong shocks (Wadsley et al., 2017). Both the thermal and turbulent diffusion of metals is accounted for following Shen et al. (2010).

Feedback from both stars and SMBHs is followed throughout the simulation. As in previous work for runs at this resolution (Stinson et al., 2006), star formation is assumed to occur with an efficiency of 15% in dense ($> 0.2 \text{ cm}^{-3}$), cold ($T < 10^4 \text{ K}$) gas on a characteristic timescale of 10^6 years. Supernova (SN) feedback follows the “blastwave” approach (Stinson et al., 2006), with each SN thermally coupling 0.75×10^{51} erg to the surrounding gas.

SMBHs are seeded based on local gas properties, assumed to form in very high density ($\rho_{\text{gas}} > 3 m_{\text{H}}/\text{cm}^3$, where m_{H} is the mass of a hydrogen atom), low metallicity ($Z < 3 \times 10^{-4} Z_{\odot}$) regions, which are self-consistently predicted to occur in the centers of low mass ($10^8 - 10^{10} M_{\odot}$) halos in the early Universe ($z > 5$). SMBHs grow through both mergers and accretion of gas via a modified Bondi-Hoyle prescription that accounts for both additional support from angular momentum (Tremmel et al., 2017) and the unresolved multiphase structure in the ISM (Booth and Schaye, 2009). A small fraction of the mass-energy of accreted material (0.2%) is transferred to nearby gas via thermal feedback and naturally results in large-scale outflows and has been shown to successfully regulate, and sometimes fully quench, star formation in massive galaxies (Pontzen et al., 2017; Tremmel et al., 2017, 2019).

The sub-grid models used here were derived from an extensive parameter calibration

program, ensuring that the ROMULUS simulations create galaxies with realistic stellar masses, SMBH masses, gas content, and angular momentum (see Tremmel et al., 2017, for more details). Importantly, the sub-grid physics used in the ROMULUS simulations is tuned to reproduce realistic galaxy properties up to Milky Way-mass halos. Despite this, the simulation successfully predicts realistic SMBH and stellar masses for halos up to $2 \times 10^{13} M_{\odot}$. No effort was made to optimize the simulation to produce a realistic galaxy cluster, so all of the results from ROMULUSC are predictions from the simulation.

Note that ROMULUSC does not include metal-line cooling for temperatures above 10^4 K. This is one of the limitations of this simulation, as metal lines are an important coolant for warm-hot gas in the ICM. More specifically, at the gas temperatures ($T \sim 10^5$ K) and metallicities ($\sim 0.1 - 0.3 Z_{\odot}$) most relevant in this chapter, the extragalactic UV background dominates the heating/cooling balance, so the lack of metal-line cooling will result in cooling times that are a factor of $\sim 3 - 5$ too long (Shen et al., 2010). Using cooling time estimates (Sanchez et al., 2018) and results from lower-mass simulations run with varying cooling prescriptions (Christensen et al., 2014), we estimate an uncertainty in the column densities of ions at the peak of the cooling curve (such as O VI) to be about 0.3 dex. Furthermore, cooling in 10^{4-5} K gas is dominated by the He Ly α line, and primordial cooling does a reasonably good job of estimating metal-line cooling (Hopkins et al., 2018). We do include metal-line cooling for gas below 10^4 K, where contribution from metals becomes especially important.

At the cluster outskirts, where much of this chapter is focused, the cooling times are already quite long, even if metal cooling was accounted for, hence the inclusion of metal line cooling does not affect accretion of gas onto massive halos (van de Voort et al., 2011). Closer to the BCG (and infalling cluster galaxies), the gas is just as sensitive to feedback physics as to the cooling model used (van de Voort et al., 2011). It is in this regime where the halo gas is strongly coupled to the ISM via feedback processes and it is not possible to separate the effects of high temperature cooling from feedback (and, therefore, ISM physics). Therefore, the robustness of the gas properties in the simulation is difficult to

estimate.

At $z = 0$, the cluster is experiencing an on-going head-on merger with 1:8 mass ratio. The infalling halo is still outside R_{200} at $z = 0.3$ and begins to have an effect on the state of the ICM in the inner cluster at $z \lesssim 0.2$. The merger results in the destruction of the cool-core of the cluster (Chadayammuri et al., in prep). For most of the following analysis, in order to avoid the effects of a transient event, we focus on the state of the ICM when the cluster is still relaxed at $z = 0.31$, though we note that this is a higher redshift than the available observations we use for comparison. The virial radius¹ of the cluster at this redshift is 810 kpc. The zoom-in Lagrangian region of ROMULUSC extends to ~ 3 Mpc from cluster center at $z = 0.3$. Since the physical state of the gas near the outskirts of the Lagrangian region is subject to numerical effects, we limit our analysis to within this region. Hence, we do not expect this to affect any of our conclusions.

5.2.2 Ion Fields and Synthetic Absorption Spectra

We analyze our simulation data with a combination of YT (Turk et al., 2011), TRIDENT (Hummels et al., 2017), PYNBODY (Pontzen et al., 2013b), and TANGOS (Pontzen and Tremmel, 2018). In this section, we describe the process of transforming the physical quantities in simulation outputs to observable quantities and, ultimately, synthetic spectra.

Keeping track of individual atomic elements throughout the simulation is computationally expensive. Although some zoom-in simulations of low-mass galaxies have successfully tracked over 11 individual elements (e.g., Oppenheimer and Schaye, 2013; Emmerick et al., 2019), such detailed tracking is computationally infeasible, with current technologies, at the cluster scale. Instead, ROMULUSC explicitly tracks hydrogen, oxygen, and iron. The metallicity used here is a weighted sum of oxygen and iron based on solar abundance ratios (Asplund et al., 2009).

¹While a number of ‘virial radius’ definitions exist in the literature, we generally adopt $R_{200} = R_{200c}$, the radius within which the average density is 200x the critical density of the Universe. Other definitions may appear in the literature, and we provide the following the approximate scaling relation: $R_{500c} : R_{200c} : R_{200m} = 1 : 1.4 : 3$.

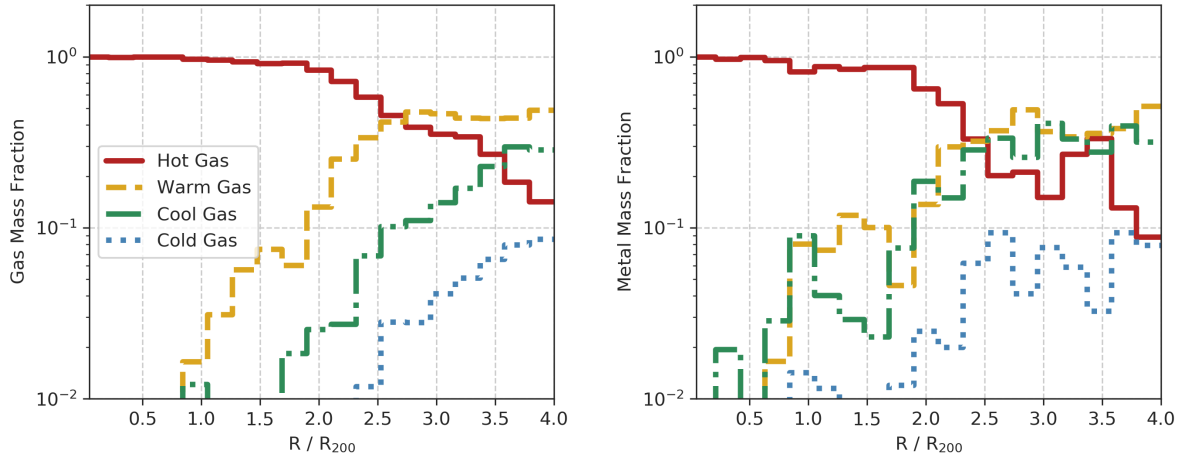


Figure 5.2 The total gas mass (left) and metal mass (right) fractions in the cold ($T < 10^4\text{K}$), cool ($10^4 < T < 10^5\text{K}$), warm ($10^5 < T < 10^6\text{K}$), and hot ($T > 10^6\text{K}$) gas phases as a function of radial distance from the cluster center in the ROMULUSC simulation at $z = 0.31$. Although hot gas dominates within R_{200} of the cluster, warm and cool gas comprise the majority of the gas mass at the cluster outskirts. Additionally, the cool and warm gas phases hold the majority of metals in the cluster outskirts.

From the metallicity, we calculate specific ion abundances and their ionization states using TRIDENT², the first open-source, standardized tool for determining ion abundances and generating synthetic spectra from simulations. TRIDENT derives the abundance of each element in the simulation, n_X , by using the local metallicity and assuming a solar abundance by number³. Then, the collisional ionization and photoionization of each element is determined from the local gas temperature, density, and metallicity, using an extensive pre-tabulated look-up table generated by CLOUDY (Ferland et al., 2013). The photoionization is calculated assuming an extragalactic UV background described in Haardt and Madau (2012). Using this method, we can determine the mass and number density of any ion throughout the simulation.

²Trident is built as an extension of the widely-used analysis tool, YT (Turk et al., 2011) and is compatible with most astrophysical simulation codes.

³ $n_X = n_H Z (n_X/n_H)_\odot$, where n_H and n_X are the number densities of Hydrogen and any element, X , Z is the metallicity, and the subscript $\odot$ indicates the solar ratio

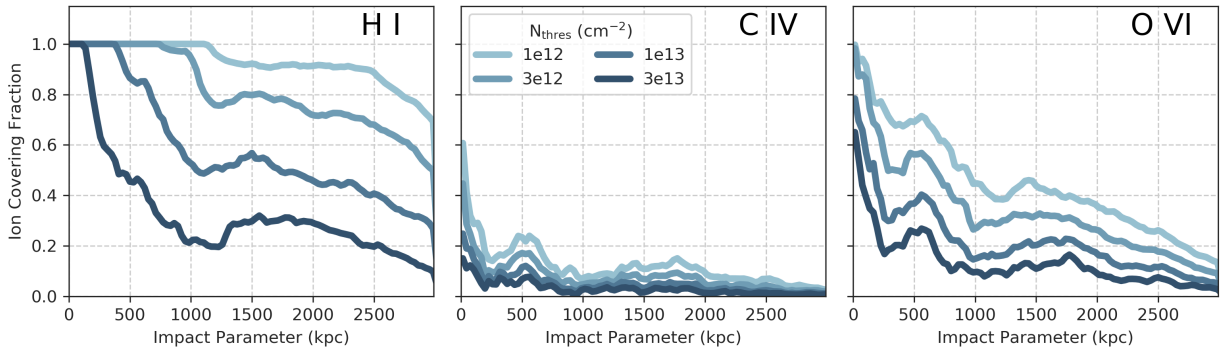


Figure 5.3 The covering fraction of H I (*left panel*), C IV (*middle panel*), and O VI (*right panel*) as a function of the impact parameter measured from the cluster center at $z = 0.31$. Each line represents the covering fraction for different observational column density thresholds. With existing observational thresholds of *HST/COS* (10^{13}cm^{-2} for H I, $10^{13.1}\text{cm}^{-2}$ for C IV and $10^{13.3}\text{cm}^{-2}$ for O VI), we can expect covering fractions above 0.5 and 0.15 for H I and O VI respectively within 1.5 Mpc of the cluster center. For reference, the R_{200} of the cluster at this redshift is 810 kpc. At existing observational column density sensitivities, the expected covering fraction for C IV, is below 0.1. Improving the observational threshold by an order of magnitude would result in roughly a 2x increase in the covering fraction of O VI.

We note that we do not explicitly include photoionization from local sources (such as nearby galaxies or AGN). This could produce a significant variation in the photionization and can have a large impact on ion abundances (Oppenheimer et al., 2018). The uncertainty in the assumed UV background is the largest source of uncertainty in the relative ionic abundances that we derive. For a detailed account of the impact of a varying UVB slope on ion abundances, see the appendix of Werk et al. (2014).

To compute column density profiles, we first generate column density projections centered on the cluster (or individual cluster galaxy) along each axis. From these projections, we gather the distribution of column densities as a function of impact parameter. The default projection depth used to calculate column densities is the line-of-sight depth of the entire simulation. We show how these integrated column densities relate to detectable spectral features in Sections 5.5 and 5.6. To convert these column density profiles to covering fractions, we count the fraction of “sightlines” in each radial bin that is above some threshold column density. We adopt column density thresholds of 10^{13} , $10^{13.1}$, $10^{13.3}$ cm^{-2} for H I, C IV, and O VI respectively, commensurate with the data quality routinely obtained in HST-COS programs.

We also use TRIDENT to generate synthetic spectra, allowing for direct comparison with existing observations. To generate a spectrum, we first designate an arbitrary sightline through the simulation volume, analogous to probing a foreground galaxy along the line-of-sight to a QSO. The sightline, l , connects points a and b in a simulation such that $\vec{l} = \vec{r}_b - \vec{r}_a \sum_{i=0}^n d\vec{l}_i$. The length of vector element, $d\vec{l}$ is set by the resolution of the simulation. Absorption features are calculated based on the species’ abundance and gas properties at each vector element. To make the synthetic spectra more similar to realistic spectra, TRIDENT adds instrument-specific line-spread functions, a Milky Way foreground, a background QSO spectrum, and variable signal-to-noise ratio (S/N). For the analysis presented in §5.5, we extract synthetic spectra using the *HST*/COS line-spread function (Ghavamian et al., 2009), wavelength coverage of the COS G130M and G160M gratings (approximately 1150-1800Å), no Milky Way foreground absorption, and S/N = 10. These choices are mo-

tivated by the feasibility with which our theoretical predictions may be observationally constrained (see discussion in §5.6).

5.3 Multiphase ICM Properties in the RomulusC simulation

5.3.1 Evidence for the multiphase ICM

We first demonstrate that the ICM in our simulation is, in fact, multiphase: that gas clouds spanning orders of magnitude in temperature and density exist co-spatially. The high resolution of ROMULUSC is well-suited for resolving the multiphase ICM. With higher resolution (more particles per volume) each spatial region in the simulation is represented with a wider distribution of temperatures and densities, so that the gas is more accurately divided into varying thermodynamic phases (Hummels et al., 2018a).

Figure 5.1 captures the state of the ROMULUSC cluster at $z = 0.31$. The top row highlights properties that are directly measured from simulations but can only be inferred from observations: the density, temperature, and metallicity. The density projection highlights the physical structure of the cluster filled with numerous satellite galaxies. The most massive halo is at the center of the projection frame, surrounded by the hottest and densest regions of the ICM. This cluster is about to undergo a major merger with another galaxy group, which is approaching from the right. Dense filaments trace galaxies flowing through the medium as well as gas being stripped from these galaxies through ram-pressure stripping.

The temperature profile is dominated by hot gas at the center of the cluster, reaching ambient temperatures above 10^7K . Although rare near the cluster center, filaments of warm gas are visible just outside of the R_{200} (also see Figure 5.2). These gaseous filaments are likely a combination of heated cool gas inflows and stripped material from infalling galaxies.

The projected metallicity in the top-right panel demonstrates the extent to which the ICM is enriched with heavy elements. The ambient ICM near the cluster center has a

density-weighted average metallicity around $0.3Z_{\odot}$, roughly consistent with values inferred from X-ray observations (Urban et al., 2017). However, the metallicity distribution is far from uniform. At the cluster outskirts, the projected metallicity spans several orders of magnitude (see Figures 5.4 and 5.5 for more quantitative analyses of the distribution of metals). The high-metallicity regions trace infalling cluster galaxies, and these structures are easily observable in H I and O VI (see bottom row). The low-metallicity regions show the more pristine ICM, which is difficult to observe with both X-ray emission and UV absorption. The metallicity distribution gradually becomes less clumpy towards the center of the ICM, where gas has had more time to mix. Understanding this distribution of metals throughout the cluster constrains the motion of galaxies through the ICM and the mechanism through which they lose gas.

While the density, temperature, and metallicity are readily available from the simulation data, these properties cannot be measured directly using observations. Rather, these properties must be inferred through careful modeling, which itself depends on various assumptions and model parameters. For this reason, we also show the “observable” cluster properties in the bottom row of Figure 5.1. The left panel shows the expected X-ray intensity in the 0.5-7.0 keV band and the subsequent middle and right panels show the O VI and H I column densities, respectively. The limits on the colorbars are chosen such that the black background roughly indicates the observational limits of existing instruments, such as *Chandra*, *XMM-Newton* and *HST/COS* (for sensitivities typically obtained, e.g., COS-Halos; Tumlinson et al., 2011).

The gaseous structure observed with X-rays traces the hot, dense gas of the ICM. In contrast, the regions traced through UV absorption comprise the cool-warm phases of the CGM. Warm gas, traced by the O VI column density (bottom row, middle panel), exists as a combination of a volume-filling halo gas and denser gas associated with galaxies. The volume-filling warm gas produces O VI column densities around 10^{13}cm^{-2} in halos of cluster galaxies, especially at the cluster outskirts. Near the centers of gas-rich cluster galaxies, the O VI column density consistently exceeds 10^{16}cm^{-2} . Galaxies moving

through the ICM at sufficiently high velocities are stripped of their gas due to ram-pressure forces. Several galaxies in Figure 5.1 are oriented so that their gas-stripped tails are bright in O VI.

The cool gas, traced by the column density of H I (bottom panel), paints a similar picture for the multiphase structure in the ICM. Compared to the warm gas, the cool gas is more concentrated in galactic centers, and the stripped gas tails of infalling galaxies appear narrower. In certain cases, the H I shows small-scale, dense structure that is washed out in the distribution of O VI. The diffuse cool gas survives in abundance, both near the cluster center and well beyond its R_{200} . The overall similarity in the structures traced by both the warm and cool gas demonstrates the existence of a multiphase medium.

5.3.2 Radial distribution of the multiphase ICM

We now quantify the mass distribution of the multiphase gas in the cluster at $z = 0.31$. Figure 5.2 shows the total mass and metal mass fractions in cold, cool, warm, and hot gas as a function of distance from the cluster center.

As expected, hot gas dominates ($> 90\%$ of the mass) in the inner cluster regions. At $r = 2.5R_{200}$ from the cluster center, there is an equal amount of mass in the hot phase and the combined cold, cool, and warm gas phases. At $r = 3R_{200}$ from the cluster center, the warm gas comprises $\sim 45\%$ of the total gas mass while the hot and cool gas phases each comprise $\sim 35\%$ and $\sim 15\%$ of the gas mass, respectively. At these radii, roughly 80% of the gas mass is in the cool-warm phase that could potentially be probed by UV observations. Furthermore, the cool and warm gas phases hold a higher proportion of the metal mass, especially beyond $2 R_{200}$.

Even at the cluster outskirts, cold gas takes up less than 10% of the total gas mass. Although we do not expect the mass fraction of cold gas to be higher than the cool or warm phases, the fraction of cold gas in our simulation may be lowered by limitations in resolution. For example, because the simulation cannot resolve very dense regions of

very cold gas, the density and temperature thresholds for star formation are relatively low and high, respectively in ROMULUSC.

These results are broadly consistent with the gas mass fractions in the Virgo-sized cluster simulation presented by [Emerick et al. \(2015\)](#). Both simulations predict that hot gas dominates in the inner ICM, that the temperature profile gradually drops with distance from the cluster, and that the cluster outskirts have substantial reservoirs of cool-warm gas. The greatest difference is that our simulations predict a larger fraction of cool and warm gas at the cluster outskirts.

5.3.3 Covering fraction

The presence of gas in the $T < 10^6$ K temperature regime manifests in observable spectral signatures, namely absorption lines of H I and metal ions. A fundamental metric of any absorption-line survey is the covering fraction, or detection rate, of a given species, defined as the number of sightlines in which that species is observed with some column density (or equivalent width) above a given threshold. To provide a quantitative measure against which our simulation may be tested, we make predictions for the covering fractions of H I C IV, and O VI absorption given a number of detection thresholds throughout the cluster. These three ions span the temperature range of the cool-warm gas phases and have strong UV transitions observable with *HST*/COS at low redshifts. With the medium-resolution *FUV* COS gratings, G130M and G160M, the H I Ly α line is observable at $z \lesssim 0.5$, while the O VI doublet ($\lambda \lambda$ 1031.9, 1037.6 Å) shifts into the sensitive wavelength regime of HST at $z \gtrsim 0.11$. The C IV doublet ($\lambda \lambda$ 1548.2, 1550.8 Å) is observable down to $z = 0$ but exits the G160M bandpass at $z > 0.16$.

Figure 5.3 shows the covering fractions of H I, C IV, and O VI as a function of impact parameter measured from the cluster center. The curves are colored according to various column density thresholds, inevitably showing higher covering fractions for more sensitive thresholds. The darker curves correspond to stronger absorption features, which

may be more easily detected in data with lower S/N. As we discuss in more detail in §5.6, S/N ~ 10 spectra are typical for COS, which correspond roughly to 3σ detection limits of 10^{13} cm^{-2} for H I and $3 \times 10^{13} \text{ cm}^{-2}$ for C IV and O VI.

Although the covering fractions of all ions decline with impact parameter, the H I covering fraction declines more slowly than the covering fractions of O VI and C IV. The gas density, temperature, and metallicity all impact the resulting ion abundances, and the various ion tracers constrain the physical conditions of the gas. With the nominal column density limits quoted above, one should detect H I in a majority of sightlines within 1.5 Mpc of the cluster center, O VI in $\sim 15\%$ of sightlines, and C IV in $< 10\%$. O VI has an ionization potential (114 eV) that is more than double that of C IV (48 eV), and it is likely that even the warm ($T > 10^5 \text{ K}$) gas present in the ICM is too hot for carbon to survive in this ionization state; C IV peaks under collisional ionization at $\sim 10^{5.1} \text{ K}$ (Gnat and Sternberg, 2007). We measured the statistics for lower ionization species observable with COS, such as C III and Si III, which showed similarly small covering fractions. Interestingly, the covering fractions suggest that it is possible to detect the presence of warm and cool gas even at the cluster center. Increasing the column density sensitivity by an order of magnitude would approximately double the expected covering fractions throughout the ICM, and we discuss prospects for increased sensitivity in §5.6.

In a survey using several sightlines probing the Virgo cluster, Yoon et al. (2012) report an *increase* in H I Ly α covering fraction between $< 1.5 \text{ Mpc}$ ($0.60_{-0.13}^{+0.16}$) and $> 1.5 \text{ Mpc}$ ($1.00_{-0.14}$) for absorbers with $N(\text{H I}) > 10^{13.3} \text{ cm}^{-2}$ and a covering fraction of unity for $N(\text{H I}) > 10^{13.1} \text{ cm}^{-2}$ absorbers. Yoon et al. (2012) attribute this to substructure within Virgo and on its outskirts. Yoon and Putman (2017) conducted a similar study on the Coma Cluster and found a similar covering fraction, albeit without such a difference between inner and outer radii. In a sample of X-ray bright clusters, Burchett et al. (2018) detected H I absorbers in 4/5 clusters. In addition, their data show a hint of increased absorption in the cluster outskirts. Muzahid et al. (2017) detected very strong H I absorbers on the outskirts of three SZ-selected clusters at $R > 1.6R_{500}$, although at higher redshift ($z > 0.4$).

Various factors such as cluster dynamical state, redshift, and mass may indeed impact the presence of these absorption-line indicators, but greater amounts of cool gas may reside in the cluster outskirts than our simulations indicate.

5.3.4 *Distribution of metals*

As stated above, the diverse range of ICM structures probed by UV absorption should detect gas with different metallicities than the gas typically observed through X-ray emission. Figure 5.4 shows the distribution of gas temperature and density around $3 R_{200}$ around the cluster center. The pixels are colored by the mass-weighted average metallicity of the gas that lies in each temperature-density bin. The black square boxes roughly outline the density and temperature ranges that are probed by X-ray and UV observations.

The metallicity of gas probed by X-rays is roughly uniformly $0.3Z_{\odot}$ with a small dispersion. At the high temperature end ($T > 3 \times 10^7 \text{K}$), the average metallicity of the gas is consistently above solar metallicity. This is likely dominated by hot, dense, and metal-rich supernova or AGN ejecta throughout the simulation. In contrast, the low-density region at lower temperatures exhibits lower metallicities, likely tracing the diffuse cluster outskirts that are, on average, less polluted with metals than the ICM near the cluster center (see Figure 5.1). Overall, the bulk of the metals traced by X-ray observations belong to the hot, dense ICM. The X-ray emission is strongest near the cluster center, where the metals have been thoroughly mixed in the turbulent ICM.

Gas traced by the UV has a significantly larger variation in its average metallicity. In this regime, the metallicity is also a tracer of the gas density. Intuitively, this wide range in metallicity traces gas being stripped from galaxies within and around the cluster. For example, in Figure 5.1, the filamentary structures in the projected metallicity often trace the filamentary structures in the temperature and density. The ISM and CGM of galaxies are stripped of their high-metallicity gas as they move through the ICM. Over time, these metals mix with the ambient ICM. With the sensitivity to a much wider range in densities,

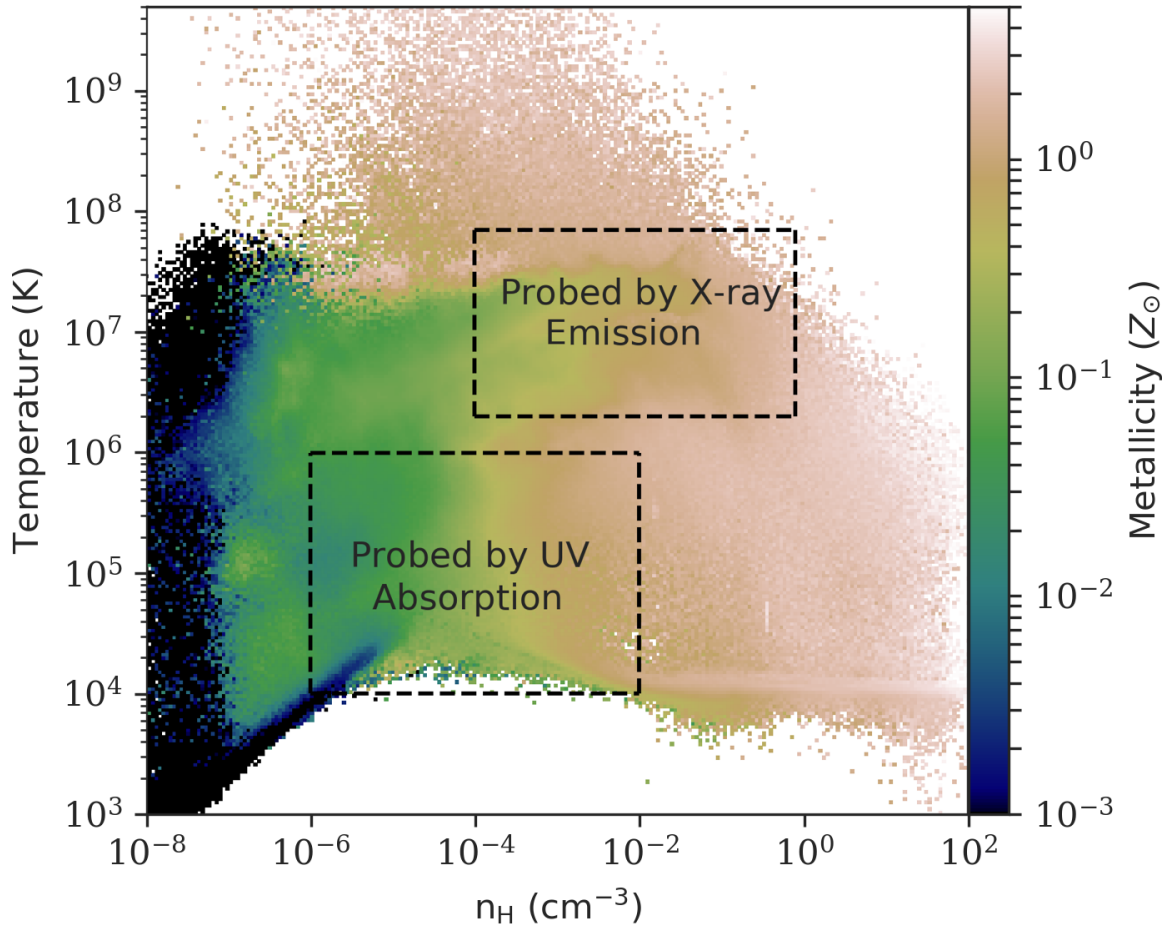


Figure 5.4 The distribution of the mass-weighted, average metallicity as a function of the temperature and hydrogen number density of the gas. The plot data was taken from a snapshot of RomulusC at $z = 0.31$, within $3 R_{200}$ of the cluster center. Gas probed by X-rays exists in a disjoint temperature and density phase from gas probed by UV-lines. The metallicity inferred from X-ray observations is likely to be higher and more uniform than the metallicity probed by UV lines.

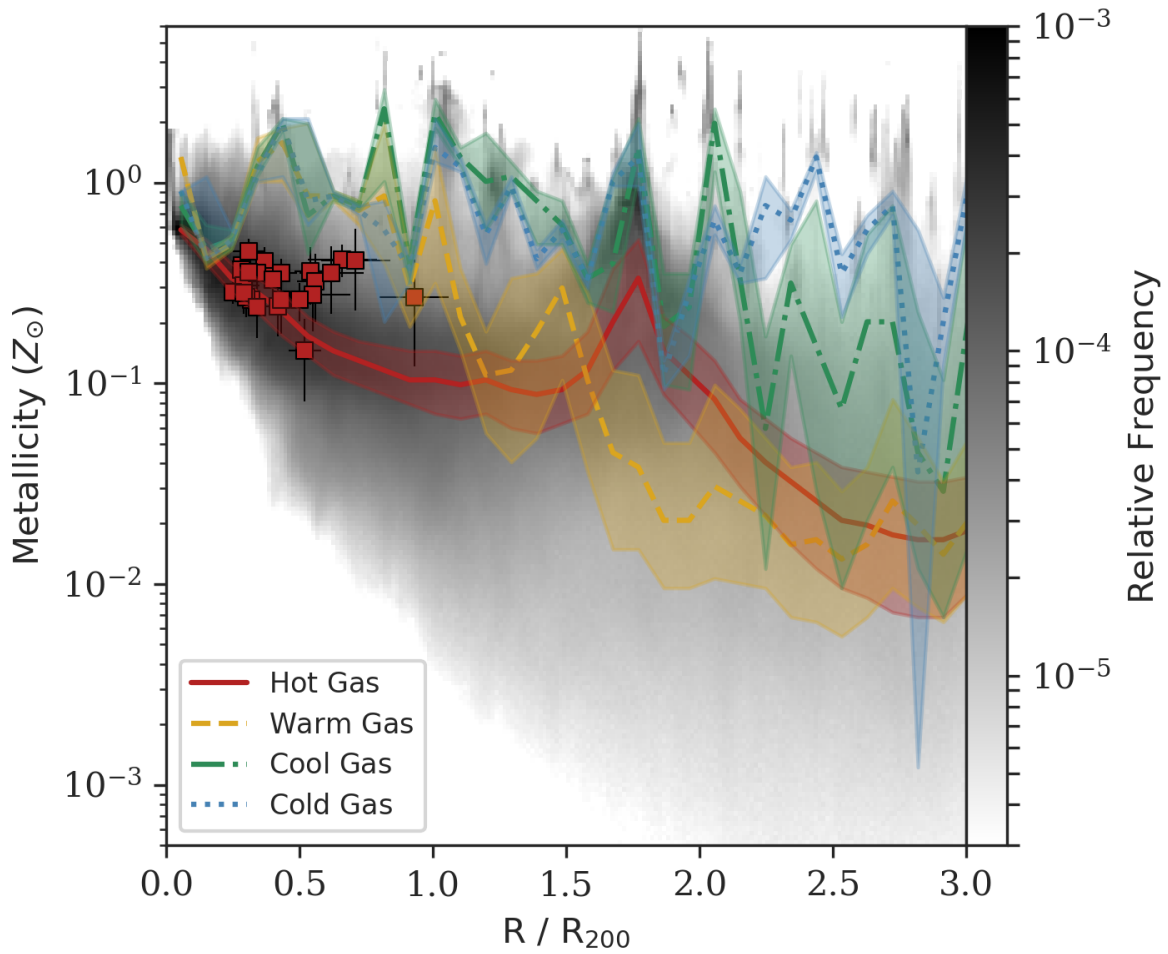


Figure 5.5 The 3D radial profiles of the median metallicity in cold ($T < 10^4 \text{K}$), cool ($10^4 < T < 10^5 \text{K}$), warm ($10^5 < T < 10^6 \text{K}$), and hot ($T < 10^6 \text{K}$) gas phases at $z = 0.31$. The shaded regions represent the 68.8% confidence intervals. The gray pixels in the background show the normalized mass distribution of all of the particles in the simulation within $3 R_{200}$ of the cluster center. The red squares denote the X-ray derived metallicities from Urban et al. (2017).

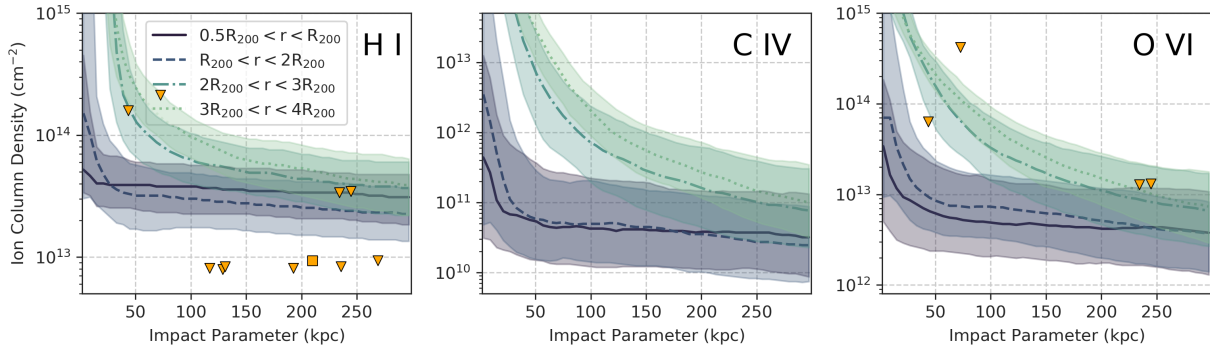


Figure 5.6 *Left to right*: The column density of H I, C IV, and O VI as a function of impact parameter for all galaxies with stellar masses $M_* > 10^9 M_\odot$ within $4 R_{200}$ of the cluster center. The lines plot the median column density profiles of galaxies within certain bins of distance from the cluster center as indicated in the legend. The shaded regions indicate the 68.8% confidence interval of the distribution. The orange shapes show the observed detections (squares) and upper limits (triangles) of H I and O VI in cluster galaxies from [Burchett et al. \(2018\)](#).

UV observations can better measure the inhomogeneity of ICM metallicity.

In Figure 5.5, we further quantify the distribution of metals in each of the different gas phases (red, orange, green, and blue for hot, warm, cool and cold, respectively) by plotting the median metallicity profiles of each temperature phase. The shaded areas show the 68.8% confidence interval of each gas distribution. The grey pixels show the normalized distribution of all gas (without temperature cuts) within 3 Mpc of the cluster center. The red squares show X-ray measured metallicities from [Urban et al. \(2017\)](#).

This radial metallicity profile highlights the range of metallicities in the multiphase gas predicted in Figure 5.4. For example, consider the inner Mpc around the cluster center, which is composed of mostly hot gas (see Figure 5.2). Although the observed metallicities are roughly constant at $0.3Z_\odot$, our simulation predicts that the spread in metallicities (considering all phases) spans significantly more than an order of magnitude. This spread is even larger at the cluster outskirts, reflecting the mixture of multiphase gas comprising the ISM, CGM and ICM with a wide range of temperatures and metallicities.

Furthermore, the different gas phases have varied metallicity profiles. The median metallicity of the hot gas phase is highest at the cluster center and decreases with radius. There is a notable exception to this trend around $1.7 R_{200}$, at which point the up-tick in the median metallicity of hot gas is due to the infalling group (see the upper-right panel of Figure 5.1). Although there is still a substantial mass of hot gas at the cluster outskirts, the metals from stripped CGM are not as well mixed as that near the cluster center.

We predict that (by mass) the median metallicity of hot gas beyond $2 R_{200}$ is actually below that reflected by X-ray observations. The metallicity profiles of the cool and cold phases have higher median metallicity values than the hot phase at nearly all radii, because of the metal-rich gas in the cool CGM and ISM of galaxies within the cluster. However, the metallicity profile of the warm gas falls off more rapidly than that of the cool or cold gas, and the warm gas metallicity is more representative of the global median at $> 1.5 R_{200}$. Near the cluster center, the hot gas comprises the majority of all ICM gas (see Figure 5.2), so the metallicity obtained from observations of the hot gas phase are good approximations of the true metallicity. However, at the cluster outskirts, where cool and warm gas dominate, X-ray obtained metallicities no longer provide an accurate estimate. For example, the average metallicity in all gas between $2-4 R_{200}$ in our simulation was $0.16 Z_{\odot}$ while the average metallicity of the hot gas was only $0.1 Z_{\odot}$. Also beyond $1.5 R_{200}$, the median profiles of the cool and cold gas show large variations due to the stochasticity in the distribution of galaxies and thus track relatively well with the infalling galaxies' CGM metal contents.

While the lack of metals present beyond $0.5 R_{200}$ may indicate that ROMULUSC fails to transport metals as effectively as it should, we stress that these results are sensitive to the redshift at which we sample the simulation. At redshifts more consistent with observations ($z < 0.2$), the cluster outskirts are more metal-enriched. For the sake of consistency, we limit our analysis to $z = 0.31$ and will explore the time evolution of the ICM in future work. We also stress that no attempt was made to mimic X-ray observations beyond selecting for hot gas. As X-ray observations are more sensitive to denser gas, they may be

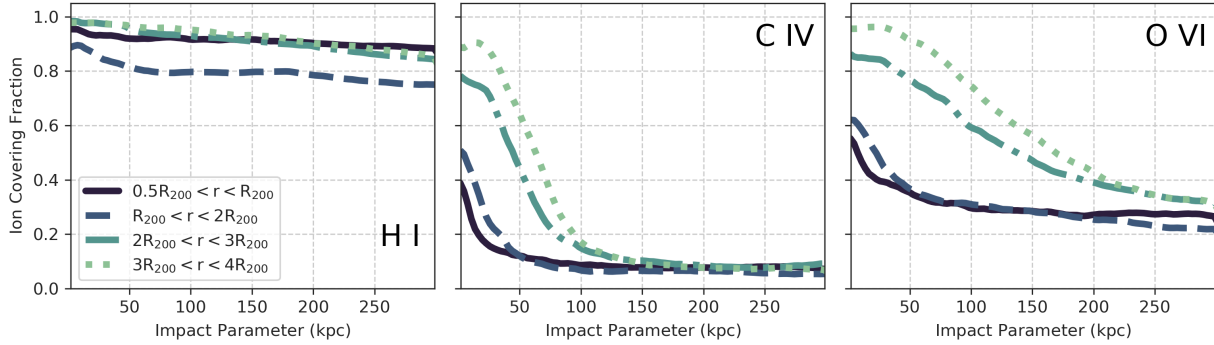


Figure 5.7 The covering fractions of H I, C IV, and O VI as a function of halo-centric impact parameter for all galaxies with $M_* > 10^9 M_\odot$ at $z = 0.31$. The different lines represent halos within the indicated distance bins from the cluster center. Covering fractions measure the fraction column densities above some threshold column density. We assume column density thresholds of 10^{13}cm^{-2} for H I, $10^{13.1} \text{cm}^{-2}$ for C IV, and $10^{13.3} \text{cm}^{-2}$ for O VI. The covering fraction of all ions is lower for galaxies nearer to the cluster center.

biased toward higher metallicity relative to the median presented in Figure 5.5.

5.4 The CGM of RomulusC Cluster Galaxies

The hot and dense ICM plays an important role in the evolution of cluster galaxies. For example, galaxies moving through the ICM often experience strong ram-pressure forces that strip them of their gas and quench star formation. Although this effect appears in many modern simulations (e.g. Bahé et al., 2017; Zinger et al., 2018; Tremmel et al., 2019), the quenching timescales differ depending on whether the ISM is stripped directly or indirectly deprived of replenishing fuel from a CGM that has been stripped early upon infall. We now explore the effects of the cluster environment upon the observable ion abundances in sightlines probing the CGM of cluster galaxies at various radii.

In Figure 5.6, we compare the ion column densities of H I, C IV, and O VI as a function of impact parameter measured from the centers of cluster-galaxy halos. Each line shows the median column density for all galaxies with stellar masses of $M_* > 10^9 M_\odot$ within the bins of projected distance from the cluster center indicated in the legend. Each shaded

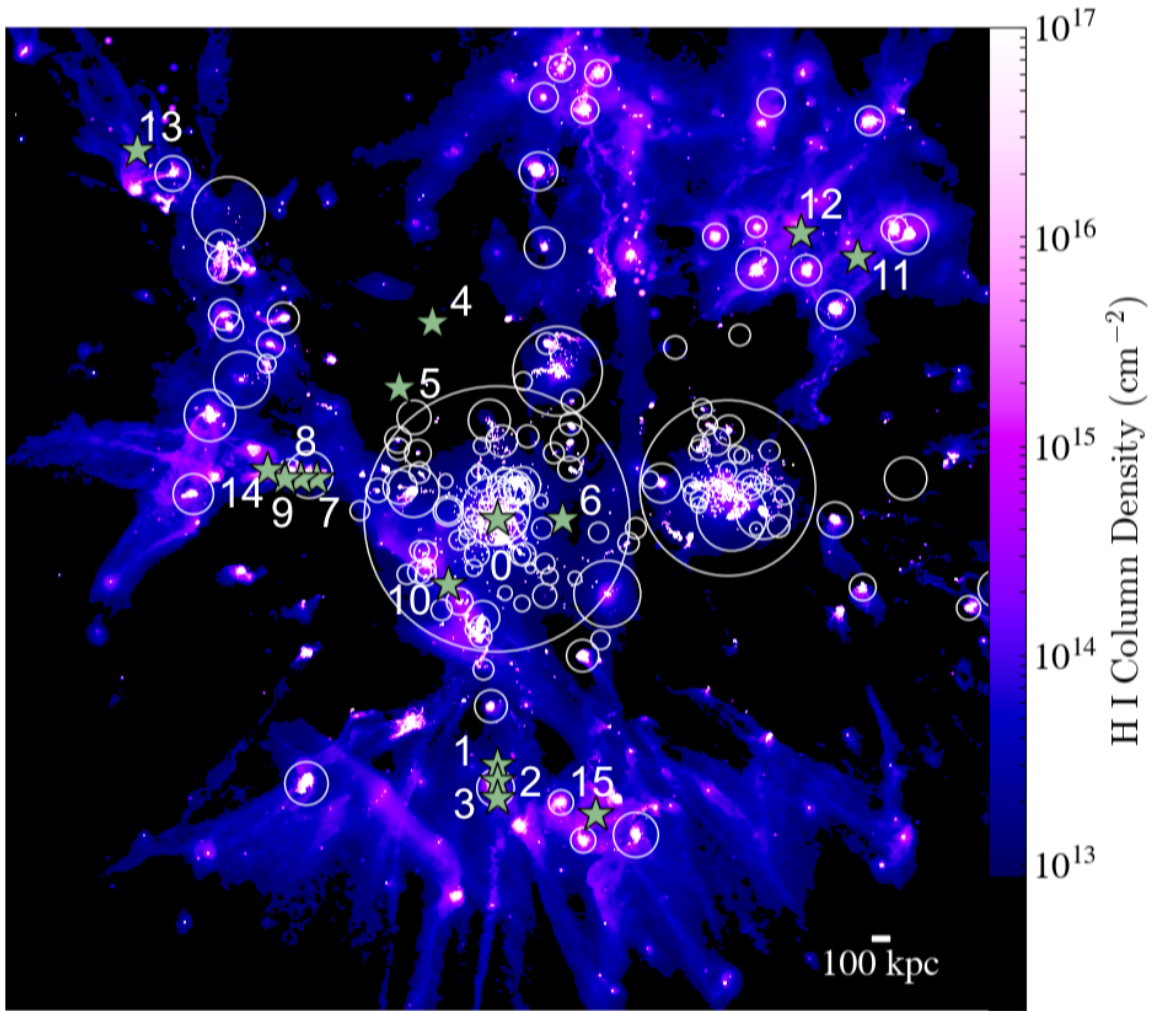


Figure 5.8 The O VI column density overplotted with locations of sightlines for which we extracted synthetic spectra. The R_{200} of cluster galaxies with stellar masses of $M_* > 10^9 M_\odot$ are indicated by circles (centered on each galaxy).

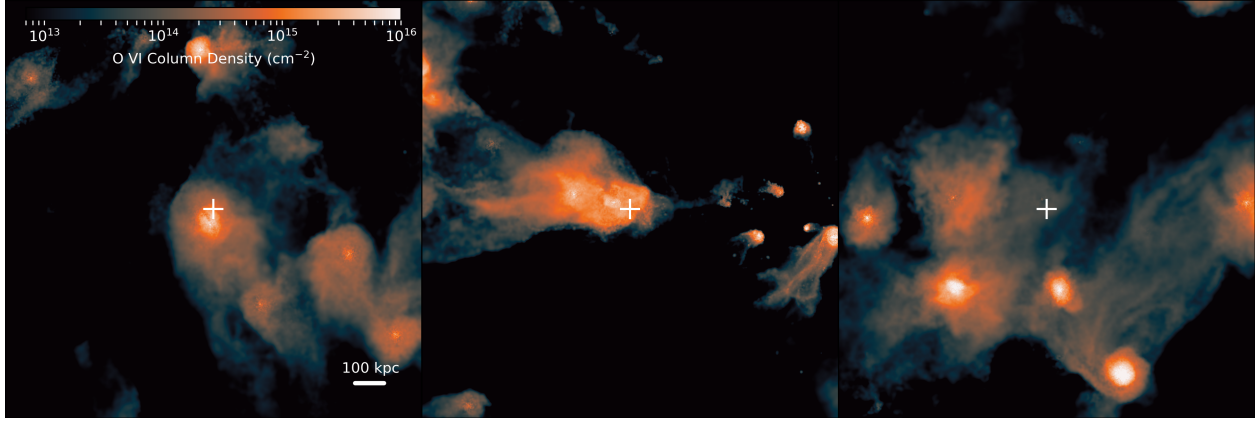


Figure 5.9 The O VI column density around the regions of the sightlines presented in Figure 5.10. Each sightline was chosen at an arbitrary location, in-between galaxies at the $z = 0.31$ snapshot of ROMULUSC. It is not required that a sightline directly intersect the CGM of a galaxy for there to be detectable amounts of O VI in the ICM.

region contains the 68% confidence interval of the distribution in each radial bin. The orange markers show the observed detections (squares) and upper limits (triangles) of H I and O VI in cluster galaxies from [Burchett et al. \(2018\)](#). Although C IV does not have comparable observations, we include its column density profile as this ion is observable with HST/COS at the lowest redshifts. Note that we do not include predictions for galaxies within $0.5R_{200}$. We find that, in this regime, the ‘detected’ ions (especially H I) are dominated by the ambient ICM and are not necessarily signatures of the CGM of individual galaxies.

Our simulation predictions are broadly consistent with the limited existing CGM O VI observations. However, the H I column densities we predict at impact parameters > 100 kpc generally exceed the observational data. A preliminary check of lower-redshift ($z = 0.1, 0.2$) simulation snapshots show lower H I CGM column densities more consistent with the observations but that are still high. We will explore this redshift evolution further in future work. Nevertheless, this inconsistency may also reflect some aspect of the galaxy-CGM-ICM interaction that is not accurately reproduced by our simulation. Larger samples of observational data will prove invaluable to constraining the simulated physics.

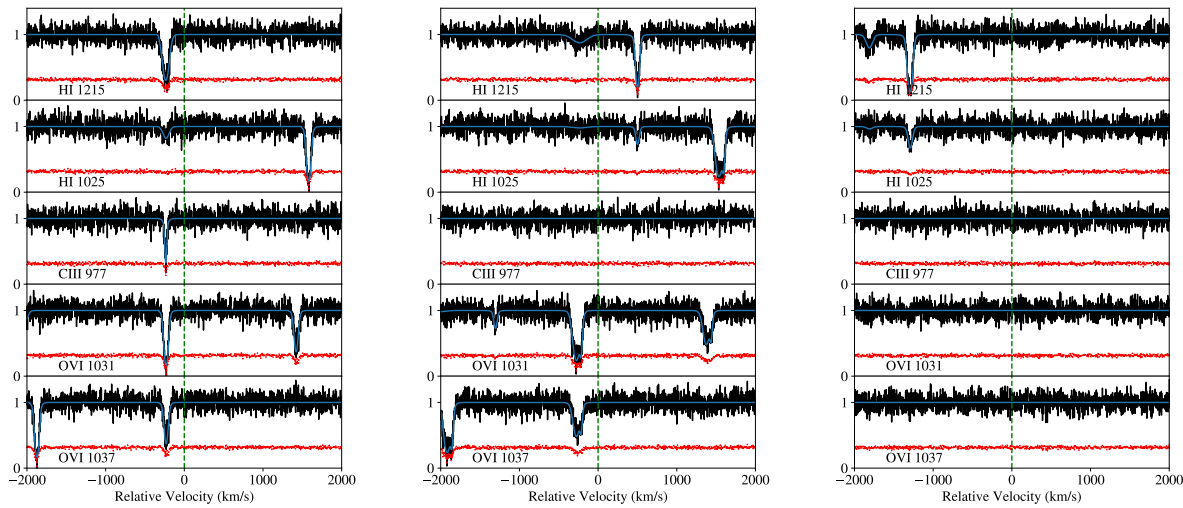


Figure 5.10 Synthetic spectra of sightlines generated using TRIDENT through the ROMULUS cluster. From left to right, the panels correspond to Sightlines 2, 7, and 12 marked in Figure 5.9. Each subpanel shows absorption (or lack thereof) for the transition labelled in its lower right corner, relative to $z = 0.31$. The blue curves mark Voigt profile fits to the visually identified absorption components. Note that the apparent absorption at > 1000 and < -1000 km/s in the Sightline 2 and 7 H I 1025, O VI 1031, and O VI 1037 panels are actually O VI 1031, O VI 1037, and O VI 1031 lines, respectively, due to the large velocity range plotted. These spectra show the diversity of absorbers predicted by our simulation, including broad and narrow H I components with and without corresponding O VI and C III.

Notably, we predict a decrease in CGM column densities at impact parameters $\lesssim 200$ kpc for galaxies with projected clustocentric distances of $< 2R_{200}$. Below distances of $2R_{200}$ there is little evolution of the column density profiles beyond the very innermost ($\lesssim 25$ kpc) impact parameters. The larger clustocentric bins show progressively decreasing profiles from $> 3R_{200}$ to $2 < r/R_{200} < 3$ before the more dramatic decline at $2R_{200}$. Thus, the majority of the CGM is stripped while galaxies are still quite far from the cluster center; however, the innermost CGM requires much greater ram pressure to become stripped, as it is the most bound. It is interesting to note that, for impact parameters above 100 kpc, the column densities we predict for O VI are lower than many of the observations from the COS-Halos isolated galaxy sample (Tumlinson et al., 2013). Simulations of isolated galaxies using the same sub-grid physics models as ROMULUSC recover the COS-Halos O VI column densities quite well (Sanchez et al., 2018), indicating that the cluster environment is inducing strong effects on the CGM of galaxies even out to clustocentric distances of $4R_{200}$. We defer a more in-depth comparison between simulated cluster and isolated galaxies as well as observations thereof to a future work.

In Figure 5.7, we show the covering fractions of H I, C IV, and O VI as a function of impact parameter for the same galaxies considered in Figure 5.6. Each line represents the combined covering fraction of all galaxies within each distance bin calculated for the observationally motivated column density thresholds of 10^{13} , $10^{13.1}$, and $10^{13.3} \text{ cm}^{-2}$ for H I, C IV, and O VI, respectively. The covering fraction of C IV is low beyond 100 kpc, even for galaxies in the outskirts of the cluster. At smaller impact parameters, C IV becomes depleted for galaxies within $2R_{200}$ from the cluster center. A similar effect is seen for O VI, although the covering fraction is generally higher than that of C IV at all impact parameters and the profile steepens significantly within $2R_{200}$. The covering fractions of H I decline very modestly with impact parameter, and the evolution with clustocentric distance is much greater for the metal ion diagnostics O VI and C IV. As a general trend, galaxies farther from the cluster center tend to retain more of their CGM, resulting in higher covering fractions of C IV and O VI; ram-pressure increases closer to the cluster

center where the density of the ICM is higher.

5.5 The physical conditions of cool and warm gas in the ICM from synthetic spectra

Herein, we discuss several facets of a multiphase ICM, which in turn have observable signatures, particularly in the UV regime for $T < 10^6 \text{K}$ gas. In this subsection, we seek to 1) further assess the observability of this material and 2) relate the observable signatures back to the physical conditions of the gas in the ROMULUSC simulation. Our intent is to provide a proof-of-concept level of analysis while sampling various regions throughout the cluster, as would be probed in an actual absorption-line spectroscopic survey using sightlines piercing galaxy clusters.

Using Trident (Hummels et al., 2017, discussed in §5.2.2), we extracted sixteen sightlines through the ROMULUSC cluster; the sightline locations are indicated in Figure 5.8. The sightlines were chosen to pass through ambient ICM regions far away from infalling galaxies, the immediate CGM of cluster galaxies, and detritus stripped as galaxies fall into the cluster. The R_{200} of subhalos within the cluster are marked with circles in Figure 5.8. We then analyzed the resulting synthetic spectra as an observer might analyze such data probing an actual cluster obtained with *HST*/COS, the only currently available instrument that is capable of producing a similar dataset (see discussion in §5.6). Upon identifying the absorption features in the synthetic spectra, we fitted Voigt profiles to each feature using the *Veep* software originally developed for the analysis of Burchett et al. (2015). Measurements for all detected H I and O VI lines as well as information about their respective sightlines are provided in Table 5.1.

Three examples of spectra we extracted are shown in Figure 5.10; in each plot, the individual panels show the would-be locations of H I Ly α and Ly β , the O VI λ 1031, 1037Å doublet, and C III λ 977Å within 2000 km/s of the cluster redshift. For each spectrum, we searched by-eye for absorption signatures of these four lines, marking the approximate velocity of each component. In total, we visually identified 19 components of H I, O VI, or C III in our synthetic spectra sample. To further validate our integrated column den-

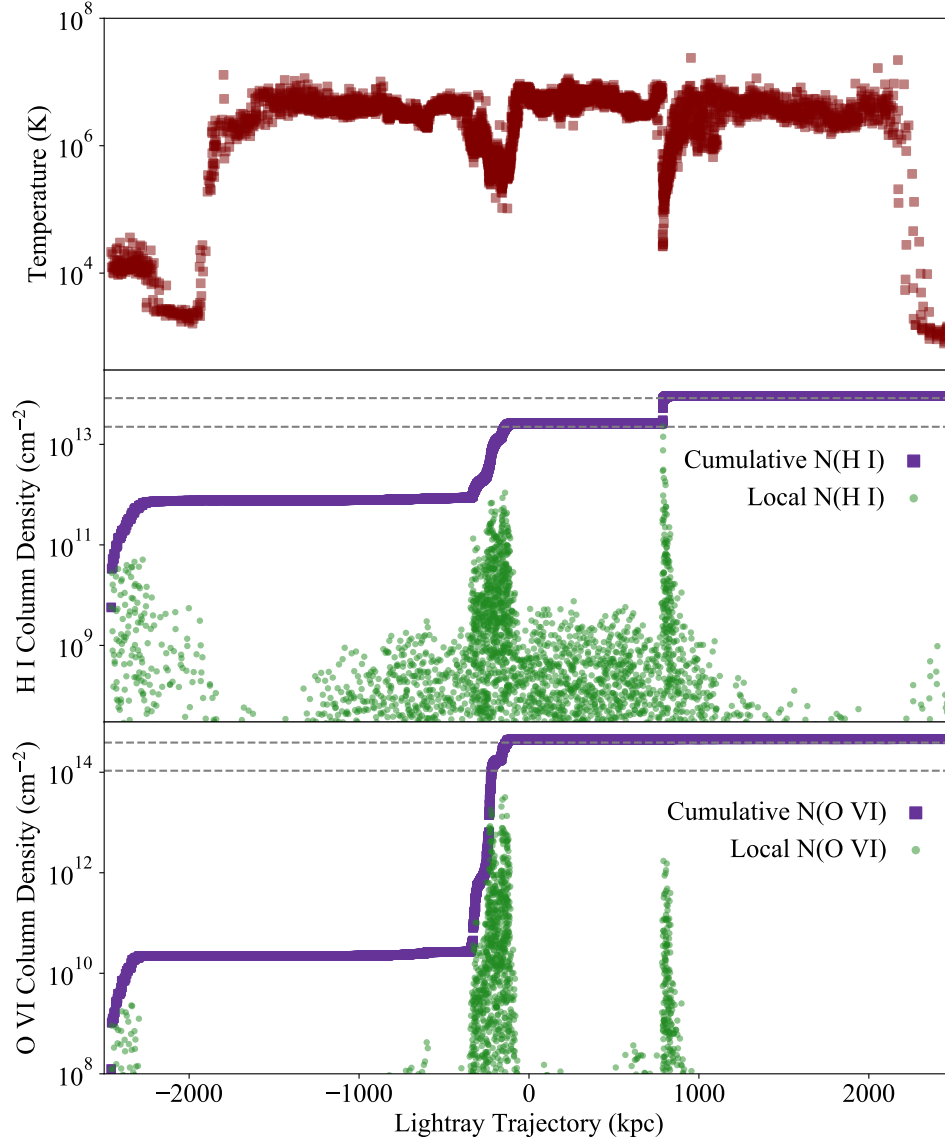


Figure 5.11 Temperatures (*top*) and column densities of H I and O VI (*middle* and *bottom*, respectively) intercepted along Sightline 7 through the RomulusC volume. In the bottom two panels, the small green circles show the column density of each ion recorded at each point along the ray’s trajectory, and the purple squares reflect the cumulative column densities along this trajectory. Horizontal dashed lines show the H I and O VI column densities measured by Voigt profile fitting from the Trident-generated (Hummels et al., 2017) synthetic spectra. The cumulative column densities exhibit sharp increases where localized overdensities of these ions occur. Furthermore, the column densities we measure from the synthetic spectra are consistent with those directly integrated from the simulation.

sities presented in previous sections against these identifications and measurements in the synthetic spectra, we inspected the cumulative and local column densities recorded along each sightline’s ray through the simulation box. Figure 5.11 shows the temperatures and column densities of H I and O VI as encountered by Sightline 7 along its trajectory. First, as the cumulative column density profiles of each ion (purple squares) exhibit step function-like behaviors that coincide with overdense peaks in the local values (by several orders of magnitude), the integrated measurements presented in Sections 5.3 and 5.4 are produced by observable, localized complexes rather than ambient trace material at low column density. Furthermore, these complexes occur where the local temperature decreases from the dominant ICM conditions at $10^{6.5}$ K to those we purport to probe at 10^{4-5} K. Second, the dashed horizontal lines show the column densities of H I and O VI we measure in individual components from the synthetic spectra. The consistency between these measured values and those directly from the simulation via Trident (Hummels et al., 2017) verifies that the integrated column densities from the simulation should indeed correspond to measurable features in actual observations using standard techniques. We inspected the remaining 15 synthetic sightlines in a similar manner and find a similar behavior (step function-like sharp increases in the cumulative profile imposed by localized overdensities) for those showing observable spectral features.

Two key factors hinder detecting weaker lines: the S/N of the data and line broadening due to thermal and non-thermal motions. Thus, the wavelength coverage of multiple transitions enables one to corroborate identifications of features using the presence of other lines. For example, a strong Ly α line should be accompanied by a weaker (the ratio set by atomic physics) Ly β line at the same velocity. Similarly, albeit with caution, one can corroborate lines of one species (e.g., O VI) with absorption by another (e.g., H I). While this practice can lead to misidentifications if applied improperly, it is occasionally necessary in cases with weak features or blending due to lines from other redshifts. Our dataset analyzed here (and as would be analyzed from an actual survey) presents a number of such challenges, as the special cluster environment contains an excess of hotter gas

relative to random CGM/IGM regions; the increased gas temperature thermally broadens H I lines substantially.

We highlight one particularly illustrative case that underscores the importance of wavelength coverage in this analysis, shown in the middle panel of Figure 5.10 at $v \sim -250$ km/s. While no Ly β is detected, a broad Ly α feature is barely apparent. However, the O VI doublet is well detected at this velocity, greatly reinforcing the broad Ly α identification. The width of the Ly α line then enables a direct constraint on the gas temperature. Furthermore, without the Ly α coverage, one may identify the O VI doublet as a spurious superposition of two Ly α lines at lower redshifts. While the O VI and Ly β lines would be covered in a COS observation with only the G130M grating, observations with the G160M would be required to cover the observed wavelength of Ly α . The symbiotic complementarity of information gleaned from both gratings is essential to both discovering this gas system and understanding its physical conditions.

Notably, we detect several broad Ly α lines, with seven components having Doppler parameter values $b > 40$ km/s, tracing warm gas at $T > 10^5$ K (assuming thermal broadening). To compare this synthetic sample with previous survey measurements of broad Ly α absorbers, we perform an approximate conversion of absorber line density as measured through our simulation to the line density metric often reported in absorption-line surveys $d\mathcal{N}/dz$, or number of absorbers per unit redshift. Our sightlines extend 5 Mpc through the ROMULUSC simulation, which corresponds to the luminosity distance difference over $\Delta z \sim 0.0008$ at $z = 0.31$ (assuming cosmological parameters from [Planck Collaboration et al. \(2016\)](#)). Thus, over the 16 sightlines we have analyzed, our broad Ly α density would translate to $d\mathcal{N}/dz \sim 540$. Compared with the broad Ly α $d\mathcal{N}/dz \sim 25$ from [Lehner et al. \(2007\)](#), our broad Ly α sample represents a $> 20x$ overdensity relative to random IGM sightlines. Of course, our measurement is heavily biased, as all of our sightlines fall within the cluster environment, and the incidence of broad Ly α absorbers should increase in such overdense regions (e.g., [Tepper-García et al., 2012](#)). Perhaps a more fair comparison is with the survey by [Tejos et al. \(2016\)](#), who examined the line

Sightline ^a	Ion	$\log(N/\text{cm}^{-2})$	b [km/s]	v_b [km/s]	ρ_{clc} [kpc]	$\log(T/\text{K})^d$	$\log(N_H/\text{cm}^{-3})$
0	H I	17.25 ± 0.30	15 ± 1	-357.7 ± 1.1	0	7.10	-1.88
0	H I	16.70 ± 0.99	20 ± 4	-170.0 ± 1.8	0	7.10	-1.88
2	O VI	14.55 ± 0.04	28 ± 3	-233.6 ± 1.8	1600	6.27	-4.65
2	H I	13.94 ± 0.04	47 ± 5	-234.8 ± 3.4	1600	6.27	-4.65
3	O VI	14.13 ± 0.06	36 ± 7	-258.7 ± 4.4	1700	6.15	-4.84
3	H I	13.62 ± 0.09	61 ± 17	-264.2 ± 10.5	1700	6.15	-4.84
7	O VI	14.03 ± 0.19	16 ± 8	-216.3 ± 4.0	1128	6.49	-4.34
7	O VI	14.59 ± 0.06	49 ± 8	-277.9 ± 6.9	1128	6.49	-4.34
7	H I	13.92 ± 0.05	24 ± 3	500.4 ± 2.2	1128	6.49	-4.34
7	H I	13.35 ± 0.16	121 ± 55	-233.9 ± 36.7	1128	6.49	-4.34
8	H I	17.40 ± 0.23	18 ± 1	-299.2 ± 1.2	1226	6.45	-4.47
8	O VI	14.64 ± 0.04	27 ± 2	-326.4 ± 1.6	1226	6.45	-4.47
9	H I	13.54 ± 0.10	49 ± 17	-279.8 ± 10.7	1324	6.40	-4.91
9	O VI	14.46 ± 0.04	25 ± 3	-284.3 ± 1.9	1324	6.40	-4.91
10	H I	13.26 ± 0.11	27 ± 10	-534.7 ± 6.7	500	6.73	-4.26
11	H I	13.23 ± 0.13	42 ± 17	-1310.8 ± 11.6	2720	5.43	-5.38
12	H I	14.11 ± 0.04	32 ± 3	-1293.5 ± 2.0	2547	5.49	-5.31
12	H I	13.23 ± 0.14	50 ± 22	-1810.2 ± 14.7	2547	5.49	-5.31
15	H I	13.55 ± 0.08	69 ± 16	-1092.0 ± 10.9	1897	5.79	-5.34

Sightline numbers correspond to those marked in Figure 5.8.

Velocities are expressed relative to the RomulusC snapshot redshift at $z = 0.31$.

Impact parameter of sightline relative to the cluster center

Quantity averaged along sightline

Table 5.1 Voigt profile fitting results for identified absorption components in

density near putative intracluster filaments and find a broad $\text{Ly}\alpha$ $d\mathcal{N}/dz = 108^{+65}_{-43}$ within 3 Mpc of such filaments. We again emphasize that these comparisons are by no means rigorous, as we furthermore did not choose our sightline locations at random locations throughout the cluster, and the pathlength calculation (denominator of these metric) requires accounting for the sensitivity limits of the spectra, etc. However, our predictions indicate that a substantial number of broad $\text{Ly}\alpha$ absorbers tracing warm gas, well in excess of the typical IGM or even Cosmic Web filaments, should await discovery within the cluster environment.

5.6 Prospects of studying the cool and warm gas in Galaxy Clusters

We now turn to using the results from our simulation to observationally constrain the multiphase ICM and the CGM of cluster galaxies. In §5.3 we show that a substantial fraction of the ICM is composed of cool and warm gas beyond $1.5 R_{200}$. This gas can be traced observationally through H I, O VI, and (to a lesser extent) C IV. In §5.3.3 and §5.4 we predict the covering fractions of these three ions as a function of both clustocentric and halo-centric impact parameters. Here, we further examine the feasibility of observing the cool and warm cluster gas with existing and future UV telescopes.

The predicted covering fractions depend on both the physical abundance of the ion and the column density sensitivity limits of the observing instrument. In our predictions above, we assumed constant column density sensitivities of *HST*/COS set by the anticipated S/N of the spectra. However, in practice, the sensitivity limits depend on several different factors, and a given S/N does not directly map onto one sensitivity limit in terms of column density. For example, warm gas will produce more thermal broadening than cool gas, which will result in shallower absorption features and a higher minimum observable column density even with the same S/N. Furthermore, stochastic noise can make some otherwise detectable lines insignificant. Instead, the more reliable metric for determining the column density sensitivity of an instrument is the detection significance. The detection significance uses the S/N, column density, temperature (assuming thermal broadening), and the instrument-specific line spread function to measure the ratio of the line's equivalent width and its uncertainty, W/σ_W . Using simulated Voigt profiles across a grid of temperature and column densities, we calculated their detection significance given range of S/N (see Burchett et al., 2018, for a detailed description of this calculation). Lines with a detection significance $\geq 3\sigma$ are considered to be detectable.

Figure 5.12 uses the detection significance described above to establish the minimum observable column density of H I and O VI as a function of temperature for several different S/N. The dotted horizontal lines indicate the average covering fractions of H I and O VI

within $R < 2$ Mpc of the cluster center at three different column density thresholds (see Figure 5.3). At each S/N line, the minimum observable column density of H I increases with temperature due to the expected thermal broadening. For both ions, increasing the S/N from 10 to 75 improves the column density sensitivity limit by ~ 1 dex.

Currently, the most sensitive UV spectrograph to H I and O VI at low and intermediate redshifts is the *HST/COS*. It consistently reaches S/N of at least 10, and can reach S/N values as high as 75 (corresponding to the full range of S/N lines in Figure 5.12). For example, as of the July 2018 data release of the Hubble Spectroscopic Legacy Archive (HSLA; Peebles et al., 2017), 300 sightlines have $S/N \geq 10$, 100 sightlines have $S/N \geq 20$, and 16 sightlines have $S/N \geq 50$. Using the covering fraction estimates presented in Figure 5.13, we predict that *HST/COS* can detect minimum covering fractions of 0.66 for H I and 0.19 for O VI.

The next-generation UV instruments are still in the concept phase, vying for recommendation by the Astro2020 Decadal Survey. Current examples include The Large Ultraviolet Optical Infrared (*LUVOIR*) observatory (Bolcar et al., 2017), which would feature a 15 meter aperture, as well as a host of instruments spanning the UV to the infrared, such as the Large Ultraviolet Multi-object Spectrograph (LUMOS; Harris et al., 2018). Although facilities of this magnitude would likely not launch until the 2030s, we explore their anticipated advancements of UV cluster observations below with the goal of understanding the prospect of studying the multiphase ICM in the coming decades.

The spectral S/N is a function of the brightness of the background source and the integration time. In Figure 5.13, we show the predicted S/N of *LUVOIR* spectra as a function of the GALEX FUV magnitude for different exposure times. The horizontal dashed lines show the covering fractions of H I and O VI in ROMULUSC for several different S/N (assuming each S/N corresponds to the median detectable column densities in Figure 5.12).

LUVOIR would dramatically increase the S/N and observable column density limits. For example, achieving the nominal $S/N = 10$ we have assumed throughout this chapter requires 5 hours of exposure time with *HST/COS* for a source with $m_{FUV} = 19.5$. Achieving a similar S/N on *LUVOIR* would only take 20 minutes. Furthermore, for modest exposure

times of 2-4 hours, *LUVOIR* can deliver $S/N \geq 50$ (corresponding to covering fractions of 0.91 for H I and 0.37 for O VI) for a large fraction of sources. However, according to our predictions, increasing the S/N to ≥ 100 brings marginal returns. In addition to only a slight increase in the covering fractions of our key ions, the gas complexes that our simulations predict give rise to integrated column densities of $N(\text{H I}) \lesssim 10^{12.0} \text{ cm}^{-2}$ would likely not be detectable. From a similar analysis of, e.g., Sightline 5 (see Figure 5.8) as that shown in Figure 5.11 for Sightline 7 and discussed in Section 5.5, the local overdensities associated with total $N(\text{H I}) \sim 10^{11-12} \text{ cm}^{-2}$ are distributed over large spatial scales ($\sim 100 - 1000$ kpc) and have local column densities on the order of $\sim 10^{10} \text{ cm}^{-2}$. The optical depth of this gas spread over such large distances would likely also be too spread out in velocity space to produce detectable spectral features. Recent hydrodynamic simulation efforts have forced high resolution in the diffuse halos of L^* galaxies, producing smaller cloud structures at low, but detectable, column densities (Hummels et al., 2018b; Peeples et al., 2019a). However, it remains to be seen whether the extreme cluster environment would yield similar results. Our data suggest a ‘detectability floor’ where pushing to extremely high S/N (by today’s standards) may not yield increased detections of cool or warm gas in the ambient ICM.

The transformational leap beyond current observational capabilities will likely come from the ability to observe a larger sample of background sources. At fainter magnitudes ($m_{FUV} > 20$), the density of background sources (e.g., QSOs and star-forming galaxies) in the sky increases sharply (Rubin et al., 2018a). For example, employing the COSMOS2015/UltraVISTA catalog (Laigle et al., 2016; McCracken et al., 2012), which includes GALEX photometry and photometric redshifts, we found that there are ≥ 75 potential background sources per square degree with $m_{FUV} < 22$ at $z = 0.2 - 1$. Considering cluster-centric impact parameters within 2 Mpc, this source density translates to ≥ 7 possible sources *per cluster* at $z = 0.2$. Therefore, one could easily subselect the cluster sample based on the properties of the cluster or study a particular cluster in exquisite detail, following a similar approach to that of Yoon et al. (2012) and Yoon and Putman (2017) for

Virgo and Coma, respectively, but *for virtually any cluster in the low-redshift Universe*.

5.7 Conclusions

We use the high-resolution hydrodynamical galaxy cluster simulation, ROMULUSC, to examine the multiphase structure of the intracluster medium (ICM) and its effect on the circumgalactic media (CGM) of constituent galaxies. We focus our analysis on cool-warm ($T = 10^4\text{--}10^6\text{K}$) gas at the cluster outskirts which is particularly difficult to observe in X-rays. We show that this gas can be observed in the ultraviolet (UV) with *HST/COS* and make predictions for observations with next-generation telescopes, such as *LUVOIR*. We summarize our key findings as follows:

1. At all clustocentric radii, we find significant quantities of multiphase gas in the cool ($10^4\text{--}10^5\text{K}$) and warm ($10^5\text{--}10^6\text{K}$) gas phase, observable in the UV. Relative to the hot ($T > 10^6\text{K}$), X-ray emitting gas, the share of cool-warm material increases rapidly toward the cluster outskirts. By $r > 2.5R_{200}$, the warm gas mass fraction exceeds that of the hot gas, and even the cool gas exceeds the hot gas at $r > 3.5R_{200}$.
2. The ICM is marked by a wide range of metallicity from $Z \approx 0.01Z_{\odot}$ to $Z > Z_{\odot}$. Our predicted metallicities of gas at temperatures and densities probed by X-rays are broadly consistent with X-ray measurements at $r < R_{200}$; however, the lower temperature and density regime to which the UV is sensitive possesses a much wider range in metallicity, including lower metallicities from the well-mixed ICM and highly enriched gas that is stripped from the CGM of infalling galaxies.
3. We predict detection rates of H I, C IV, and O VI which sample different temperatures of the cool-warm gas, throughout the ICM. We find that the detection profiles of all three ions decline from the cluster center out to 1 Mpc but remain relatively flat out to the edge of the simulated volume, at 3 Mpc.

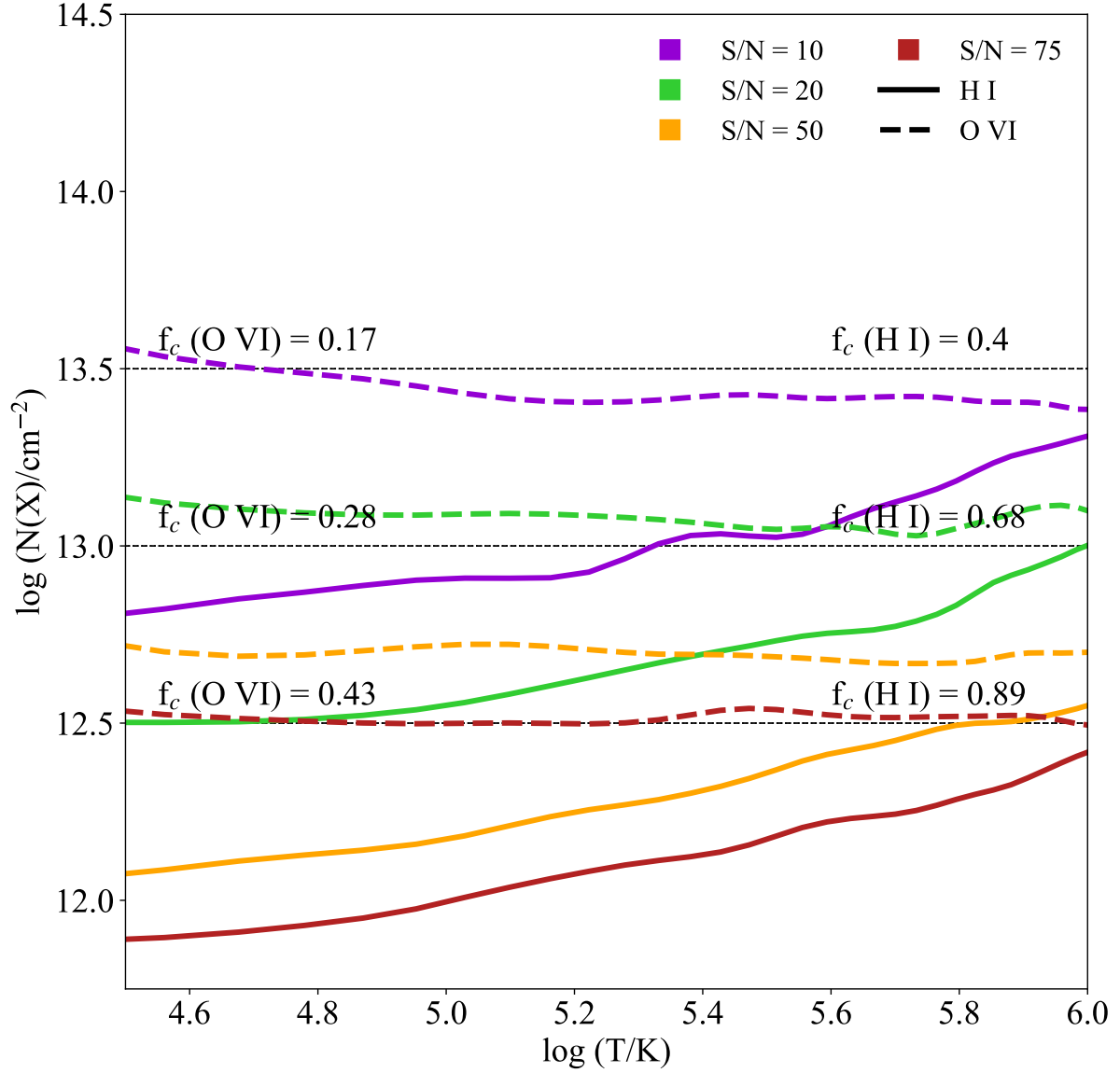


Figure 5.12 The detectability (at 3σ) of H I Ly α (solid) and O VI λ 1032Å (dashed) lines over a range of column densities and temperatures (via the Doppler b parameter) given several levels of S/N achieved (see color-coding in legend). Our predicted covering fractions of H I and O VI for three column density thresholds (for $\rho < 2$ Mpc) are indicated by horizontal dotted lines, and a given column density is considered detectable if a colored curve falls at or below that value in the plot. For example, a S/N = 10 spectrum should return a covering fraction $\gtrsim 17\%$ for O VI (dashed purple line) across the warm temperature regime but $f_c = 50 - 70\%$ for H I (solid purple line) across this same temperature range.

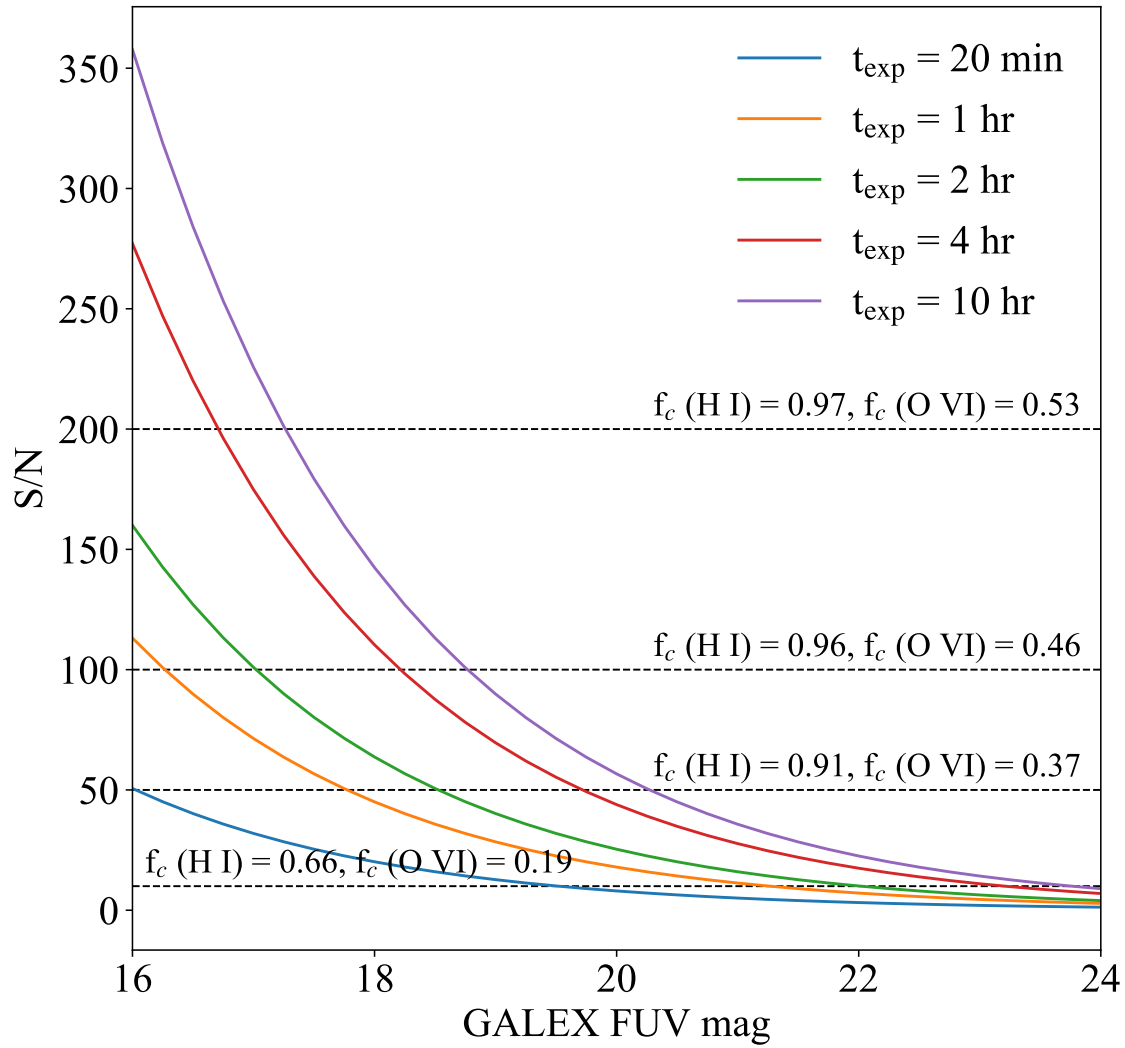


Figure 5.13 Signal-to-noise (S/N) ratio achieved under the current *LUVUOIR* 15m telescope concept when observing UV-bright sources at various exposure times (color coding indicated in legend). The horizontal lines indicate covering fractions of H I and O VI assuming the column densities detectable of each ion at the indicated S/N (see Figure 5.12).

4. The CGM of cluster galaxies are readily stripped during the early stages of infall. CGM stripping is apparent in galaxies as far as $4R_{200}$ from the cluster center and becomes progressively more pronounced near the cluster center. This stripping is observable in the halo-centric covering fractions of H I, C IV, and O VI for galaxies at various distances from the cluster center.
5. To test the feasibility of confronting our galaxy cluster simulation and the physics therein with observations, we generate and analyze synthetic UV spectra of sightlines piercing the ROMULUS ICM and CGM of cluster galaxies. Within 16 synthetic sightlines, we detect 19 components of H I, O VI, and C III, including several broad Ly α components tracing the elusive warm gas regime, in various environments from the cluster center to the outskirts. These synthetic data demonstrate that a large UV spectroscopic survey using currently available instrumentation can effectively be leveraged to test cluster formation and evolution models.
6. Considering current and future UV spectroscopic capabilities, we examine potential observing strategies to constrain the multiphase ICM and cluster galaxy CGM. Substantive, important progress can be made now with *HST/COS* given modest investments of telescope time, for an ensemble of clusters probed by UV-bright ($m_{\text{FUV}} < 19$) QSOs to constrain the cool-warm gas profiles, metal enrichment, and CGM in cluster models. Dramatically improved diagnostic power would be afforded by a large-aperture space-borne UV-sensitive telescope such as the *LUVOIR* concept currently being considered. For the same ensemble of clusters one could observe at $S/N \sim 10$ with *HST/COS*, *LUVOIR* would deliver $S/N = 50 - 100$ and detect extremely diffuse cool-warm gas approaching detection rates of 90%.

UV spectroscopy provides unique insights into the cold-warm gas in and around the most massive structures in the Universe and offers a highly complementary view of the baryonic contents of galaxy clusters derived from X-ray and microwave observations. To-

gether, these forthcoming multiwavelength observations will provide a comprehensive view of the multiphase gas in the ICM of galaxy clusters and the CGM of cluster galaxies to transform our understanding of galaxy cluster physics and galaxy evolution.

Chapter 6

SUMMARY AND FUTURE WORK

6.1 Summary

The goal of this dissertation has been to develop a physical model of the CGM that can explain a wide range of observed properties of low-redshift L^* galaxies, in particular, (1) the presence of multiphase ions out to large distances from the galaxy (1.2.1), (2) the inferred low densities of cool gas (1.2.2), and (3) the kinematic alignment between multiphase ions (1.2.3).

Throughout this work, I demonstrated how cosmic rays offer a natural explanation for all three science drivers. The buildup of cosmic-ray pressure in the galactic disk drives gentle, mass-loaded outflows that populate the CGM with multiphase metals (chapter 2). Cosmic-ray pressure support allows cold gas clouds to maintain lower densities and be more buoyant (chapter 3). The presence of buoyant, low-density cold CGM gas in a cosmic-ray-pressure-supported CGM naturally leads to kinematic alignment between multiphase ions (chapter 4). Using synthetic spectroscopy, I also showed that studying diffuse, multiphase gas with UV absorption spectroscopy can shed unprecedented insights into the structures of halos around the most massive galaxies.

By constraining the role of cosmic rays in shaping the CGM, this research takes important steps towards developing a complete theory of galaxy evolution. However, existing models of cosmic-ray hydrodynamics must be constrained in order for galaxy simulations to have predictive power.

6.2 Future Work: Towards Better Models of Cosmic-ray Hydrodynamics

Existing cosmic-ray hydrodynamics models are severely under-constrained. While cosmic rays are confirmed to be an important energy source in the ISM, the amount of cosmic-ray energy in the CGM around L^* and dwarf galaxies is unknown. Therefore, simulations with small differences in cosmic-ray transport models, even those calibrated against gamma ray observations in the ISM, can produce a wide variety of CGM structures. In order to develop a robust model of cosmic-ray hydrodynamics, we need to (1) improve

existing theoretical models of cosmic rays in the fluid approximation and (2) constrain simulations against a wider range of observations.

Recent theoretical advancements have developed models of simulating cosmic-rays using a two-moment approach (Jiang and Oh, 2017; Thomas and Pfrommer, 2019; Hopkins et al., 2021c). These models can simultaneously model cosmic-ray diffusion and streaming while getting rid of some of the computational costs associated with modeling traditional diffusion. However, there is still great uncertainty in the scattering terms that drive cosmic-ray transport, and there is a strong need for both theoretical advancements and idealized simulation work to constrain these scattering terms.

Most existing simulations model cosmic rays as a single fluid, assuming that all cosmic rays are protons with GeV energies. While this is a reasonable starting point, especially when up against computational limits, this assumption neglects the role of low-energy cosmic rays in cool gas and restricts detailed comparisons to observations. Realistically, cosmic rays span a wide range of energies (MeV – TeV) and species (electrons, protons, positrons, etc). Explicitly modeling these ranges, even in a handful of discretized bins, will be helpful to constrain models of cosmic-ray transport by comparing against a wider range of observations, for example, synchrotron emission from cosmic-ray electrons and the ratios of primary to secondary cosmic-ray species.

6.3 Future Work: Simulating Cool Gas with a New Subgrid Model

Existing galaxy simulations cannot resolve the small-scale structures of cool CGM gas. The characteristic scale of cool gas is theoretically expected to be the minimum of the gas cooling time and the gas sound speed, $l \sim \min(c_s t_{\text{cool}})$ (McCourt et al., 2018). For the range of gas pressures expected in the CGM, the characteristic size of cool gas clouds is expected to be between 0.1 and 100 pc — significantly smaller than the typical resolution in the CGM (~ 500 pc) of the best-resolved simulations today.

Of course, there are some nuances that can help this discrepancy. For example, although the characteristic scale of a cool cloud is very small, cool clouds may coagulate to

form larger structures. The characteristic scale of cool clouds may also be amplified in plasmas with non-thermal pressure support from magnetic fields, or turbulence, or cosmic rays. In the extreme case of a cosmic-ray-pressure-supported halo, cool clouds may even span tens of kpc. However, even in such galaxies, cool clouds would still likely have small sizes at high redshifts, before the cosmic-ray pressure has built up sufficiently in the CGM. However, it is unclear if these aspects are enough to sufficiently bridge the gap between the physical scale of the cool cloudlets and computational power.

While the minimum necessary resolution to capture cool gas physics remains unclear, directly resolving the CGM with $\sim$ pc resolution is computationally infeasible.¹ Resolution studies of the CGM find that the cool gas properties do not converge, even at the highest resolutions (Hummels et al., 2019; Peebles et al., 2019b; Suresh et al., 2019; van de Voort et al., 2019). By under-resolving cool gas structures, current simulations are likely misrepresenting cool gas properties.

In the absence of direct resolution, I believe the way forward is to explicitly model unresolved cool gas as its own fluid, separate from the resolved gas fluid. Analogous to the treatment of dust in protoplanetary disk simulations (e.g., Laibe and Price, 2012), this fluid would track the total mass and momentum of cool gas in a cell, with the assumption that the cool gas structure is a collection of unresolved cloudlets. The unresolved cool gas fluid could exchange mass and momentum with the regular gas fluid following predictions from idealized simulations of thermal instability and cloud crushing.

Explicitly modeling unresolved cool gas, informed by high-resolution idealized simulations, would allow for galaxy simulations to gain predictive power without waiting decades for the computational power to directly resolve the cool CGM.

¹To put this in context, resolving the CGM of a galaxy with a virial radius of 200 kpc would take about ten million times more computational voxels than the largest existing cosmological volumes. Assuming Moore’s law, directly resolving the CGM with pc resolution will be infeasible for the next $\sim$ 30 years.

BIBLIOGRAPHY

Abadi, M. G., Navarro, J. F., Steinmetz, M., and Eke, V. R. (2003). Simulations of Galaxy Formation in a Λ Cold Dark Matter Universe. II. The Fine Structure of Simulated Galactic Disks. *ApJ*, 597:21–34.

Ackermann, M., Ajello, M., Allafort, A., Baldini, L., Ballet, J., Barbiellini, G., Baring, M. G., Bastieri, D., Bechtol, K., Bellazzini, R., Blandford, R. D., Bloom, E. D., Bonamente, E., Borgland, A. W., Bottacini, E., Brandt, T. J., Bregeon, J., Brigida, M., Bruel, P., Buehler, R., Busetto, G., Buson, S., Caliendo, G. A., Cameron, R. A., Caraveo, P. A., Casandjian, J. M., Cecchi, C., Çelik, Ö., Charles, E., Chaty, S., Chaves, R. C. G., Chekhtman, A., Cheung, C. C., Chiang, J., Chiaro, G., Cillis, A. N., Ciprini, S., Claus, R., Cohen-Tanugi, J., Cominsky, L. R., Conrad, J., Corbel, S., Cutini, S., D’Ammando, F., de Angelis, A., de Palma, F., Dermer, C. D., do Couto e Silva, E., Drell, P. S., Drlica-Wagner, A., Falletti, L., Favuzzi, C., Ferrara, E. C., Franckowiak, A., Fukazawa, Y., Funk, S., Fusco, P., Gargano, F., Germani, S., Giglietto, N., Giommi, P., Giordano, F., Giroletti, M., Glanzman, T., Godfrey, G., Grenier, I. A., Grondin, M.-H., Grove, J. E., Guiriec, S., Hadasch, D., Hanabata, Y., Harding, A. K., Hayashida, M., Hayashi, K., Hays, E., Hewitt, J. W., Hill, A. B., Hughes, R. E., Jackson, M. S., Jogler, T., Jóhannesson, G., Johnson, A. S., Kamae, T., Kataoka, J., Katsuta, J., Knödlseider, J., Kuss, M., Lande, J., Larsson, S., Latronico, L., Lemoine-Goumard, M., Longo, F., Loparco, F., Lovellette, M. N., Lubrano, P., Madejski, G. M., Massaro, F., Mayer, M., Mazziotta, M. N., McEnery, J. E., Mehault, J., Michelson, P. F., Mignani, R. P., Mitthumsiri, W., Mizuno, T., Moiseev, A. A., Monzani, M. E., Morselli, A., Moskalenko, I. V., Murgia, S., Nakamori, T., Nemmen, R., Nuss, E., Ohno, M., Ohsugi, T., Omodei, N., Orienti, M., Orlando, E., Ormes, J. F., Paneque, D., Perkins, J. S., Pesce-Rollins, M., Piron, F., Pivato, G., Rainò,

S., Rando, R., Razzano, M., Razzaque, S., Reimer, A., Reimer, O., Ritz, S., Romoli, C., Sánchez-Conde, M., Schulz, A., Sgrò, C., Simeon, P. E., Siskind, E. J., Smith, D. A., Spandre, G., Spinelli, P., Stecker, F. W., Strong, A. W., Suson, D. J., Tajima, H., Takahashi, H., Takahashi, T., Tanaka, T., Thayer, J. G., Thayer, J. B., Thompson, D. J., Thorsett, S. E., Tibaldo, L., Tibolla, O., Tinivella, M., Troja, E., Uchiyama, Y., Usher, T. L., Vandenbroucke, J., Vasileiou, V., Vianello, G., Vitale, V., Waite, A. P., Werner, M., Winer, B. L., Wood, K. S., Wood, M., Yamazaki, R., Yang, Z., and Zimmer, S. (2013). Detection of the Characteristic Pion-Decay Signature in Supernova Remnants. *Science*, 339:807–811.

Ackermann, M., Ajello, M., Atwood, W. B., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., Bechtol, K., Bellazzini, R., Berenji, B., Blandford, R. D., Bloom, E. D., Bonamente, E., Borgland, A. W., Brandt, T. J., Bregeon, J., Brigida, M., Bruel, P., Buehler, R., Buson, S., Caliendo, G. A., Cameron, R. A., Caraveo, P. A., Cavazzuti, E., Cecchi, C., Charles, E., Chekhtman, A., Chiang, J., Ciprini, S., Claus, R., Cohen-Tanugi, J., Conrad, J., Cutini, S., de Angelis, A., de Palma, F., Dermer, C. D., Digel, S. W., Silva, E. d. C. e., Drell, P. S., Drlica-Wagner, A., Falletti, L., Favuzzi, C., Fegan, S. J., Ferrara, E. C., Focke, W. B., Fortin, P., Fukazawa, Y., Funk, S., Fusco, P., Gaggero, D., Gargano, F., Germani, S., Giglietto, N., Giordano, F., Giroletti, M., Glanzman, T., Godfrey, G., Grove, J. E., Guiriec, S., Gustafsson, M., Hadasch, D., Hanabata, Y., Harding, A. K., Hayashida, M., Hays, E., Horan, D., Hou, X., Hughes, R. E., Jóhannesson, G., Johnson, A. S., Johnson, R. P., Kamae, T., Katagiri, H., Kataoka, J., Knödlseider, J., Kuss, M., Lande, J., Latronico, L., Lee, S.-H., Lemoine-Goumard, M., Longo, F., Loparco, F., Lott, B., Lovellette, M. N., Lubrano, P., Mazziotta, M. N., McEnery, J. E., Michelson, P. F., Mitthumsiri, W., Mizuno, T., Monte, C., Monzani, M. E., Morselli, A., Moskalenko, I. V., Murgia, S., Naumann-Godo, M., Norris, J. P., Nuss, E., Ohsugi, T., Okumura, A., Omodei, N., Orlando, E., Ormes, J. F., Paneque, D., Panetta, J. H., Parent, D., Pesce-Rollins, M., Pierbattista, M., Piron, F., Pivato, G., Porter, T. A., Rainò, S., Rando, R., Razzano, M., Razzaque, S., Reimer, A., Reimer, O., Sadrozinski, H. F.-W., Sgrò, C., Siskind, E. J.,

- Spandre, G., Spinelli, P., Strong, A. W., Suson, D. J., Takahashi, H., Tanaka, T., Thayer, J. G., Thayer, J. B., Thompson, D. J., Tibaldo, L., Tinivella, M., Torres, D. F., Tosti, G., Troja, E., Usher, T. L., Vandenbroucke, J., Vasileiou, V., Vianello, G., Vitale, V., Waite, A. P., Wang, P., Winer, B. L., Wood, K. S., Wood, M., Yang, Z., Ziegler, M., and Zimmer, S. (2012). Fermi-LAT Observations of the Diffuse γ -Ray Emission: Implications for Cosmic Rays and the Interstellar Medium. *ApJ*, 750:3.
- Agertz, O., Kravtsov, A. V., Leitner, S. N., and Gnedin, N. Y. (2013). Toward a Complete Accounting of Energy and Momentum from Stellar Feedback in Galaxy Formation Simulations. *ApJ*, 770:25.
- Allen, S. W., Evrard, A. E., and Mantz, A. B. (2011). Cosmological Parameters from Observations of Galaxy Clusters. *ARA&A*, 49:409–470.
- Anglés-Alcázar, D., Faucher-Giguère, C.-A., Kereš, D., Hopkins, P. F., Quataert, E., and Murray, N. (2017). The cosmic baryon cycle and galaxy mass assembly in the FIRE simulations. *MNRAS*, 470(4):4698–4719.
- Ashley, T., Fox, A. J., Jenkins, E. B., Wakker, B. P., Bordoloi, R., Lockman, F. J., Savage, B. D., and Karim, T. (2020). Mapping Outflowing Gas in the Fermi Bubbles: a UV Absorption Survey of the Galactic Nuclear Wind. *arXiv e-prints*, page arXiv:2006.13254.
- Asplund, M., Grevesse, N., Sauval, A. J., and Scott, P. (2009). The Chemical Composition of the Sun. *ARA&A*, 47:481–522.
- Backus, I. (2017). sphglass. <https://github.com/ibackus/sphglass>.
- Bahcall, J. N. and Spitzer, Lyman, J. (1969). Absorption Lines Produced by Galactic Halos. *ApJ*, 156:L63.

- Bahé, Y. M., Barnes, D. J., Dalla Vecchia, C., Kay, S. T., White, S. D. M., McCarthy, I. G., Schaye, J., Bower, R. G., Crain, R. A., Theuns, T., Jenkins, A., McGee, S. L., Schaller, M., Thomas, P. A., and Trayford, J. W. (2017). The Hydrangea simulations: galaxy formation in and around massive clusters. *MNRAS*, 470:4186–4208.
- Berg, M. A., Howk, J. C., Lehner, N., Wotta, C. B., O’Meara, J. M., Bowen, D. V., Burchett, J. N., Peeples, M. S., and Tejos, N. (2019). The Red Dead Redemption Survey of Circumgalactic Gas about Massive Galaxies. I. Mass and Metallicity of the Cool Phase. *ApJ*, 883(1):5.
- Bergeron, J. and Stasińska, G. (1986). Absorption line systems in QSO spectra : properties derived from observations and from photoionization models. *A&A*, 169:1–3.
- Binney, J. (1977). The physics of dissipational galaxy formation. *ApJ*, 215:483–491.
- Bish, H. V., Werk, J. K., Prochaska, J. X., Rubin, K. H. R., Zheng, Y., O’Meara, J. M., and Deason, A. J. (2019). Galactic Gas Flows from Halo to Disk: Tomography and Kinematics at the Milky Way’s Disk-Halo Interface. *ApJ*, 882(2):76.
- Bolcar, M. R., Aloezos, S., Bly, V. T., Collins, C., Crooke, J., Dressing, C. D., Fantano, L., Feinberg, L. D., France, K., Gochar, G., Gong, Q., Hylan, J. E., Jones, A., Linares, I., Postman, M., Pueyo, L., Roberge, A., Sacks, L., Tompkins, S., and West, G. (2017). The Large UV/Optical/Infrared Surveyor (LUVOIR): Decadal Mission concept design update. In *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, volume 10398 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 1039809.
- Booth, C. M., Agertz, O., Kravtsov, A. V., and Gnedin, N. Y. (2013). Simulations of Disk Galaxies with Cosmic Ray Driven Galactic Winds. *ApJ*, 777:L16.

- Booth, C. M. and Schaye, J. (2009). Cosmological simulations of the growth of supermassive black holes and feedback from active galactic nuclei: method and tests. *MNRAS*, 398:53–74.
- Bordoloi, R., Lilly, S. J., Knobel, C., Bolzonella, M., Kampczyk, P., Carollo, C. M., Iovino, A., Zucca, E., Contini, T., Kneib, J.-P., Le Fevre, O., Mainieri, V., Renzini, A., Scodeggio, M., Zamorani, G., Balestra, I., Bardelli, S., Bongiorno, A., Caputi, K., Cucciati, O., de la Torre, S., de Ravel, L., Garilli, B., Kovač, K., Lamareille, F., Le Borgne, J.-F., Le Brun, V., Maier, C., Mignoli, M., Pello, R., Peng, Y., Perez Montero, E., Presotto, V., Scarlata, C., Silverman, J., Tanaka, M., Tasca, L., Tresse, L., Vergani, D., Barnes, L., Cappi, A., Cimatti, A., Coppa, G., Diener, C., Franzetti, P., Koekemoer, A., López-Sanjuan, C., McCracken, H. J., Moresco, M., Nair, P., Oesch, P., Pozzetti, L., and Welikala, N. (2011). The Radial and Azimuthal Profiles of Mg II Absorption around $0.5 < z < 0.9$ zCOSMOS Galaxies of Different Colors, Masses, and Environments. *ApJ*, 743:10.
- Bordoloi, R., Tumlinson, J., Werk, J. K., Oppenheimer, B. D., Peebles, M. S., Prochaska, J. X., Tripp, T. M., Katz, N., Davé, R., Fox, A. J., Thom, C., Ford, A. B., Weinberg, D. H., Burchett, J. N., and Kollmeier, J. A. (2014). The COS-Dwarfs Survey: The Carbon Reservoir around Sub- L^* Galaxies. *ApJ*, 796:136.
- Borthakur, S., Heckman, T., Tumlinson, J., Bordoloi, R., Thom, C., Catinella, B., Schiminovich, D., Davé, R., Kauffmann, G., Moran, S. M., and Saintonge, A. (2015). Connection between the Circumgalactic Medium and the Interstellar Medium of Galaxies: Results from the COS-GASS Survey. *ApJ*, 813(1):46.
- Boulares, A. and Cox, D. P. (1990). Galactic hydrostatic equilibrium with magnetic tension and cosmic-ray diffusion. *ApJ*, 365:544–558.
- Bowen, D. V., Jenkins, E. B., Tripp, T. M., Sembach, K. R., Savage, B. D., Moos, H. W., Oegerle, W. R., Friedman, S. D., Gry, C., Kruk, J. W., Murphy, E., Sankrit, R., Shull,

- J. M., Sonneborn, G., and York, D. G. (2008). The Far Ultraviolet Spectroscopic Explorer Survey of O VI Absorption in the Disk of the Milky Way. *ApJS*, 176(1):59–163.
- Brio, M. and Wu, C. C. (1988). An upwind differencing scheme for the equations of ideal magnetohydrodynamics. *Journal of Computational Physics*, 75:400–422.
- Brummel-Smith, C., Bryan, G., Butsky, I., Corlies, L., Emerick, A., Forbes, J., Fujimoto, Y., Goldbaum, N., Grete, P., Hummels, C., Kim, J.-h., Koh, D., Li, M., Li, Y., Li, X., OShea, B., Peeples, M., Regan, J., Salem, M., Schmidt, W., Simpson, C., Smith, B., Tumlinson, J., Turk, M., Wise, J., Abel, T., Bordner, J., Cen, R., Collins, D., Crosby, B., Edelmann, P., Hahn, O., Harkness, R., Harper-Clark, E., Kong, S., Kritsuk, A., Kuhlen, M., Larrue, J., Lee, E., Meece, G., Norman, M., Oishi, J., Paschos, P., Peruta, C., Razoumov, A., Reynolds, D., Silvia, D., Skillman, S., Skory, S., So, G., Tasker, E., Wagner, R., Wang, P., Xu, H., and Zhao, F. (2019). ENZO: An Adaptive Mesh Refinement Code for Astrophysics (Version 2.6). *The Journal of Open Source Software*, 4(42):1636.
- Bryan, G. L., Norman, M. L., O’Shea, B. W., Abel, T., Wise, J. H., Turk, M. J., Reynolds, D. R., Collins, D. C., Wang, P., Skillman, S. W., Smith, B., Harkness, R. P., Bordner, J., Kim, J.-h., Kuhlen, M., Xu, H., Goldbaum, N., Hummels, C., Kritsuk, A. G., Tasker, E., Skory, S., Simpson, C. M., Hahn, O., Oishi, J. S., So, G. C., Zhao, F., Cen, R., Li, Y., and Enzo Collaboration (2014). ENZO: An Adaptive Mesh Refinement Code for Astrophysics. *ApJS*, 211:19.
- Buck, T., Pfrommer, C., Pakmor, R., Grand, R. J. J., and Springel, V. (2020). The effects of cosmic rays on the formation of Milky Way-mass galaxies in a cosmological context. *MNRAS*.
- Burchett, J. N., Rubin, K. H. R., Prochaska, J. X., Coil, A. L., Rickards Vaught, R., and Hennawi, J. F. (2020). Circumgalactic Mg II Emission from an Isotropic Starburst Galaxy Outflow Mapped by KCWI. *arXiv e-prints*, page arXiv:2005.03017.

- Burchett, J. N., Tripp, T. M., Prochaska, J. X., Werk, J. K., Tumlinson, J., Howk, J. C., Willmer, C. N. A., Lehner, N., Meiring, J. D., Bowen, D. V., Bordoloi, R., Peeples, M. S., Jenkins, E. B., O’Meara, J. M., Tejos, N., and Katz, N. (2019). The COS Absorption Survey of Baryon Harbors (CASBaH): Warm-Hot Circumgalactic Gas Reservoirs Traced by Ne VIII Absorption. *ApJ*, 877(2):L20.
- Burchett, J. N., Tripp, T. M., Prochaska, J. X., Werk, J. K., Tumlinson, J., O’Meara, J. M., Bordoloi, R., Katz, N., and Willmer, C. N. A. (2015). A Deep Search For Faint Galaxies Associated With Very Low-redshift C IV Absorbers: II. Program Design, Absorption-line Measurements, and Absorber Statistics. *ApJ*, 815(2):91.
- Burchett, J. N., Tripp, T. M., Wang, Q. D., Willmer, C. N. A., Bowen, D. V., and Jenkins, E. B. (2018). Warm-hot gas in X-ray bright galaxy clusters and the H I-deficient circumgalactic medium in dense environments. *MNRAS*, 475:2067–2085.
- Bustard, C., Zweibel, E. G., D’Onghia, E., Gallagher, J. S., I., and Farber, R. (2020). Cosmic-Ray-driven Outflows from the Large Magellanic Cloud: Contributions to the LMC Filament. *ApJ*, 893(1):29.
- Butsky, I. and Quinn, R. (2018). The Role of Cosmic Ray Transport in Shaping the Simulated Circumgalactic Medium. *ArXiv e-prints*.
- Butsky, I., Zrake, J., Kim, J.-h., Yang, H.-I., and Abel, T. (2017). Ab initio Simulations of a Supernova Driven Galactic Dynamo in an Isolated Disk Galaxy. *ApJ*, 843:113.
- Butsky, I. S., Burchett, J. N., Nagai, D., Tremmel, M., Quinn, T. R., and Werk, J. K. (2019). Ultraviolet signatures of the multiphase intracluster and circumgalactic media in the ROMULUSC simulation. *MNRAS*, 490(3):4292–4306.
- Butsky, I. S., Fielding, D. B., Hayward, C. C., Hummels, C. B., Quinn, T. R., and Werk, J. K.

- (2020). The impact of cosmic rays on thermal instability in the circumgalactic medium. *ApJ*, 903(2):77.
- Cen, R. and Ostriker, J. P. (1992). Galaxy formation and physical bias. *ApJ*, 399:L113–L116.
- Cen, R. and Ostriker, J. P. (1999). Where Are the Baryons? *ApJ*, 514:1–6.
- Chan, T. K., Kereš, D., Hopkins, P. F., Quataert, E., Su, K. Y., Hayward, C. C., and Faucher-Giguère, C. A. (2019). Cosmic ray feedback in the FIRE simulations: constraining cosmic ray propagation with GeV γ -ray emission. *MNRAS*, 488(3):3716–3744.
- Chen, H.-W., Gauthier, J.-R., Sharon, K., Johnson, S. D., Nair, P., and Liang, C. J. (2014). Spatially resolved velocity maps of halo gas around two intermediate-redshift galaxies. *MNRAS*, 438(2):1435–1450.
- Chen, H.-W., Helsby, J. E., Gauthier, J.-R., Shectman, S. A., Thompson, I. B., and Tinker, J. L. (2010). An Empirical Characterization of Extended Cool Gas Around Galaxies Using Mg II Absorption Features. *ApJ*, 714:1521–1541.
- Chen, H.-W., Lanzetta, K. M., Webb, J. K., and Barcons, X. (1998). The Gaseous Extent of Galaxies and the Origin of Ly α Absorption Systems. III. Hubble Space Telescope Imaging of Ly α -absorbing Galaxies at $z < 1$. *ApJ*, 498(1):77–94.
- Cheng, B., Schramm, D. N., and Truran, J. W. (1994). Constraints on the strength of a primordial magnetic field from big bang nucleosynthesis. *Phys. Rev. D*, 49:5006–5018.
- Choudhury, P. P. and Sharma, P. (2016). Cold gas in cluster cores: global stability analysis and non-linear simulations of thermal instability. *MNRAS*, 457(3):2554–2568.
- Choudhury, P. P., Sharma, P., and Quataert, E. (2019). Multiphase gas in the circumgalactic medium: relative role of t_{cool}/t_{ff} and density fluctuations. *MNRAS*, 488(3):3195–3210.

- Christensen, C. R., Brooks, A. M., Fisher, D. B., Governato, F., McCleary, J., Quinn, T. R., Shen, S., and Wadsley, J. (2014). Simulating disc galaxy bulges that are consistent with observed scaling relations. *MNRAS*, 440:L51–L55.
- Collins, D. C., Xu, H., Norman, M. L., Li, H., and Li, S. (2010). Cosmological Adaptive Mesh Refinement Magnetohydrodynamics with Enzo. *ApJS*, 186:308–333.
- Creasey, P., Theuns, T., and Bower, R. G. (2013). How supernova explosions power galactic winds. *MNRAS*, 429:1922–1948.
- Crighton, N. H. M., Hennawi, J. F., Simcoe, R. A., Cooksey, K. L., Murphy, M. T., Fumagalli, M., Prochaska, J. X., and Shanks, T. (2015). Metal-enriched, subkiloparsec gas clumps in the circumgalactic medium of a faint $z = 2.5$ galaxy. *MNRAS*, 446(1):18–37.
- Davé, R., Oppenheimer, B. D., and Finlator, K. (2011). Galaxy evolution in cosmological simulations with outflows - I. Stellar masses and star formation rates. *MNRAS*, 415:11–31.
- Davies, R. D. and Lewis, B. M. (1973). Neutral hydrogen in Virgo cluster galaxies. *MNRAS*, 165:231–244.
- Dedner, A., Kemm, F., Kröner, D., Munz, C.-D., Schnitzer, T., and Wesenberg, M. (2002). Hyperbolic Divergence Cleaning for the MHD Equations. *Journal of Computational Physics*, 175:645–673.
- Dressler, A. (1980). Galaxy morphology in rich clusters - Implications for the formation and evolution of galaxies. *ApJ*, 236:351–365.
- Drury, L. O. and Falle, S. A. E. G. (1986). On the Stability of Shocks Modified by Particle Acceleration. *MNRAS*, 223:353.

- Durrer, R. and Neronov, A. (2013). Cosmological magnetic fields: their generation, evolution and observation. *A&A Rev.*, 21:62.
- Ellison, D. C., Patnaude, D. J., Slane, P., and Raymond, J. (2010). Efficient Cosmic Ray Acceleration, Hydrodynamics, and Self-Consistent Thermal X-Ray Emission Applied to Supernova Remnant RX J1713.7-3946. *ApJ*, 712:287–293.
- Emerick, A., Bryan, G., and Putman, M. E. (2015). Warm gas in and around simulated galaxy clusters as probed by absorption lines. *MNRAS*, 453:4051–4069.
- Emerick, A., Bryan, G. L., and Mac Low, M.-M. (2019). Simulating an isolated dwarf galaxy with multichannel feedback and chemical yields from individual stars. *MNRAS*, 482:1304–1329.
- Enßlin, T. A., Pfrommer, C., Springel, V., and Jubelgas, M. (2007). Cosmic ray physics in calculations of cosmological structure formation. *A&A*, 473:41–57.
- Esmerian, C. J., Kravtsov, A. V., Hafen, Z., Faucher-Giguere, C.-A., Quataert, E., Stern, J., Keres, D., and Wetzel, A. (2020). Thermal Instability in the CGM of $L_\star$ Galaxies: Testing “Precipitation” Models with the FIRE Simulations. *arXiv e-prints*, page arXiv:2006.13945.
- Farber, R., Ruszkowski, M., Yang, H.-Y. K., and Zweibel, E. G. (2017). Impact of Cosmic Ray Transport on Galactic Winds. *ArXiv e-prints*.
- Farber, R., Ruszkowski, M., Yang, H.-Y. K., and Zweibel, E. G. (2018). Impact of cosmic-ray transport on galactic winds. *The Astrophysical Journal*, 856(2):112.
- Feldmann, R., Hooper, D., and Gnedin, N. Y. (2013). Circum-galactic Gas and the Isotropic Gamma-Ray Background. *ApJ*, 763:21.

- Ferland, G. J., Porter, R. L., van Hoof, P. A. M., Williams, R. J. R., Abel, N. P., Lykins, M. L., Shaw, G., Henney, W. J., and Stancil, P. C. (2013). The 2013 Release of Cloudy. *Rev. Mexicana Astron. Astrofis.*, 49:137–163.
- Field, G. B. (1965). Thermal Instability. *ApJ*, 142:531.
- Fielding, D., Quataert, E., McCourt, M., and Thompson, T. A. (2017). The impact of star formation feedback on the circumgalactic medium. *MNRAS*, 466:3810–3826.
- Fielding, D. B., Ostriker, E. C., Bryan, G. L., and Jermyn, A. S. (2020a). Multiphase Gas and the Fractal Nature of Radiative Turbulent Mixing Layers. *ApJ*, 894(2):L24.
- Fielding, D. B., Tonnesen, S., DeFelippis, D., Li, M., Su, K.-Y., Bryan, G. L., Kim, C.-G., Forbes, J. C., Somerville, R. S., Battaglia, N., Schneider, E. E., Li, Y., Choi, E., Hayward, C. C., and Hernquist, L. (2020b). First results from SMAUG: Uncovering the Origin of the Multiphase Circumgalactic Medium with a Comparative Analysis of Idealized and Cosmological Simulations. *arXiv e-prints*, page arXiv:2006.16316.
- Fluetsch, A., Maiolino, R., Carniani, S., Arribas, S., Belfiore, F., Bellocchi, E., Cazzoli, S., Cicone, C., Cresci, G., Fabian, A. C., Gallagher, R., Ishibashi, W., Mannucci, F., Marconi, A., Perna, M., Sturm, E., and Venturi, G. (2020). Properties of the Multiphase Outflows in Local (Ultra)luminous Infrared Galaxies. *arXiv e-prints*, page arXiv:2006.13232.
- Ford, A. B., Davé, R., Oppenheimer, B. D., Katz, N., Kollmeier, J. A., Thompson, R., and Weinberg, D. H. (2014). Tracing inflows and outflows with absorption lines in circumgalactic gas. *MNRAS*, 444(2):1260–1281.
- Fox, A. J., Richter, P., Ashley, T., Heckman, T. M., Lehner, N., Werk, J. K., Bordoloi, R., and Peebles, M. S. (2019). The Mass Inflow and Outflow Rates of the Milky Way. *ApJ*, 884(1):53.

- Fraser-McKelvie, A., Brown, M. J. I., Pimbblet, K., Dolley, T., and Bonne, N. J. (2018). Multiple mechanisms quench passive spiral galaxies. *MNRAS*, 474:1909–1921.
- Fumagalli, M., Fossati, M., Hau, G. K. T., Gavazzi, G., Bower, R., Sun, M., and Boselli, A. (2014). MUSE sneaks a peek at extreme ram-pressure stripping events - I. A kinematic study of the archetypal galaxy ESO137-001. *MNRAS*, 445:4335–4344.
- Gaspari, M., Ruszkowski, M., and Sharma, P. (2012). Cause and Effect of Feedback: Multiphase Gas in Cluster Cores Heated by AGN Jets. *ApJ*, 746(1):94.
- Gauthier, J.-R., Chen, H.-W., and Tinker, J. L. (2010). The Incidence of Cool Gas in $\sim 10^{13} M_{\text{sun}}$ Halos. *ApJ*, 716:1263–1268.
- Ge, C., Wang, Q. D., Tripp, T. M., Li, Z., Gu, Q., and Ji, L. (2016). Baryon content and dynamic state of galaxy clusters: XMM-Newton observations of A1095 and A1926. *MNRAS*, 459:366–386.
- Genel, S., Bryan, G. L., Springel, V., Hernquist, L., Nelson, D., Pillepich, A., Weinberger, R., Pakmor, R., Marinacci, F., and Vogelsberger, M. (2019). A Quantification of the Butterfly Effect in Cosmological Simulations and Implications for Galaxy Scaling Relations. *ApJ*, 871(1):21.
- Ghavamian, P., Aloisi, A., Lennon, D., Hartig, G., Kriss, G. A., Oliveira, C., Massa, D., Keyes, T., Proffitt, C., Delker, T., and Osterman, S. (2009). Preliminary Characterization of the Post-Launch Line Spread Function of COS. Technical report.
- Ginzburg, V. L. and Ptuskin, V. S. (1985). The origin of cosmic rays. *Astrophys. Space Phys. Res.*, 4:161–256.
- Girichidis, P., Naab, T., Hanasz, M., and Walch, S. (2018). Cooler and smoother - the impact of cosmic rays on the phase structure of galactic outflows. *MNRAS*, 479(3):3042–3067.

- Girichidis, P., Naab, T., Walch, S., Hanasz, M., Mac Low, M.-M., Ostriker, J. P., Gatto, A., Peters, T., Wünsch, R., Glover, S. C. O., Klessen, R. S., Clark, P. C., and Baczynski, C. (2016). Launching Cosmic-Ray-driven Outflows from the Magnetized Interstellar Medium. *ApJ*, 816:L19.
- Gnat, O. and Sternberg, A. (2007). Time-dependent Ionization in Radiatively Cooling Gas. *ApJS*, 168:213–230.
- Governato, F., Zolotov, A., Pontzen, A., Christensen, C., Oh, S. H., Brooks, A. M., Quinn, T., Shen, S., and Wadsley, J. (2012). Cuspy no more: how outflows affect the central dark matter and baryon distribution in Λ cold dark matter galaxies. *MNRAS*, 422:1231–1240.
- Green, J. C., Froning, C. S., Osterman, S., Ebbets, D., Heap, S. H., Leitherer, C., Linsky, J. L., Savage, B. D., Sembach, K., Shull, J. M., Siegmund, O. H. W., Snow, T. P., Spencer, J., Stern, S. A., Stocke, J., Welsh, B., Béland, S., Burgh, E. B., Danforth, C., France, K., Keeney, B., McPhate, J., Penton, S. V., Andrews, J., Brownsberger, K., Morse, J., and Wilkinson, E. (2012). The Cosmic Origins Spectrograph. *ApJ*, 744:60.
- Gronke, M. and Oh, S. P. (2018). The growth and entrainment of cold gas in a hot wind. *MNRAS*, 480(1):L111–L115.
- Gronke, M. and Oh, S. P. (2020). Is multiphase gas cloudy or misty? *MNRAS*, 494(1):L27–L31.
- Gunn, J. E. and Gott, III, J. R. (1972). On the Infall of Matter Into Clusters of Galaxies and Some Effects on Their Evolution. *ApJ*, 176:1.
- Guo, F. and Oh, S. P. (2008). Feedback heating by cosmic rays in clusters of galaxies. *MNRAS*, 384(1):251–266.

- Gutcke, T. A., Stinson, G. S., Macciò, A. V., Wang, L., and Dutton, A. A. (2017). NIHAO - VIII. Circum-galactic medium and outflows - The puzzles of H I and O VI gas distributions. *MNRAS*, 464:2796–2815.
- Haardt, F. and Madau, P. (2012). Radiative Transfer in a Clumpy Universe. IV. New Synthesis Models of the Cosmic UV/X-Ray Background. *ApJ*, 746:125.
- Hafen, Z., Faucher-Giguère, C.-A., Anglés-Alcázar, D., Stern, J., Kereš, D., Hummels, C., Esmerian, C., Garrison-Kimmel, S., El-Badry, K., Wetzel, A., Chan, T. K., Hopkins, P. F., and Murray, N. (2019). The origins of the circumgalactic medium in the FIRE simulations. *MNRAS*, 488(1):1248–1272.
- Harris, W., France, K., Fleming, B., and Bolcar, M. (2018). The LUVOIR Ultraviolet Multi-Object Spectrograph (LUMOS). *AGU Fall Meeting Abstracts*.
- Heckman, T. M., Lehnert, M. D., Strickland, D. K., and Armus, L. (2000). Absorption-Line Probes of Gas and Dust in Galactic Superwinds. *ApJS*, 129(2):493–516.
- Hernquist, L. (1990). An analytical model for spherical galaxies and bulges. *ApJ*, 356:359–364.
- Hopkins, P. F., Chan, T. K., Garrison-Kimmel, S., Ji, S., Su, K.-Y., Hummels, C. B., Kereš, D., Quataert, E., and Faucher-Giguère, C.-A. (2020). But what about...: cosmic rays, magnetic fields, conduction, and viscosity in galaxy formation. *MNRAS*, 492(3):3465–3498.
- Hopkins, P. F., Chan, T. K., Ji, S., Hummels, C. B., Kereš, D., Quataert, E., and Faucher-Giguère, C.-A. (2021a). Cosmic ray driven outflows to Mpc scales from L_* galaxies. *MNRAS*, 501(3):3640–3662.

- Hopkins, P. F., Chan, T. K., Squire, J., Quataert, E., Ji, S., Kereš, D., and Faucher-Giguère, C.-A. (2021b). Effects of different cosmic ray transport models on galaxy formation. *MNRAS*, 501(3):3663–3669.
- Hopkins, P. F., Quataert, E., and Murray, N. (2012). Stellar feedback in galaxies and the origin of galaxy-scale winds. *MNRAS*, 421:3522–3537.
- Hopkins, P. F., Squire, J., and Butsky, I. S. (2021c). A Consistent Reduced-Speed-of-Light Formulation of Cosmic Ray Transport Valid in Weak and Strong-Scattering Regimes. *arXiv e-prints*, page arXiv:2103.10443.
- Hopkins, P. F., Squire, J., Chan, T. K., Quataert, E., Ji, S., Kereš, D., and Faucher-Giguère, C.-A. (2021d). Testing physical models for cosmic ray transport coefficients on galactic scales: self-confinement and extrinsic turbulence at $\sim$ GeV energies. *MNRAS*, 501(3):4184–4213.
- Hopkins, P. F., Wetzel, A., Kereš, D., Faucher-Giguère, C.-A., Quataert, E., Boylan-Kolchin, M., Murray, N., Hayward, C. C., Garrison-Kimmel, S., Hummels, C., Feldmann, R., Torrey, P., Ma, X., Anglés-Alcázar, D., Su, K.-Y., Orr, M., Schmitz, D., Escala, I., Sanderson, R., Grudić, M. Y., Hafen, Z., Kim, J.-H., Fitts, A., Bullock, J. S., Wheeler, C., Chan, T. K., Elbert, O. D., and Narayanan, D. (2018). FIRE-2 simulations: physics versus numerics in galaxy formation. *MNRAS*, 480:800–863.
- Hummels, C. B. and Bryan, G. L. (2012). Adaptive Mesh Refinement Simulations of Galaxy Formation: Exploring Numerical and Physical Parameters. *ApJ*, 749:140.
- Hummels, C. B., Bryan, G. L., Smith, B. D., and Turk, M. J. (2013). Constraints on hydrodynamical subgrid models from quasar absorption line studies of the simulated circumgalactic medium. *MNRAS*, 430:1548–1565.

- Hummels, C. B., Smith, B. D., Hopkins, P. F., O’Shea, B. W., Silvia, D. W., Werk, J. K., Lehner, N., Wise, J. H., Collins, D. C., and Butsky, I. S. (2018a). The Impact of Enhanced Halo Resolution on the Simulated Circumgalactic Medium. *arXiv e-prints*.
- Hummels, C. B., Smith, B. D., Hopkins, P. F., O’Shea, B. W., Silvia, D. W., Werk, J. K., Lehner, N., Wise, J. H., Collins, D. C., and Butsky, I. S. (2018b). The Impact of Enhanced Halo Resolution on the Simulated Circumgalactic Medium. *arXiv e-prints*, page arXiv:1811.12410.
- Hummels, C. B., Smith, B. D., Hopkins, P. F., O’Shea, B. W., Silvia, D. W., Werk, J. K., Lehner, N., Wise, J. H., Collins, D. C., and Butsky, I. S. (2019). The Impact of Enhanced Halo Resolution on the Simulated Circumgalactic Medium. *ApJ*, 882(2):156.
- Hummels, C. B., Smith, B. D., and Silvia, D. W. (2017). Trident: A Universal Tool for Generating Synthetic Absorption Spectra from Astrophysical Simulations. *ApJ*, 847:59.
- Ipavich, F. M. (1975). Galactic winds driven by cosmic rays. *ApJ*, 196:107–120.
- Jáchym, P., Combes, F., Cortese, L., Sun, M., and Kenney, J. D. P. (2014). Abundant Molecular Gas and Inefficient Star Formation in Intracluster Regions: Ram Pressure Stripped Tail of the Norma Galaxy ESO137-001. *ApJ*, 792:11.
- Jacob, S., Pakmor, R., Simpson, C. M., Springel, V., and Pfrommer, C. (2017). The dependence of cosmic ray driven galactic winds on halo mass. *ArXiv e-prints*.
- Jacob, S. and Pfrommer, C. (2017a). Cosmic ray heating in cool core clusters - I. Diversity of steady state solutions. *MNRAS*, 467(2):1449–1477.
- Jacob, S. and Pfrommer, C. (2017b). Cosmic ray heating in cool core clusters - II. Self-regulation cycle and non-thermal emission. *MNRAS*, 467:1478–1495.

- Jana, R., Gupta, S., and Nath, B. B. (2020). Role of cosmic rays in the early stages of galactic outflows. *MNRAS*, 497(3):2623–2640.
- Ji, S., Chan, T. K., Hummels, C. B., Hopkins, P. F., Stern, J., Kereš, D., Quataert, E., Faucher-Giguère, C.-A., and Murray, N. (2020a). Properties of the Circumgalactic Medium in Cosmic Ray-Dominated Galaxy Halos. *MNRAS*.
- Ji, S., Kereš, D., Chan, T. K., Stern, J., Hummels, C. B., Hopkins, P. F., Quataert, E., and Faucher-Giguère, C.-A. (2020b). Virial shocks are suppressed in cosmic ray-dominated galaxy halos. *arXiv e-prints*, page arXiv:2011.04706.
- Ji, S., Oh, S. P., and McCourt, M. (2017). The impact of magnetic fields on thermal instability. *ArXiv e-prints*.
- Ji, S., Oh, S. P., and McCourt, M. (2018). The impact of magnetic fields on thermal instability. *MNRAS*, 476(1):852–867.
- Jiang, Y.-F. and Oh, P. (2017). A New Numerical Scheme for Cosmic Ray Transport. *ArXiv e-prints*.
- Johnson, S. D., Chen, H.-W., and Mulchaey, J. S. (2015). On the possible environmental effect in distributing heavy elements beyond individual gaseous haloes. *MNRAS*, 449:3263–3273.
- Joung, M. R., Mac Low, M.-M., and Bryan, G. L. (2009). Dependence of Interstellar Turbulent Pressure on Supernova Rate. *ApJ*, 704:137–149.
- Jubelgas, M., Springel, V., Enßlin, T., and Pfrommer, C. (2008). Cosmic ray feedback in hydrodynamical simulations of galaxy formation. *A&A*, 481:33–63.
- Jun, B.-I., Clarke, D. A., and Norman, M. L. (1994). The evolution of cosmic-ray-mediated magnetohydrodynamic shocks: A two-fluid approach. *ApJ*, 429:748–758.

- Kacprzak, G. G., Churchill, C. W., Ceverino, D., Steidel, C. C., Klypin, A., and Murphy, M. T. (2010). Halo Gas and Galaxy Disk Kinematics Derived from Observations and Λ CDM Simulations of Mg II Absorption-selected Galaxies at Intermediate Redshift. *ApJ*, 711:533–558.
- Keeney, B. A., Stocke, J. T., Pratt, C. T., Davis, J. D., Syphers, D., Danforth, C. W., Shull, J. M., Froning, C. S., Green, J. C., Penton, S. V., and Savage, B. D. (2018). A Galaxy Redshift Survey Near HST/COS AGN Sight Lines. *ApJS*, 237(1):11.
- Keller, B. W., Wadsley, J., and Couchman, H. M. P. (2015). Cosmological galaxy evolution with superbubble feedback - I. Realistic galaxies with moderate feedback. *MNRAS*, 453:3499–3509.
- Keller, B. W., Wadsley, J., and Couchman, H. M. P. (2016). Cosmological galaxy evolution with superbubble feedback - II. The limits of supernovae. *MNRAS*, 463:1431–1445.
- Kempster, P. and Quataert, E. (2020). Thermal instability of halo gas heated by streaming cosmic rays. *MNRAS*, 493(2):1801–1817.
- Kim, J.-h., Abel, T., Agertz, O., Bryan, G. L., Ceverino, D., Christensen, C., Conroy, C., Dekel, A., Gnedin, N. Y., Goldbaum, N. J., Guedes, J., Hahn, O., Hobbs, A., Hopkins, P. F., Hummels, C. B., Iannuzzi, F., Keres, D., Klypin, A., Kravtsov, A. V., Krumholz, M. R., Kuhlen, M., Leitner, S. N., Madau, P., Mayer, L., Moody, C. E., Nagamine, K., Norman, M. L., Onorbe, J., O’Shea, B. W., Pillepich, A., Primack, J. R., Quinn, T., Read, J. I., Robertson, B. E., Rocha, M., Rudd, D. H., Shen, S., Smith, B. D., Szalay, A. S., Teyssier, R., Thompson, R., Todoroki, K., Turk, M. J., Wadsley, J. W., Wise, J. H., Zolotov, A., and AGORA Collaboration²⁹, t. (2014). The AGORA High-resolution Galaxy Simulations Comparison Project. *ApJS*, 210:14.

- Kim, J.-h., Wise, J. H., Alvarez, M. A., and Abel, T. (2011). Galaxy Formation with Self-consistently Modeled Stars and Massive Black Holes. I. Feedback-regulated Star Formation and Black Hole Growth. *ApJ*, 738:54.
- Kravtsov, A. V. and Borgani, S. (2012). Formation of Galaxy Clusters. *ARA&A*, 50:353–409.
- Kroupa, P. (2001). On the variation of the initial mass function. *MNRAS*, 322:231–246.
- Kulsrud, R. and Pearce, W. P. (1969). The Effect of Wave-Particle Interactions on the Propagation of Cosmic Rays. *ApJ*, 156:445.
- Kumar, R. and Eichler, D. (2014). Large-scale Anisotropy of TeV-band Cosmic Rays. *ApJ*, 785(2):129.
- Kuntz, K. D. and Snowden, S. L. (2000). Deconstructing the Spectrum of the Soft X-Ray Background. *ApJ*, 543(1):195–215.
- Kurganov, A. and Tadmor, E. (2000). New High-Resolution Central Schemes for Nonlinear Conservation Laws and Convection-Diffusion Equations. *Journal of Computational Physics*, 160:241–282.
- Laibe, G. and Price, D. J. (2012). Dusty gas with smoothed particle hydrodynamics - I. Algorithm and test suite. *MNRAS*, 420(3):2345–2364.
- Laigle, C., McCracken, H. J., Ilbert, O., Hsieh, B. C., Davidzon, I., Capak, P., Hasinger, G., Silverman, J. D., Pichon, C., Coupon, J., Aussel, H., Le Borgne, D., Caputi, K., Cassata, P., Chang, Y. Y., Civano, F., Dunlop, J., Fynbo, J., Kartaltepe, J. S., Koekemoer, A., Le Fèvre, O., Le Floch, E., Leauthaud, A., Lilly, S., Lin, L., Marchesi, S., Milvang-Jensen, B., Salvato, M., Sanders, D. B., Scoville, N., Smolcic, V., Stockmann, M., Taniguchi, Y., Tasca, L., Toft, S., Vaccari, M., and Zabl, J. (2016). The COSMOS2015 Catalog: Exploring the $1 < z < 6$ Universe with Half a Million Galaxies. *ApJS*, 224(2):24.

- Lake, G., Katz, N., and Moore, B. (1998). The Formation of Quasars in Low-Luminosity Hosts via Galaxy Harassment. *ApJ*, 495:152–156.
- Lan, T.-W. and Prochaska, J. X. (2020). Constraining magnetic fields in the circumgalactic medium. *MNRAS*, 496(3):3142–3151.
- Lau, E. T., Kravtsov, A. V., and Nagai, D. (2009). Residual Gas Motions in the Intracluster Medium and Bias in Hydrostatic Measurements of Mass Profiles of Clusters. *ApJ*, 705:1129–1138.
- Lau, E. T., Nagai, D., Avestruz, C., Nelson, K., and Vikhlinin, A. (2015). Mass Accretion and its Effects on the Self-similarity of Gas Profiles in the Outskirts of Galaxy Clusters. *ApJ*, 806:68.
- Lehner, N., Howk, J. C., Tripp, T. M., Tumlinson, J., Prochaska, J. X., O’Meara, J. M., Thom, C., Werk, J. K., Fox, A. J., and Ribaud, J. (2013). The Bimodal Metallicity Distribution of the Cool Circumgalactic Medium at $z < \sim 1$. *ApJ*, 770(2):138.
- Lehner, N., Savage, B. D., Richter, P., Sembach, K. R., Tripp, T. M., and Wakker, B. P. (2007). Physical Properties, Baryon Content, and Evolution of the Ly α Forest: New Insights from High-Resolution Observations at $z < \sim 0.4$. *ApJ*, 658:680–709.
- Lehner, N., Wotta, C. B., Howk, J. C., O’Meara, J. M., Oppenheimer, B. D., and Cooksey, K. L. (2019). The COS CGM Compendium. III. Metallicity and Physical Properties of the Cool Circumgalactic Medium at $z \lesssim 1$. *ApJ*, 887(1):5.
- Li, Z., Hopkins, P. F., Squire, J., and Hummels, C. (2020). On the survival of cool clouds in the circumgalactic medium. *MNRAS*, 492(2):1841–1854.
- Liang, C. J. and Chen, H.-W. (2014). Mining circumgalactic baryons in the low-redshift universe. *MNRAS*, 445(2):2061–2081.

- Liang, C. J. and Remming, I. (2020). On the model of the circumgalactic mist: the implications of cloud sizes in galactic winds and haloes. *MNRAS*, 491(4):5056–5072.
- Maller, A. H. and Bullock, J. S. (2004). Multiphase galaxy formation: high-velocity clouds and the missing baryon problem. *MNRAS*, 355(3):694–712.
- Mandelker, N., van den Bosch, F. C., Springel, V., and van de Voort, F. (2019). Shattering of Cosmic Sheets due to Thermal Instabilities: A Formation Channel for Metal-free Lyman Limit Systems. *ApJ*, 881(1):L20.
- Marasco, A., Debattista, V. P., Fraternali, F., van der Hulst, T., Wadsley, J., Quinn, T., and Roškar, R. (2015). The effect of stellar feedback on a Milky Way-like galaxy and its gaseous halo. *MNRAS*, 451:4223–4237.
- McCourt, M., Oh, S. P., O’Leary, R., and Madigan, A.-M. (2018). A characteristic scale for cold gas. *MNRAS*, 473(4):5407–5431.
- McCourt, M., O’Leary, R. M., Madigan, A.-M., and Quataert, E. (2015). Magnetized gas clouds can survive acceleration by a hot wind. *MNRAS*, 449(1):2–7.
- McCourt, M., Sharma, P., Quataert, E., and Parrish, I. J. (2012). Thermal instability in gravitationally stratified plasmas: implications for multiphase structure in clusters and galaxy haloes. *MNRAS*, 419:3319–3337.
- McCracken, H. J., Milvang-Jensen, B., Dunlop, J., Franx, M., Fynbo, J. P. U., Le Fèvre, O., Holt, J., Caputi, K. I., Goranova, Y., Buitrago, F., Emerson, J. P., Freudling, W., Hudelot, P., López-Sanjuan, C., Magnard, F., Mellier, Y., Møller, P., Nilsson, K. K., Sutherland, W., Tasca, L., and Zabl, J. (2012). UltraVISTA: a new ultra-deep near-infrared survey in COSMOS. *A&A*, 544:A156.

- McKee, C. F. and Cowie, L. L. (1975). The interaction between the blast wave of a supernova remnant and interstellar clouds. *ApJ*, 195:715–725.
- McNamara, B. R. and Nulsen, P. E. J. (2007). Heating Hot Atmospheres with Active Galactic Nuclei. *ARA&A*, 45:117–175.
- McQuinn, M. and Werk, J. K. (2017). Implications of the large OVI columns around low-redshift L_* galaxies. *ArXiv e-prints*.
- Meece, G. R., O’Shea, B. W., and Voit, G. M. (2015). Growth and Evolution of Thermal Instabilities in Idealized Galaxy Cluster Cores. *ApJ*, 808(1):43.
- Menon, L., Wesolowski, F., Zheng, G., Jetley, P., Kale, L. V., Quinn, T. R., and Governato, F. (2015). In *Adaptive Techniques for Clustered N-Body Cosmological Simulations. Computational Astrophysics and Cosmology*, 2, 1.
- Mernier, F., Biffi, V., Yamaguchi, H., Medvedev, P., Simionescu, A., Ettori, S., Werner, N., Kaastra, J. S., de Plaa, J., and Gu, L. (2018). Enrichment of the Hot Intracluster Medium: Observations. *Space Sci. Rev.*, 214:129.
- Miniati, F., Jones, T. W., Kang, H., and Ryu, D. (2001). Cosmic-Ray Electrons in Groups and Clusters of Galaxies: Primary and Secondary Populations from a Numerical Cosmological Simulation. *ApJ*, 562:233–253.
- Mo, H. J. and Miralda-Escude, J. (1996). Gaseous Galactic Halos and Quasi-stellar Object Absorption-Line Systems. *ApJ*, 469:589.
- Moore, B., Katz, N., Lake, G., Dressler, A., and Oemler, A. (1996). Galaxy harassment and the evolution of clusters of galaxies. *Nature*, 379:613–616.

- Mroczkowski, T., Nagai, D., Basu, K., Chluba, J., Sayers, J., Adam, R., Churazov, E., Crites, A., Di Mascolo, L., Eckert, D., Macias-Perez, J., Mayet, F., Perotto, L., Pointecouteau, E., Romero, C., Ruppén, F., Scannapieco, E., and ZuHone, J. (2019). Astrophysics with the Spatially and Spectrally Resolved Sunyaev-Zeldovich Effects. A Millimetre/Submillimetre Probe of the Warm and Hot Universe. *Space Sci. Rev.*, 215:17.
- Münch, G. and Zirin, H. (1961). Interstellar Matter at Large Distances from the Galactic Plane. *ApJ*, 133:11.
- Murray, N., Ménard, B., and Thompson, T. A. (2011). Radiation Pressure from Massive Star Clusters as a Launching Mechanism for Super-galactic Winds. *ApJ*, 735:66.
- Muzahid, S., Charlton, J., Nagai, D., Schaye, J., and Srianand, R. (2017). Discovery of an H i-rich Gas Reservoir in the Outskirts of SZ-effect-selected Clusters. *The Astrophysical Journal Letters*, 846:L8.
- Nagai, D. and Lau, E. T. (2011). Gas Clumping in the Outskirts of Λ CDM Clusters. *ApJ*, 731:L10.
- Nagai, D., Lau, E. T., Avestruz, C., Nelson, K., and Rudd, D. H. (2013). Predicting Merger-induced Gas Motions in Λ CDM Galaxy Clusters. *ApJ*, 777:137.
- Navarro, J. F., Frenk, C. S., and White, S. D. M. (1997). A Universal Density Profile from Hierarchical Clustering. *ApJ*, 490:493–508.
- Nelson, D., Kauffmann, G., Pillepich, A., Genel, S., Springel, V., Pakmor, R., Hernquist, L., Weinberger, R., Torrey, P., Vogelsberger, M., and Marinacci, F. (2018). The abundance, distribution, and physical nature of highly ionized oxygen O VI, O VII, and O VIII in IllustrisTNG. *MNRAS*, 477(1):450–479.

- Nelson, D., Pillepich, A., Springel, V., Pakmor, R., Weinberger, R., Genel, S., Torrey, P., Vogelsberger, M., Marinacci, F., and Hernquist, L. (2019). First Results from the TNG50 Simulation: Galactic outflows driven by supernovae and black hole feedback. *arXiv e-prints*.
- Nelson, D., Sharma, P., Pillepich, A., Springel, V., Pakmor, R., Weinberger, R., Vogelsberger, M., Marinacci, F., and Hernquist, L. (2020). Resolving small-scale cold circumgalactic gas in TNG50. *arXiv e-prints*, page arXiv:2005.09654.
- Nelson, K., Lau, E. T., and Nagai, D. (2014). Hydrodynamic Simulation of Non-thermal Pressure Profiles of Galaxy Clusters. *ApJ*, 792:25.
- Nielsen, N. M., Churchill, C. W., and Kacprzak, G. G. (2013). MAGIICAT II. General Characteristics of the Mg II Absorbing Circumgalactic Medium. *ApJ*, 776:115.
- Nielsen, N. M., Kacprzak, G. G., Pointon, S. K., Churchill, C. W., and Murphy, M. T. (2018). MAGIICAT VI. The Mg II Intragroup Medium Is Kinematically Complex. *ApJ*, 869:153.
- Oppenheimer, B. D. and Davé, R. (2006). Cosmological simulations of intergalactic medium enrichment from galactic outflows. *MNRAS*, 373:1265–1292.
- Oppenheimer, B. D. and Schaye, J. (2013). Non-equilibrium ionization and cooling of metal-enriched gas in the presence of a photoionization background. *MNRAS*, 434:1043–1062.
- Oppenheimer, B. D., Segers, M., Schaye, J., Richings, A. J., and Crain, R. A. (2017). Flickering AGN can explain the strong circumgalactic O VI observed by COS-Halos. *ArXiv e-prints*.

- Oppenheimer, B. D., Segers, M., Schaye, J., Richings, A. J., and Crain, R. A. (2018). Flickering AGN can explain the strong circumgalactic O VI observed by COS-Halos. *MNRAS*, 474:4740–4755.
- Pakmor, R., Pfrommer, C., Simpson, C. M., Kannan, R., and Springel, V. (2016a). Semi-implicit anisotropic cosmic ray transport on an unstructured moving mesh. *MNRAS*, 462:2603–2616.
- Pakmor, R., Pfrommer, C., Simpson, C. M., and Springel, V. (2016b). Galactic Winds Driven by Isotropic and Anisotropic Cosmic-Ray Diffusion in Disk Galaxies. *ApJ*, 824:L30.
- Pakmor, R., Pfrommer, C., Simpson, C. M., and Springel, V. (2016c). Galactic Winds Driven by Isotropic and Anisotropic Cosmic-Ray Diffusion in Disk Galaxies. *ApJ*, 824(2):L30.
- Pakmor, R., van de Voort, F., Bieri, R., Gomez, F. A., Grand, R. J. J., Guillet, T., Marinacci, F., Pfrommer, C., Simpson, C. M., and Springel, V. (2019). Magnetising the circumgalactic medium of disk galaxies. *arXiv e-prints*, page arXiv:1911.11163.
- Parrish, I. J. and Stone, J. M. (2005). Nonlinear Evolution of the Magnetothermal Instability in Two Dimensions. *ApJ*, 633:334–348.
- Peeples, M., Tumlinson, J., Fox, A., Aloisi, A., Fleming, S., Jedrzejewski, R., Oliveira, C., Ayres, T., Danforth, C., Keeney, B., and Jenkins, E. (2017). The Hubble Spectroscopic Legacy Archive. Technical report.
- Peeples, M. S., Corlies, L., Tumlinson, J., O’Shea, B. W., Lehner, N., O’Meara, J. M., Howk, J. C., Earl, N., Smith, B. D., and Wise, J. H. (2019a). Figuring Out Gas & Galaxies in Enzo (FOGGIE). I. Resolving Simulated Circumgalactic Absorption at $2 \leq z \leq 2.5$. *ApJ*, 873(2):129.

- Peeples, M. S., Corlies, L., Tumlinson, J., O’Shea, B. W., Lehner, N., O’Meara, J. M., Howk, J. C., Earl, N., Smith, B. D., Wise, J. H., and Hummels, C. B. (2019b). Figuring Out Gas & Galaxies in Enzo (FOGGIE). I. Resolving Simulated Circumgalactic Absorption at $2 \leq z \leq 2.5$. *ApJ*, 873(2):129.
- Peeples, M. S., Werk, J. K., Tumlinson, J., Oppenheimer, B. D., Prochaska, J. X., Katz, N., and Weinberg, D. H. (2014). A Budget and Accounting of Metals at $z \sim 0$: Results from the COS-Halos Survey. *ApJ*, 786:54.
- Pfrommer, C., Enßlin, T. A., and Springel, V. (2008). Simulating cosmic rays in clusters of galaxies - II. A unified scheme for radio haloes and relics with predictions of the γ -ray emission. *MNRAS*, 385:1211–1241.
- Pfrommer, C., Springel, V., Enßlin, T. A., and Jubelgas, M. (2006). Detecting shock waves in cosmological smoothed particle hydrodynamics simulations. *MNRAS*, 367:113–131.
- Pillepich, A., Nelson, D., Springel, V., Pakmor, R., Torrey, P., Weinberger, R., Vogelsberger, M., Marinacci, F., Genel, S., van der Wel, A., and Hernquist, L. (2019). First Results from the TNG50 Simulation: The evolution of stellar and gaseous disks across cosmic time. *MNRAS*, page 2024.
- Pizzolato, F. and Soker, N. (2005). On the Nature of Feedback Heating in Cooling Flow Clusters. *ApJ*, 632(2):821–830.
- Planck Collaboration, Ade, P. A. R., Aghanim, N., Arnaud, M., Ashdown, M., Aumont, J., Baccigalupi, C., Banday, A. J., Barreiro, R. B., Bartlett, J. G., Bartolo, N., Battaner, E., Battye, R., Benabed, K., Benoît, A., Benoit-Lévy, A., Bernard, J.-P., Bersanelli, M., Bielewicz, P., Bock, J. J., Bonaldi, A., Bonavera, L., Bond, J. R., Borrill, J., Bouchet, F. R., Boulanger, F., Bucher, M., Burigana, C., Butler, R. C., Calabrese, E., Cardoso, J.-F., Catalano, A., Challinor, A., Chamballu, A., Chary, R.-R., Chiang, H. C., Chluba, J.,

Christensen, P. R., Church, S., Clements, D. L., Colombi, S., Colombo, L. P. L., Combet, C., Coulais, A., Crill, B. P., Curto, A., Cuttaia, F., Danese, L., Davies, R. D., Davis, R. J., de Bernardis, P., de Rosa, A., de Zotti, G., Delabrouille, J., Désert, F.-X., Di Valentino, E., Dickinson, C., Diego, J. M., Dolag, K., Dole, H., Donzelli, S., Doré, O., Douspis, M., Ducout, A., Dunkley, J., Dupac, X., Efstathiou, G., Elsner, F., Enßlin, T. A., Eriksen, H. K., Farhang, M., Fergusson, J., Finelli, F., Forni, O., Frailis, M., Fraisse, A. A., Franceschi, E., Frejsel, A., Galeotta, S., Galli, S., Ganga, K., Gauthier, C., Gerbino, M., Ghosh, T., Giard, M., Giraud-Héraud, Y., Giusarma, E., Gjerløw, E., González-Nuevo, J., Górski, K. M., Gratton, S., Gregorio, A., Gruppuso, A., Gudmundsson, J. E., Hamann, J., Hansen, F. K., Hanson, D., Harrison, D. L., Helou, G., Henrot-Versillé, S., Hernández-Monteagudo, C., Herranz, D., Hildebrandt, S. R., Hivon, E., Hobson, M., Holmes, W. A., Hornstrup, A., Hovest, W., Huang, Z., Huppenberger, K. M., Hurier, G., Jaffe, A. H., Jaffe, T. R., Jones, W. C., Juvela, M., Keihänen, E., Keskitalo, R., Kisner, T. S., Kneissl, R., Knoche, J., Knox, L., Kunz, M., Kurki-Suonio, H., Lagache, G., Lähteenmäki, A., Lamarre, J.-M., Lasenby, A., Lattanzi, M., Lawrence, C. R., Leahy, J. P., Leonardi, R., Lesgourgues, J., Levrier, F., Lewis, A., Liguori, M., Lilje, P. B., Linden-Vørnle, M., López-Caniego, M., Lubin, P. M., Macías-Pérez, J. F., Maggio, G., Maino, D., Mandolesi, N., Mangilli, A., Marchini, A., Maris, M., Martin, P. G., Martinelli, M., Martínez-González, E., Masi, S., Matarrese, S., McGehee, P., Meinhold, P. R., Melchiorri, A., Melin, J.-B., Mendes, L., Mennella, A., Migliaccio, M., Millea, M., Mitra, S., Miville-Deschênes, M.-A., Moneti, A., Montier, L., Morgante, G., Mortlock, D., Moss, A., Munshi, D., Murphy, J. A., Naselsky, P., Nati, F., Natoli, P., Netterfield, C. B., Nørgaard-Nielsen, H. U., Noviello, F., Novikov, D., Novikov, I., Oxborrow, C. A., Paci, F., Pagano, L., Pajot, F., Paladini, R., Paoletti, D., Partridge, B., Pasian, F., Patanchon, G., Pearson, T. J., Perdureau, O., Perotto, L., Perrotta, F., Pettorino, V., Piacentini, F., Piat, M., Pierpaoli, E., Pietrobon, D., Plaszczynski, S., Pointecouteau, E., Polenta, G., Popa, L., Pratt, G. W., Prézeau, G., Prunet, S., Puget, J.-L., Rachen, J. P., Reach, W. T., Rebolo, R., Reinecke, M., Remazeilles, M., Renault, C., Renzi, A., Ristorcelli, I., Rocha, G., Rosset, C.,

- Rossetti, M., Roudier, G., Rouillé d'Orfeuil, B., Rowan-Robinson, M., Rubiño-Martín, J. A., Rusholme, B., Said, N., Salvatelli, V., Salvati, L., Sandri, M., Santos, D., Savellainen, M., Savini, G., Scott, D., Seiffert, M. D., Serra, P., Shellard, E. P. S., Spencer, L. D., Spinelli, M., Stolyarov, V., Stompor, R., Sudiwala, R., Sunyaev, R., Sutton, D., Suur-Uski, A.-S., Sygnet, J.-F., Tauber, J. A., Terenzi, L., Toffolatti, L., Tomasi, M., Tristram, M., Trombetti, T., Tucci, M., Tuovinen, J., Türlér, M., Umana, G., Valenziano, L., Valiviita, J., Van Tent, F., Vielva, P., Villa, F., Wade, L. A., Wandelt, B. D., Wehus, I. K., White, M., White, S. D. M., Wilkinson, A., Yvon, D., Zacchei, A., and Zonca, A. (2016). Planck 2015 results. XIII. Cosmological parameters. *Astronomy and Astrophysics*, 594:A13.
- Pointon, S. K., Nielsen, N. M., Kacprzak, G. G., Muzahid, S., Churchill, C. W., and Charlton, J. C. (2017). The Impact of the Group Environment on the O VI Circumgalactic Medium. *ApJ*, 844:23.
- Pontzen, A., Roškar, R., Stinson, G. S., Woods, R., Reed, D. M., Coles, J., and Quinn, T. R. (2013a). pynbody: Astrophysics Simulation Analysis for Python. Astrophysics Source Code Library, ascl:1305.002.
- Pontzen, A., Roškar, R., Stinson, G. S., Woods, R., Reed, D. M., Coles, J., and Quinn, T. R. (2013b). pynbody: Astrophysics Simulation Analysis for Python. Astrophysics Source Code Library, ascl:1305.002.
- Pontzen, A. and Tremmel, M. (2018). TANGOS: The Agile Numerical Galaxy Organization System. *ApJS*, 237:23.
- Pontzen, A., Tremmel, M., Roth, N., Peiris, H. V., Saintonge, A., Volonteri, M., Quinn, T., and Governato, F. (2017). How to quench a galaxy. *MNRAS*, 465:547–558.

- Prasad, D., Sharma, P., and Babul, A. (2018). Cool-core Clusters: The Role of BCG, Star Formation, and AGN-driven Turbulence. *ApJ*, 863(1):62.
- Pratt, G. W., Arnaud, M., Biviano, A., Eckert, D., Ettori, S., Nagai, D., Okabe, N., and Reiprich, T. H. (2019). The Galaxy Cluster Mass Scale and Its Impact on Cosmological Constraints from the Cluster Population. *Space Sci. Rev.*, 215:25.
- Prochaska, J. X. and Hennawi, J. F. (2009). Quasars Probing Quasars. III. New Clues to Feedback, Quenching, and the Physics of Massive Galaxy Formation. *ApJ*, 690(2):1558–1584.
- Prochaska, J. X., Weiner, B., Chen, H.-W., Mulchaey, J., and Cooksey, K. (2011). Probing the Intergalactic Medium/Galaxy Connection. V. On the Origin of Ly α and O VI Absorption at $z \approx 0.2$. *ApJ*, 740:91.
- Prochaska, J. X., Werk, J. K., Worseck, G., Tripp, T. M., Tumlinson, J., Burchett, J. N., Fox, A. J., Fumagalli, M., Lehner, N., Peebles, M. S., and Tejos, N. (2017). The COS-Halos Survey: Metallicities in the Low-redshift Circumgalactic Medium. *ApJ*, 837(2):169.
- Ptuskin, V. S., Moskalenko, I. V., Jones, F. C., Strong, A. W., and Zirakashvili, V. N. (2006). Dissipation of Magnetohydrodynamic Waves on Energetic Particles: Impact on Interstellar Turbulence and Cosmic-Ray Transport. *ApJ*, 642:902–916.
- Puchwein, E. and Springel, V. (2013). Shaping the galaxy stellar mass function with supernova- and AGN-driven winds. *MNRAS*, 428:2966–2979.
- Putman, M. E., Peek, J. E. G., and Jounge, M. R. (2012). Gaseous Galaxy Halos. *ARA&A*, 50:491–529.
- Rasia, E., Lau, E. T., Borgani, S., Nagai, D., Dolag, K., Avestruz, C., Granato, G. L., Mazzotta, P., Murante, G., Nelson, K., and Ragone-Figueroa, C. (2014). Temperature Struc-

- ture of the Intracluster Medium from Smoothed-particle Hydrodynamics and Adaptive-mesh Refinement Simulations. *ApJ*, 791:96.
- Rauch, M., Sargent, W. L. W., and Barlow, T. A. (2001). Small-Scale Structure at High Redshift. II. Physical Properties of the C IV Absorbing Clouds. *ApJ*, 554(2):823–840.
- Rees, M. J. and Ostriker, J. P. (1977). Cooling, dynamics and fragmentation of massive gas clouds - Clues to the masses and radii of galaxies and clusters. *MNRAS*, 179:541–559.
- Roediger, E., Kraft, R. P., Nulsen, P. E. J., Forman, W. R., Machacek, M., Randall, S., Jones, C., Churazov, E., and Kokotanekova, R. (2015). Stripped Elliptical Galaxies as Probes of ICM Physics: II. Stirred, but Mixed? Viscous and Inviscid Gas Stripping of the Virgo Elliptical M89. *ApJ*, 806:104.
- Rosolowsky, E. W., Pineda, J. E., Kauffmann, J., and Goodman, A. A. (2008). Structural Analysis of Molecular Clouds: Dendrograms. *ApJ*, 679(2):1338–1351.
- Rubin, K. H. R., Diamond-Stanic, A. M., Coil, A. L., Crighton, N. H. M., and Moustakas, J. (2018a). Galaxies Probing Galaxies in PRIMUS. I. Sample, Spectroscopy, and Characteristics of the $z \sim 0.5$ Mg II Absorbing Circumgalactic Medium. *ApJ*, 853:95.
- Rubin, K. H. R., Diamond-Stanic, A. M., Coil, A. L., Crighton, N. H. M., and Stewart, K. R. (2018b). Galaxies Probing Galaxies in PRIMUS. II. The Coherence Scale of the Cool Circumgalactic Medium. *ApJ*, 868(2):142.
- Rudie, G. C., Steidel, C. C., Pettini, M., Trainor, R. F., Strom, A. L., Hummels, C. B., Reddy, N. A., and Shapley, A. E. (2019). Column Density, Kinematics, and Thermal State of Metal-bearing Gas within the Virial Radius of $z \sim 2$ Star-forming Galaxies in the Keck Baryonic Structure Survey. *ApJ*, 885(1):61.

- Rudie, G. C., Steidel, C. C., Trainor, R. F., Rakic, O., Bogosavljević, M., Pettini, M., Reddy, N., Shapley, A. E., Erb, D. K., and Law, D. R. (2012). The Gaseous Environment of High- z Galaxies: Precision Measurements of Neutral Hydrogen in the Circumgalactic Medium of $z \sim 2-3$ Galaxies in the Keck Baryonic Structure Survey. *ApJ*, 750:67.
- Ruszkowski, M., Yang, H.-Y. K., and Zweibel, E. (2017). Global Simulations of Galactic Winds Including Cosmic-ray Streaming. *ApJ*, 834:208.
- Salem, M. and Bryan, G. L. (2014). Cosmic ray driven outflows in global galaxy disc models. *MNRAS*, 437:3312–3330.
- Salem, M., Bryan, G. L., and Corlies, L. (2016). Role of cosmic rays in the circumgalactic medium. *MNRAS*, 456:582–601.
- Samui, S., Subramanian, K., and Srianand, R. (2018). Efficient cold outflows driven by cosmic rays in high redshift galaxies and their global effects on the IGM. *MNRAS*.
- Sanchez, N. N., Tremmel, M., Werk, J. K., Pontzen, A., Christensen, C., Quinn, T., Loebman, S., and Cruz, A. (2020). One-Two Quench: A Double Minor Merger Scenario. *arXiv e-prints*, page arXiv:2009.05581.
- Sanchez, N. N., Werk, J. K., Tremmel, M., Pontzen, A., Christensen, C., Quinn, T., and Cruz, A. (2018). Not So Heavy Metals: Black Hole Feedback Enriches The Circumgalactic Medium. *arXiv e-prints*.
- Sanchez, N. N., Werk, J. K., Tremmel, M., Pontzen, A., Christensen, C., Quinn, T., and Cruz, A. (2019). Not So Heavy Metals: Black Hole Feedback Enriches the Circumgalactic Medium. *ApJ*, 882(1):8.
- Sandage, A., Binggeli, B., and Tammann, G. A. (1985). Studies of the Virgo Cluster - Part Five - Luminosity Functions of Virgo Cluster Galaxies. *AJ*, 90:1759–1771.

- Savage, B. D. and Sembach, K. R. (1991). The Analysis of Apparent Optical Depth Profiles for Interstellar Absorption Lines. *ApJ*, 379:245.
- Schaye, J., Crain, R. A., Bower, R. G., Furlong, M., Schaller, M., Theuns, T., Dalla Vecchia, C., Frenk, C. S., McCarthy, I. G., Helly, J. C., Jenkins, A., Rosas-Guevara, Y. M., White, S. D. M., Baes, M., Booth, C. M., Camps, P., Navarro, J. F., Qu, Y., Rahmati, A., Sawala, T., Thomas, P. A., and Trayford, J. (2015). The EAGLE project: simulating the evolution and assembly of galaxies and their environments. *MNRAS*, 446:521–554.
- Schaye, J., Dalla Vecchia, C., Booth, C. M., Wiersma, R. P. C., Theuns, T., Haas, M. R., Bertone, S., Duffy, A. R., McCarthy, I. G., and van de Voort, F. (2010). The physics driving the cosmic star formation history. *MNRAS*, 402:1536–1560.
- Schmidt, M. (1963). 3C 273 : A Star-Like Object with Large Red-Shift. *Nature*, 197(4872):1040.
- Schneider, E. E., Robertson, B. E., and Thompson, T. A. (2018). Production of Cool Gas in Thermally Driven Outflows. *ApJ*, 862(1):56.
- Sharma, M. and Nath, B. B. (2012a). The Roles of Radiation and Ram Pressure in Driving Galactic Winds. *ApJ*, 750:55.
- Sharma, M. and Nath, B. B. (2012b). The Roles of Radiation and Ram Pressure in Driving Galactic Winds. *ApJ*, 750:55.
- Sharma, P., Chandran, B. D. G., Quataert, E., and Parrish, I. J. (2009). Buoyancy Instabilities in Galaxy Clusters: Convection Due to Adiabatic Cosmic Rays and Anisotropic Thermal Conduction. *ApJ*, 699:348–361.
- Sharma, P. and Hammett, G. W. (2007). Preserving monotonicity in anisotropic diffusion. *Journal of Computational Physics*, 227:123–142.

- Sharma, P., McCourt, M., Quataert, E., and Parrish, I. J. (2012). Thermal instability and the feedback regulation of hot haloes in clusters, groups and galaxies. *MNRAS*, 420(4):3174–3194.
- Sharma, P., Parrish, I. J., and Quataert, E. (2010). Thermal Instability with Anisotropic Thermal Conduction and Adiabatic Cosmic Rays: Implications for Cold Filaments in Galaxy Clusters. *ApJ*, 720:652–665.
- Shen, S., Wadsley, J., and Stinson, G. (2010). The enrichment of the intergalactic medium with adiabatic feedback - I. Metal cooling and metal diffusion. *MNRAS*, 407:1581–1596.
- Shu, C.-W. and Osher, S. (1988). Efficient implementation of essentially non-oscillatory shock-capturing schemes. *Journal of Computational Physics*, 77:439–471.
- Silk, J. (1977). On the fragmentation of cosmic gas clouds. I - The formation of galaxies and the first generation of stars. *ApJ*, 211:638–648.
- Simpson, C. M., Pakmor, R., Marinacci, F., Pfrommer, C., Springel, V., Glover, S. C. O., Clark, P. C., and Smith, R. J. (2016). The Role of Cosmic-Ray Pressure in Accelerating Galactic Outflows. *ApJ*, 827:L29.
- Singh, A. and Sharma, P. (2015). The cold mode: a phenomenological model for the evolution of density perturbations in the intracluster medium. *MNRAS*, 446(2):1895–1906.
- Smith, B. D., Bryan, G. L., Glover, S. C. O., Goldbaum, N. J., Turk, M. J., Regan, J., Wise, J. H., Schive, H.-Y., Abel, T., Emerick, A., O’Shea, B. W., Anninos, P., Hummels, C. B., and Khochfar, S. (2017). GRACKLE: a chemistry and cooling library for astrophysics. *MNRAS*, 466:2217–2234.
- Socrates, A., Davis, S. W., and Ramirez-Ruiz, E. (2008). The Eddington Limit in Cosmic

- Rays: An Explanation for the Observed Faintness of Starbursting Galaxies. *ApJ*, 687:202–215.
- Sod, G. A. (1978). A survey of several finite difference methods for systems of nonlinear hyperbolic conservation laws. *Journal of Computational Physics*, 27:1–31.
- Spitzer, Lyman, J. (1956). On a Possible Interstellar Galactic Corona. *ApJ*, 124:20.
- Springel, V. and Hernquist, L. (2003). Cosmological smoothed particle hydrodynamics simulations: a hybrid multiphase model for star formation. *MNRAS*, 339:289–311.
- Steidel, C. C., Erb, D. K., Shapley, A. E., Pettini, M., Reddy, N., Bogosavljević, M., Rudie, G. C., and Rakic, O. (2010). The Structure and Kinematics of the Circumgalactic Medium from Far-ultraviolet Spectra of $z \sim 2-3$ Galaxies. *ApJ*, 717:289–322.
- Steidel, C. C. and Sargent, W. L. W. (1992). MG II Absorption in the Spectra of 103 QSOs: Implications for the Evolution of Gas in High-Redshift Galaxies. *ApJS*, 80:1.
- Stern, J., Hennawi, J. F., Prochaska, J. X., and Werk, J. K. (2016). A Universal Density Structure for Circumgalactic Gas. *ApJ*, 830(2):87.
- Stinson, G., Seth, A., Katz, N., Wadsley, J., Governato, F., and Quinn, T. (2006). Star formation and feedback in smoothed particle hydrodynamic simulations - I. Isolated galaxies. *MNRAS*, 373:1074–1090.
- Stinson, G. S., Bovy, J., Rix, H.-W., Brook, C., Roškar, R., Dalcanton, J. J., Macciò, A. V., Wadsley, J., Couchman, H. M. P., and Quinn, T. R. (2013). MaGICC thick disc - I. Comparing a simulated disc formed with stellar feedback to the Milky Way. *MNRAS*, 436:625–634.

- Stocke, J. T., Keeney, B. A., Danforth, C. W., Oppenheimer, B. D., Pratt, C. T., Berlind, A. A., Impey, C., and Jannuzi, B. (2019). The Ultraviolet Detection of Diffuse Gas in Galaxy Groups. *ApJS*, 240:15.
- Stocke, J. T., Keeney, B. A., Danforth, C. W., Shull, J. M., Froning, C. S., Green, J. C., Penton, S. V., and Savage, B. D. (2013). Characterizing the Circumgalactic Medium of Nearby Galaxies with HST/COS and HST/STIS Absorption-line Spectroscopy. *ApJ*, 763:148.
- Stone, J. M. and Norman, M. L. (1992). ZEUS-2D: A radiation magnetohydrodynamics code for astrophysical flows in two space dimensions. I - The hydrodynamic algorithms and tests. *ApJS*, 80:753–790.
- Strong, A. W. and Moskalenko, I. V. (1998). Propagation of Cosmic-Ray Nucleons in the Galaxy. *ApJ*, 509:212–228.
- Su, K.-Y., Hopkins, P. F., Hayward, C. C., Faucher-Giguère, C.-A., Kereš, D., Ma, X., Orr, M. E., Chan, T. K., and Robles, V. H. (2020). Cosmic rays or turbulence can suppress cooling flows (where thermal heating or momentum injection fail). *MNRAS*, 491(1):1190–1212.
- Suresh, J., Bird, S., Vogelsberger, M., Genel, S., Torrey, P., Sijacki, D., Springel, V., and Hernquist, L. (2015). The impact of galactic feedback on the circumgalactic medium. *MNRAS*, 448:895–909.
- Suresh, J., Nelson, D., Genel, S., Rubin, K. H. R., and Hernquist, L. (2019). Zooming in on accretion - II. Cold circumgalactic gas simulated with a super-Lagrangian refinement scheme. *MNRAS*, 483(3):4040–4059.
- Tabatabaei, F. S., Schinnerer, E., Murphy, E. J., Beck, R., Groves, B., Meidt, S., Krause, M., Rix, H.-W., Sandstrom, K., Crocker, A. F., Galametz, M., Helou, G., Wilson, C. D.,

- Kennicutt, R., Calzetti, D., Draine, B., Aniano, G., Dale, D., Dumas, G., Engelbracht, C. W., Gordon, K. D., Hinz, J., Kreckel, K., Montiel, E., and Roussel, H. (2013). A detailed study of the radio-FIR correlation in NGC 6946 with Herschel-PACS/SPIRE from KINGFISH. *A&A*, 552:A19.
- Tasker, E. J. and Bryan, G. L. (2008). The Effect of the Interstellar Model on Star Formation Properties in Galactic Disks. *ApJ*, 673:810–831.
- Tejos, N., Prochaska, J. X., Crighton, N. H. M., Morris, S. L., Werk, J. K., Theuns, T., Padilla, N., Bielby, R. M., and Finn, C. W. (2016). Towards the statistical detection of the warm-hot intergalactic medium in intercluster filaments of the cosmic web. *MNRAS*, 455:2662–2697.
- Tepper-García, T., Richter, P., Schaye, J., Booth, C. M., Dalla Vecchia, C., and Theuns, T. (2012). Absorption signatures of warm-hot gas at low redshift: broad H I Ly α absorbers. *MNRAS*, 425:1640–1663.
- Thom, C., Tumlinson, J., Werk, J. K., Prochaska, J. X., Oppenheimer, B. D., Peebles, M. S., Tripp, T. M., Katz, N. S., O’Meara, J. M., Ford, A. B., Davé, R., Sembach, K. R., and Weinberg, D. H. (2012). Not Dead Yet: Cool Circumgalactic Gas in the Halos of Early-type Galaxies. *ApJ*, 758:L41.
- Thomas, T. and Pfrommer, C. (2019). Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays. *MNRAS*, 485(3):2977–3008.
- Thompson, T. A., Quataert, E., Zhang, D., and Weinberg, D. H. (2016). An origin for multiphase gas in galactic winds and haloes. *MNRAS*, 455(2):1830–1844.
- Tonnesen, S., Bryan, G. L., and van Gorkom, J. H. (2007). Environmentally Driven Evolution of Simulated Cluster Galaxies. *ApJ*, 671:1434–1445.

- Toomre, A. and Toomre, J. (1972). Galactic Bridges and Tails. *ApJ*, 178:623–666.
- Tremmel, M., Governato, F., Volonteri, M., and Quinn, T. R. (2015). Off the beaten path: a new approach to realistically model the orbital decay of supermassive black holes in galaxy formation simulations. *MNRAS*, 451:1868–1874.
- Tremmel, M., Karcher, M., Governato, F., Volonteri, M., Quinn, T. R., Pontzen, A., Anderson, L., and Bellovary, J. (2017). The Romulus cosmological simulations: a physical approach to the formation, dynamics and accretion models of SMBHs. *MNRAS*, 470:1121–1139.
- Tremmel, M., Quinn, T. R., Ricarte, A., Babul, A., Chadayammuri, U., Natarajan, P., Nagai, D., Pontzen, A., and Volonteri, M. (2019). Introducing ROMULUS: a cosmological simulation of a galaxy cluster with an unprecedented resolution. *MNRAS*, 483:3336–3362.
- Tremonti, C. A., Heckman, T. M., Kauffmann, G., Brinchmann, J., Charlot, S., White, S. D. M., Seibert, M., Peng, E. W., Schlegel, D. J., Uomoto, A., Fukugita, M., and Brinkmann, J. (2004). The Origin of the Mass-Metallicity Relation: Insights from 53,000 Star-forming Galaxies in the Sloan Digital Sky Survey. *ApJ*, 613:898–913.
- Tripp, T. M., Meiring, J. D., Prochaska, J. X., Willmer, C. N. A., Howk, J. C., Werk, J. K., Jenkins, E. B., Bowen, D. V., Lehner, N., Sembach, K. R., Thom, C., and Tumlinson, J. (2011a). The Hidden Mass and Large Spatial Extent of a Post-Starburst Galaxy Outflow. *Science*, 334(6058):952.
- Tripp, T. M., Meiring, J. D., Prochaska, J. X., Willmer, C. N. A., Howk, J. C., Werk, J. K., Jenkins, E. B., Bowen, D. V., Lehner, N., Sembach, K. R., Thom, C., and Tumlinson, J. (2011b). The Hidden Mass and Large Spatial Extent of a Post-Starburst Galaxy Outflow. *Science*, 334:952.

- Tumlinson, J., Peebles, M. S., and Werk, J. K. (2017a). The Circumgalactic Medium. *ARA&A*, 55(1):389–432.
- Tumlinson, J., Peebles, M. S., and Werk, J. K. (2017b). The Circumgalactic Medium. *ARA&A*, 55:389–432.
- Tumlinson, J., Thom, C., Werk, J. K., Prochaska, J. X., Tripp, T. M., Katz, N., Davé, R., Oppenheimer, B. D., Meiring, J. D., Ford, A. B., O’Meara, J. M., Peebles, M. S., Sembach, K. R., and Weinberg, D. H. (2013). The COS-Halos Survey: Rationale, Design, and a Census of Circumgalactic Neutral Hydrogen. *ApJ*, 777:59.
- Tumlinson, J., Werk, J. K., Thom, C., Meiring, J. D., Prochaska, J. X., Tripp, T. M., O’Meara, J. M., Okrochkov, M., and Sembach, K. R. (2011). Multiphase Gas in Galaxy Halos: The O VI Lyman-limit System toward J1009+0713. *ApJ*, 733:111.
- Turk, M. J., Oishi, J. S., Abel, T., and Bryan, G. L. (2012). Magnetic Fields in Population III Star Formation. *ApJ*, 745:154.
- Turk, M. J., Smith, B. D., Oishi, J. S., Skory, S., Skillman, S. W., Abel, T., and Norman, M. L. (2011). yt: A Multi-code Analysis Toolkit for Astrophysical Simulation Data. *ApJS*, 192:9.
- Turner, M. L., Schaye, J., Steidel, C. C., Rudie, G. C., and Strom, A. L. (2014). Metal-line absorption around $z \sim 2.4$ star-forming galaxies in the Keck Baryonic Structure Survey. *MNRAS*, 445:794–822.
- Turner, M. L., Schaye, J., Steidel, C. C., Rudie, G. C., and Strom, A. L. (2015). Detection of hot, metal-enriched outflowing gas around $z \approx 2.3$ star-forming galaxies in the Keck Baryonic Structure Survey. *MNRAS*, 450(2):2067–2082.
- Uhlig, M., Pfrommer, C., Sharma, M., Nath, B. B., Enßlin, T. A., and Springel, V. (2012). Galactic winds driven by cosmic ray streaming. *MNRAS*, 423:2374–2396.

- Urban, O., Werner, N., Allen, S. W., Simionescu, A., and Mantz, A. (2017). A uniform metallicity in the outskirts of massive, nearby galaxy clusters. *MNRAS*, 470:4583–4599.
- van de Voort, F., Bieri, R., Pakmor, R., Gómez, F. A., Grand, R. J. J., and Marinacci, F. (2020). The effect of magnetic fields on properties of the circumgalactic medium. *arXiv e-prints*, page arXiv:2008.07537.
- van de Voort, F., Schaye, J., Booth, C. M., and Dalla Vecchia, C. (2011). The drop in the cosmic star formation rate below redshift 2 is caused by a change in the mode of gas accretion and by active galactic nucleus feedback. *MNRAS*, 415:2782–2789.
- van de Voort, F., Springel, V., Mandelker, N., van den Bosch, F. C., and Pakmor, R. (2019). Cosmological simulations of the circumgalactic medium with 1 kpc resolution: enhanced H I column densities. *MNRAS*, 482(1):L85–L89.
- van Leer, B. (1977). Towards the Ultimate Conservative Difference Scheme. IV. A New Approach to Numerical Convection. *Journal of Computational Physics*, 23:276.
- Vazza, F., Brüggen, M., Gheller, C., and Brunetti, G. (2012). Modelling injection and feedback of cosmic rays in grid-based cosmological simulations: effects on cluster outskirts. *MNRAS*, 421:3375–3398.
- Vazza, F., Eckert, D., Simionescu, A., Brüggen, M., and Ettori, S. (2013). Properties of gas clumps and gas clumping factor in the intra-cluster medium. *MNRAS*, 429:799–814.
- Voit, G. M. (2018). A Role for Turbulence in Circumgalactic Precipitation. *ApJ*, 868(2):102.
- Voit, G. M., Donahue, M., Bryan, G. L., and McDonald, M. (2015). Regulation of star formation in giant galaxies by precipitation, feedback and conduction. *Nature*, 519(7542):203–206.

- Voit, G. M., Donahue, M., Zahedy, F., Chen, H.-W., Werk, J., Bryan, G. L., and O'Shea, B. W. (2019). Circumgalactic Pressure Profiles Indicate Precipitation-limited Atmospheres for $\{M\}_{*}^{10^9-10^{11.5}}\backslash, \{M\}_{\odot}$. *ApJ*, 879(1):L1.
- Voit, G. M., Meece, G., Li, Y., O'Shea, B. W., Bryan, G. L., and Donahue, M. (2017). A Global Model for Circumgalactic and Cluster-core Precipitation. *ApJ*, 845(1):80.
- Wadsley, J. W., Keller, B. W., and Quinn, T. R. (2017). Gasoline2: a modern smoothed particle hydrodynamics code. *MNRAS*, 471:2357–2369.
- Wadsley, J. W., Stadel, J., and Quinn, T. (2004). Gasoline: a flexible, parallel implementation of TreeSPH. *New A*, 9:137–158.
- Wadsley, J. W., Veeravalli, G., and Couchman, H. M. P. (2008). On the treatment of entropy mixing in numerical cosmology. *MNRAS*, 387:427–438.
- Wagh, B., Sharma, P., and McCourt, M. (2014). Thermal conduction and multiphase gas in cluster cores. *MNRAS*, 439(3):2822–2827.
- Walker, S., Simionescu, A., Nagai, D., Okabe, N., Eckert, D., Mroczkowski, T., Akamatsu, H., Ettori, S., and Ghirardini, V. (2019). The Physics of Galaxy Cluster Outskirts. *Space Sci. Rev.*, 215:7.
- Wang, P. and Abel, T. (2009). Magnetohydrodynamic Simulations of Disk Galaxy Formation: The Magnetization of the Cold and Warm Medium. *ApJ*, 696:96–109.
- Wang, P., Abel, T., and Zhang, W. (2008). Relativistic Hydrodynamic Flows Using Spatial and Temporal Adaptive Structured Mesh Refinement. *ApJS*, 176:467–483.
- Wang, Q. D., Owen, F., and Ledlow, M. (2004). X-Raying A2125: A Large-Scale Hierarchical Complex of Galaxies and Hot Gas. *ApJ*, 611:821–834.

- Wang, Q. D. and Walker, S. (2014). X-ray mapping the outer regions of galaxy clusters at $z = 0.23$ and 0.45 . *MNRAS*, 439:1796–1806.
- Wefel, J. P. (1987). Origin and transport of high energy particles in the galaxy. Technical report.
- Werk, J. K., Prochaska, J. X., Cantalupo, S., Fox, A. J., Oppenheimer, B., Tumlinson, J., Tripp, T. M., Lehner, N., and McQuinn, M. (2016). The COS-Halos Survey: Origins of the Highly Ionized Circumgalactic Medium of Star-Forming Galaxies. *ApJ*, 833(1):54.
- Werk, J. K., Prochaska, J. X., Thom, C., Tumlinson, J., Tripp, T. M., O’Meara, J. M., and Peeples, M. S. (2013). The COS-Halos Survey: An Empirical Description of Metal-line Absorption in the Low-redshift Circumgalactic Medium. *ApJS*, 204:17.
- Werk, J. K., Prochaska, J. X., Tumlinson, J., Peeples, M. S., Tripp, T. M., Fox, A. J., Lehner, N., Thom, C., O’Meara, J. M., Ford, A. B., Bordoloi, R., Katz, N., Tejos, N., Oppenheimer, B. D., Davé, R., and Weinberg, D. H. (2014). The COS-Halos Survey: Physical Conditions and Baryonic Mass in the Low-redshift Circumgalactic Medium. *ApJ*, 792:8.
- Werk, J. K., Rubin, K. H. R., Bish, H. V., Prochaska, J. X., Zheng, Y., O’Meara, J. M., Lenz, D., Hummels, C., and Deason, A. J. (2019). The Nature of Ionized Gas in the Milky Way Galactic Fountain. *ApJ*, 887(1):89.
- Werner, N., Urban, O., Simionescu, A., and Allen, S. W. (2013). A uniform metal distribution in the intergalactic medium of the Perseus cluster of galaxies. *Nature*, 502:656–658.
- White, S. D. M. and Rees, M. J. (1978). Core condensation in heavy halos - A two-stage theory for galaxy formation and clustering. *MNRAS*, 183:341–358.
- Wiener, J., Pfrommer, C., and Peng Oh, S. (2017). Cosmic ray-driven galactic winds: streaming or diffusion? *MNRAS*, 467:906–921.

- Wise, J. H., Abel, T., Turk, M. J., Norman, M. L., and Smith, B. D. (2012). The birth of a galaxy - II. The role of radiation pressure. *MNRAS*, 427:311–326.
- Yoon, J. H. and Putman, M. E. (2013). The Influence of Environment on the Circumgalactic Medium. *ApJ*, 772:L29.
- Yoon, J. H. and Putman, M. E. (2017). Ly α Absorbers and the Coma Cluster. *The Astrophysical Journal*, 839:117.
- Yoon, J. H., Putman, M. E., Thom, C., Chen, H.-W., and Bryan, G. L. (2012). Warm Gas in the Virgo Cluster. I. Distribution of Ly α Absorbers. *ApJ*, 754:84.
- Zahedy, F. S., Chen, H.-W., Johnson, S. D., Pierce, R. M., Rauch, M., Huang, Y.-H., Weiner, B. J., and Gauthier, J.-R. (2019). Characterizing circumgalactic gas around massive ellipticals at $z \sim 0.4$ - II. Physical properties and elemental abundances. *MNRAS*, 484(2):2257–2280.
- Zhang, D., Thompson, T. A., Quataert, E., and Murray, N. (2017). Entrainment in trouble: cool cloud acceleration and destruction in hot supernova-driven galactic winds. *MNRAS*, 468(4):4801–4814.
- Zhang, H., Zaritsky, D., Zhu, G., Ménard, B., and Hogg, D. W. (2016). Hydrogen Emission from the Ionized Gaseous Halos of Low-redshift Galaxies. *ApJ*, 833:276.
- Zhuravleva, I., Churazov, E., Kravtsov, A., Lau, E. T., Nagai, D., and Sunyaev, R. (2013). Quantifying properties of ICM inhomogeneities. *MNRAS*, 428:3274–3287.
- Zinger, E., Dekel, A., Birnboim, Y., Kravtsov, A., and Nagai, D. (2016). The role of penetrating gas streams in setting the dynamical state of galaxy clusters. *MNRAS*, 461:412–432.
- Zinger, E., Dekel, A., Kravtsov, A. V., and Nagai, D. (2018). Quenching of satellite galaxies at the outskirts of galaxy clusters. *MNRAS*, 475:3654–3681.

Zweibel, E. G. (2017). The basis for cosmic ray feedback: Written on the wind. *Physics of Plasmas*, 24(5):055402.

Chapter 7

VITA

Iryna Butsky

🔄 Last Updated June 8, 2021

contact

✉ ibutsky@uw.edu
🐙 github.com/ibutsky
👤 irynabutsky.me
🌐 US citizen

about

I am a PhD candidate at the University of Washington, using simulations to understand galaxy evolution. I am broadly interested in 1) the galactic baryon cycle and the structure of the circumgalactic medium, 2) how cosmic rays interact with gas in various regimes and their impact on galaxy evolution, and 3) improving models of subgrid physics in galaxy simulations.

code

enzo 2014 - 2020

+ Added cosmic rays to the MHD Riemann solvers along with anisotropic diffusion and streaming
+ Implemented magnetic supernova feedback

ChaNGa 2015 - 2020

+ Added cosmic rays as a second fluid, including advection and isotropic diffusion
+ Implemented an improved artificial viscosity method

stats

Total Pubs	9
Refereed	8
First Author	5
Citations	250
h-index	7

education

2015-2021	PhD Astronomy	University of Washington, Seattle WA
	+ Advised by Tom Quinn and Jessica Werk	
2015-2017	MSc Astronomy	University of Washington, Seattle WA
2010-2014	BS Astrophysics	California Institute of Technology, Pasadena CA

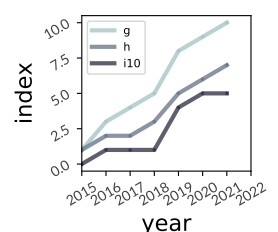
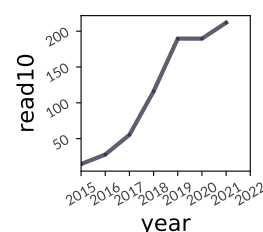
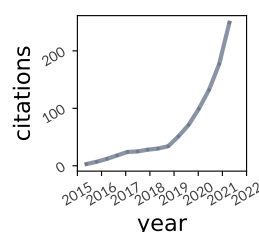
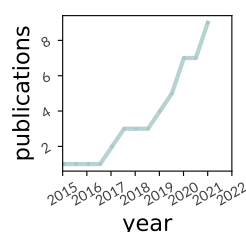
positions

2016-2020	Research Assistant	University of Washington
	+ Designed several simulation suites to test impact of cosmic rays on the CGM + Developing subgrid model for unresolved cold gas in galaxy simulations	
2019-2020	Research Analyst	Flatiron Institute Center for Computational Astrophysics
	+ Ran the first suite of 3D simulations studying the impact of cosmic rays on thermal instability in a stratified medium	
2014-2015	Research Assistant	KIPAC, SLAC National Accelerator Laboratory
	+ Implemented magnetic supernova feedback in enzo and demonstrated how supernovae seed galactic magnetic field growth	
2013	Summer Undergraduate Research Fellow	Max Planck Institute for Astronomy
	+ Quantified impact of baryons on dark matter halos in the NIHAO simulations	
2012	Summer Undergraduate Research Fellow	California Institute of Technology
	+ Modified ray-tracing methods to make observational predictions for iron-line variability due to discoseismic corrugation modes in accretion disks	
2011	LIGO SURF	California Institute of Technology
	+ Implemented method for quadrupolar perturbations in SpEC simulation code	

grants and awards (\$571,240)

2019	(Co-PI) NASA HST Legacy (AR-15800)	\$364,204
2019	Flatiron Pre-Doctoral Fellow	\$21,684
2018	Blue Waters Allocation Renewal	50,000 node-hours
2017	(Funded co-I) NASA HST (AR-15046)	25,000 SUs on Pleiades and \$123,352
2016	Blue Waters Graduate Fellow	50,000 node-hours on Blue Waters and \$50,000
2013	Flintridge Foundation SURF Fellow	\$6,000
2012	Nellie Bergen and Adrian Foster Tillotson SURF Fellow	\$6,000

metrics



students

Shreya Nakum
MAGIC, 2018–

Joseph Breneman
UW, 2019–2021

Daniel Piacitelli
UW, 2018–2021

Daven Cocroft
UW, 2018–2019

Joshua Smith
UW, 2018

Jasmine Smith
UW PreMAP, 2018

Julia Jansen
UW, 2017–2018

Eliana Sisman
MAGIC, 2017–2018

Tessa Pargiter-Hatem
UW PreMAP, 2017

references

Tom Quinn
trq@uw.edu

Jessica Werk
jwerk@uw.edu

Chris Hayward
chayward@
flatironinstitute.org

Cameron Hummels
chummels@caltech.edu

Philip Hopkins
phopkins@caltech.edu

Daisuke Nagai
daisuke.nagai@yale.edu

telescope time

2020

(Co-I) Keck II - Keck Cosmic Web Imager - 2020A

1 night

teaching & outreach

- 2017–2019 **Mentor, More Active Girls in Computing (MAGIC)** **Remote**
+ Mentored middle and high school girls in computational astronomy projects
- 2017–2019 **Mentor and Volunteer, PreMAP** **University of Washington**
+ Mentored undergraduate students in computational astronomy projects.
+ Organized overnight field trips to UBC (Vancouver) and LIGO (Livingston)
- 2012–2019 **Teaching Assistant (4 classes, 9 quarters)** **University of Washington / Caltech**
+ UW ASTR 101, “The Evolving Universe” Fall 2015, Spring 2016, Spring 2019
+ UW ASTR 150, “Planets” Winter 2016
+ Caltech Ay 1, “Intro to Astronomy” Spring 2012, 2013, 2014
+ Caltech Ay 21, “Galaxies and Cosmology” Winter 2013, 2014
- 2018–2019 **UW Prospective Visit Organizer** **University of Washington**
+ Organized the travel, lodging, department meetings, and social events for UW astronomy grad students
- 2018–2019 **Equity and Inclusion Committee Member** **University of Washington**
+ Helped foster cultural and departmental changes to promote equity
- 2017–2018 **UW EquiTea Organizer** **University of Washington**
+ Organized and led quarterly discussions on equity and inclusion
- 2016–2018 **UW Astronomy Major Mentor** **University of Washington**
+ Met monthly with two undergrad students to discuss schoolwork and research
- 2011–2014 **Caltech Y RISE Tutor** **California Institute of Technology**
+ Tutored local high school students in math, physics, and SAT preparation
- 2012 **InnoWorks Mentor** **Pasadena, CA**
+ Taught at a week-long science camp for middle school students

media

2020

RomulusC

- + Articles on my 2019 RomulusC paper were published online in Primeur, News-wise, Sciencenewsnet, Long Room, and Phys.org.
- + A figure from this work was selected for the 2021 Coalition for Academic Scientific Computation brochure.

other

- 2012–2013 **Caltech Dance Troupe President** **California Institute of Technology**
+ Organized various dance classes for the Caltech community
- 2011–2012 **Caltech Fleming House Social Team** **California Institute of Technology**
+ Organized monthly events for a community of ~ 80 people
- Languages**
+ Ukrainian (native), Russian (native), French (conversational), Spanish (conversational), German (intermediate)

refereed publications (citation count on left)

- 1 Hopkins, P., Squire, J., & **Butsky, I.**, 2021, [A Consistent Reduced-Speed-of-Light Formulation of Cosmic Ray Transport Valid in Weak and Strong-Scattering Regimes](#), arXiv e-prints
- 8 **Butsky, I.**, Fielding, D., Hayward, C., Hummels, C., Quinn, T., & Werk, J., 2020, [The Impact of Cosmic Rays on Thermal Instability in the Circumgalactic Medium](#), *ApJ*, **903**, 77
- 7 **Butsky, I.**, Burchett, J., Nagai, D., Tremmel, M., Quinn, T., & Werk, J., 2019, [Ultraviolet Signatures of the Multiphase Intra-cluster and Circumgalactic Media in the ROMULUSC Simulation](#), *MNRAS*, **490**, 4292
- 18 Brummel-Smith, C., Bryan, G., **Butsky, I.**, Corlies, L., Emerick, A., Forbes, J., Fujimoto, Y., Goldbaum, N., Grete, P., Hummels, C., et al., 2019, [ENZO: An Adaptive Mesh Refinement Code for Astrophysics \(Version 2.6\)](#), *The Journal of Open Source Software*, **4**, 1636
- 85 Hummels, C., Smith, B., Hopkins, P., O'Shea, B., Silvia, D., Werk, J., Lehner, N., Wise, J., Collins, D., & **Butsky, I.**, 2019, [The Impact of Enhanced Halo Resolution on the Simulated Circumgalactic Medium](#), *ApJ*, **882**, 156
- 51 **Butsky, I.**, & Quinn, T., 2018, [The Role of Cosmic-Ray Transport in Shaping the Simulated Circumgalactic Medium](#), *ApJ*, **868**, 108
- 20 **Butsky, I.**, Zrake, J., Kim, J., Yang, H., & Abel, T., 2017, [Ab Initio Simulations of a Supernova-Driven Galactic Dynamo in an Isolated Disk Galaxy](#), *ApJ*, **843**, 113
- 52 **Butsky, I.**, Macciò, A., Dutton, A., Wang, L., Obreja, A., Stinson, G., Penzo, C., Kang, X., Keller, B., & Wadsley, J., 2016, [NIHAO Project II: Halo Shape, Phase-Space Density and Velocity Distribution of Dark Matter in Galaxy Formation Simulations](#), *MNRAS*, **462**, 663
- 8 Tsang, D., & **Butsky, I.**, 2013, [Iron Line Variability of Discoseismic Corrugation Modes](#), *MNRAS*, **435**, 749

white papers and other publications

- Burchett, J., **Butsky, I.**, Tremmel, M., Bordoloi, R., Bryan, G., Cai, Z., Canning, R., Chen, H., Coil, A., Fielding, D., et al., 2019, [Ultraviolet Perspectives on Diffuse Gas in the Largest Cosmic Structures](#), *Bulletin of the American Astronomical Society*, **51**, 534

research talks

- 31 Cosmic Rays and the Circumgalactic Medium, 27th Young Scientists' Conference on Astronomy and Space Physics, **Kiev, Ukraine (Zoom)**, April 2021
- 30 Cosmic Rays and Synthetic Spectroscopy in ChaNGa, N-body Shop Excellence Conference, **Seattle, Washington (Zoom)**, January 2021
- 29 Cosmic Rays and Thermal Instability in the CGM, Arizona University Galaxy Crawl, **Tucson, Arizona (Zoom)**, January 2021
- 28 Cosmic Rays and Thermal Instability in the CGM, Princeton Galaxy Journal Club, **Princeton, NJ (Zoom)**, November 2020
- 27 Cosmic Rays and Thermal Instability in the CGM, STScI Galaxy Journal Club, **Baltimore, MD (Zoom)**, October 2020
- 26 Cosmic Rays and Thermal Instability in the CGM, Caltech TAPIR Seminar, **Pasadena, CA (Zoom)**, October 2020
- 25 Cosmic Rays and Thermal Instability in the CGM, KIPAC Tea Talk, **Menlo Park, CA (Zoom)**, October 2020
- 24 [Cosmic Rays and Thermal Instability in the CGM](#), On the Origin, Nature, and Mixing of Multiphase Gas in Astrophysics, **KITP, Santa Barbara (Zoom)**, October 2020
- 23 Cosmic Rays and Thermal Instability in the CGM, Carnegie Observatories Lunch Talk, **Pasadena, CA (Zoom)**, September 2020
- 22 Cosmic Rays and Thermal Instability in the CGM, The Role of Cosmic Rays in Driving Galactic Outflows (canceled due to COVID-19), **Chicago, IL**, March 2020
- 21 [Cosmic Rain and Cosmic Rays](#), Astronomy on Tap, **Seattle, WA**, January 2020

- 20 Cosmic Rays and Thermal Instability in the CGM, Columbia Astronomy Seminar, **New York, NY**, January 2020
- 19 Cosmic Rays and Thermal Instability in the CGM, Rutgers University Lunch Talk, **New Brunswick, NJ**, January 2020
- 18 Cosmic Rays and Thermal Instability in the CGM, CCA Predoctoral Fellowship Symposium, **New York, NY**, January 2020
- 17 UV Signatures of the Multiphase ICM and CGM in the RomulusC Simulation, Gothamfest NYU, **New York, NY**, September 2019
- 16 UV Signatures of the Multiphase ICM and CGM in the RomulusC Simulation, UCSB Astro Lunch Talk, **Santa Barbara, CA**, May 2019
- 15 The Role of Cosmic Rays in Shaping the Circumgalactic Medium, UC Berkeley TAC Seminar, **Berkeley, CA**, February 2019
- 14 Genetically Modified Halos with Cosmic Ray Feedback, AAS Astronomical Society Meeting, **Seattle, WA**, January 2019
- 13 The Role of Cosmic Rays in Shaping the Simulated CGM, Santa Cruz Galaxy Workshop, **Santa Cruz, CA**, July 2018
- 12 The Role of Cosmic Rays in Shaping the Simulated CGM, Circumgalactic Medium Workshop, **Evanston, IL**, July 2018
- 11 The Role of Cosmic Rays in Shaping the Simulated CGM, Blue Waters Symposium, **Sunriver, OR**, June 2018
- 10 The Role of Cosmic Rays in Shaping the Simulated CGM, ENZO Workshop, **Atlanta, GA**, May 2018
- 9 Simulating the CGM: The Case for Anisotropic Cosmic Ray Diffusion, CTAC University of Zurich Lunch Talk, **Zurich, Switzerland**, September 2017
- 8 The Role of Cosmic Rays in Isolated Disk Galaxies, Blue Waters Symposium, **Sunriver, OR**, June 2017
- 7 Galactic Magnetic Fields Originating from Supernovae, KIPAC Tea Talk, **Menlo Park, CA**, June 2015
- 6 The Effect of Baryons on the Dark Matter Halo Shape, Theoretical Astrophysics in Southern California Meeting, **Los Angeles, CA**, December 2013
- 5 The Effect of Baryons on the Dark Matter Halo Shape, Caltech SURF Seminar, **Pasadena, CA**, October 2013
- 4 The Effect of Baryons on the Dark Matter Halo Shape, MPA Galaxy Coffee, **Heidelberg, Germany**, September 2013
- 3 X-ray Signatures of Low Frequency Disk Oscillations Around Black Holes, Southern California Conferences for Undergraduate Research, **Camarillo, CA**, November 2012
- 2 Low-Frequency Quasi-Periodic Oscillations and Iron Line Variability of Discoseismic Corrugation Modes, Caltech SURF Seminar, **Pasadena, CA**, August 2012
- 1 Properties of Neutron Stars, Their Pulsational Modes, and Gravitational Wave Emission, Caltech SURF Seminar, **Pasadena, CA**, October 2011