Seeking Self-regulating Simulations of Idealized Milky Way–like Galaxies

Claire Kopenhafer1,2, Brian W. O’Shea1,2,3, and G. Mark Voit1

1 Department of Physics & Astronomy, Michigan State University, USA; kopenhaf@msu.edu
2 Department of Computational Mathematics, Science, & Engineering, Michigan State University, USA
3 Facility for Rare Isotope Beams, Michigan State University, USA

Received 2022 June 9; revised 2023 April 4; accepted 2023 April 6; published 2023 July 6

Abstract

Precipitation is potentially a mechanism through which the circumgalactic medium (CGM) can regulate a galaxy’s star formation. Here, we present idealized simulations of isolated Milky Way–like galaxies intended to examine the ability of galaxies to self-regulate their star formation, in particular via precipitation. We also examine the impact of rotation in the CGM. Using six simulations, we explore variations in the initial CGM t_{cool}/t_{ff} ratio and rotation profile. Those variations affect the amount of gas accretion and star formation within the galactic disk. To encourage this accretion and better study its dependence on CGM structure, we gradually increase the efficiency of stellar feedback during the first half of our simulations. Yet despite this gradual increase, the resulting outflows quickly evacuate large, hot cavities within the CGM and even beyond r_{200}. Some of the CGM gas avoids interacting with the cavities and is able to feed the disk along its midplane, but the cooling of feedback-heated gas far from the midplane is too slow to supply the disk with additional gas. Our simulations illustrate the importance of physical mechanisms in the outer CGM and IGM for star formation regulation in Milky Way–scale halos.

Unified Astronomy Thesaurus concepts: Stellar feedback (1602); Galaxy processes (614); Galaxy evolution (594); Circumgalactic medium (1879); Hydrodynamical simulations (767)

1. Introduction

Galaxies obey a number of scaling relations that suggest they have a mechanism for regulating their star formation rates (SFRs). These scaling relations include the star-forming main sequence (e.g., Renzini & Peng 2015; Sherman et al. 2021; Popesso et al. 2023) and the stellar mass–halo mass (SMHM) relation (Somerville & Davé 2015; Behroozi et al. 2019). Gas must be continually supplied to a star-forming galaxy, as its own interstellar medium (ISM) only contains enough gas to fuel star formation for a few gigayears. The circumgalactic medium (CGM) has gained much attention as a possible locale for self-regulation because it mediates both inflowing and outflowing gas in addition to functioning as a substantial baryonic reservoir in its own right (Tumlinson et al. 2017).

One potential self-regulation mechanism is known as “precipitation” (Voit et al. 2015). Under this framework, feedback (either stellar or from an AGN) works to maintain the median t_{cool}/t_{ff} ratio around 10. Throughout this paper, we will refer to the median value τ of t_{cool}/t_{ff} in the CGM as the “precipitation limit parameter.” Importantly, τ is the median of a t_{cool}/t_{ff} distribution for the CGM gas that may have a broad dispersion (Voit 2021). When t_{cool}/t_{ff} is above 10, the t_{cool}/t_{ff} distribution should allow for the formation of a multiphase medium. If τ declines, additional cold dense gas is able to accrete onto the galaxy, driving a burst of star formation and feedback. This feedback in turn heats and inflates the CGM, lowering its density and reducing its ability to cool. Conversely, a CGM driven above τ ∼ 10 should feed less cold, dense gas into the galaxy. This reduction of the cold gas supply then stalls feedback until the CGM is again able to cool and contract, thereby lowering τ.

Precipitation as a regulation mechanism was originally proposed for galaxy cluster cores heated by active galactic nuclei (AGN). It was motivated by observations suggesting that the black hole fueling rate depends on the development of a multiphase medium (Pizzolato & Soker 2005; Cavagnolo et al. 2008; Voit et al. 2008), which happens in simulations when a CGM in approximate thermal balance becomes thermally unstable (Pizzolato & Soker 2010; McCourt et al. 2012; Sharma et al. 2012). In simulated multiphase media, cold clouds are able to precipitate out of the hot, ambient medium when t_{cool} ≲ 10 t_{ff} (Gaspari et al. 2012, 2013; Li & Bryan 2014a, 2014b; Gaspari et al. 2015; Prasad et al. 2015). If the medium is sufficiently turbulent, these cold clouds are then able to accrete chaotically toward the center, and in the systems originally considered, they trigger a strong AGN feedback response. This feedback then heats and expands the CGM, raising t_{cool} and diminishing accretion. See Donahue & Voit (2022) for an in-depth review of this process.

Regulation via precipitation is observationally supported in both clusters (Voit & Donahue 2015) and elliptical galaxies (Frisbie et al. 2020). The physical principles that underpin precipitation regulation are agnostic to the source of feedback in a galaxy, and so they could extend to smaller galaxies not dominated by AGN feedback. This possibility is supported by recent theoretical (Voit et al. 2019) and observational (Babiyk et al. 2018) developments.

In this work, we explore the viability of precipitation as a regulatory mechanism for star formation in Milky Way–like galaxies lacking AGN activity. Self-regulation is broadly defined as a balance between gas accretion on the one hand and stellar feedback on the other (Bouché et al. 2010; Schaye et al. 2010; Davé et al. 2012; Zaragoza-Cardiel et al. 2019). This balance might ultimately be what places galaxies on the stellar mass–halo mass relation (Voit et al. 2015; Mitchell & Schaye 2022).
Spiral galaxies like the Milky Way tend to live in complex environments where they are continuously interacting with companion galaxies and cosmological filaments. Such environments make it difficult to isolate the interactions of the CGM and its host galaxy and to understand the long-term behavior of an undisturbed Milky Way–like halo. We therefore use idealized simulations of an isolated galaxy for our investigation, seeking to understand what a Milky Way–like galaxy would look like without external interference. Idealized simulations also allow us to maintain a constant dark matter halo mass, as changing the dark matter mass should eventually change the stellar mass of the galaxy according to the SMIH relation. With idealized simulations, we are also able to achieve higher spatial resolution in the CGM for reasonable computational cost. High CGM resolution broadens the distributions of gas densities and temperatures (Corlies et al. 2020) and increases the overall amount of neutral hydrogen (van de Voort et al. 2019). Both of these effects should have an impact on precipitation (Voit 2021).

Historically, idealized simulations of isolated Milky Way–like galaxies have largely fallen into two types: simulations of a star-forming gaseous disk with no CGM, and simulations of a CGM with no explicit star formation. The former include the AGORA simulations of Kim et al. (2016), works using the AGORA initial conditions such as Butsky & Quinn (2018) and Shin et al. (2021), and others (Benincasa et al. 2016). Instead of a CGM, the gas disk of these simulations is surrounded by a very low-density medium with very long cooling times and low total mass. In the latter category are the simulations from Fielding et al. (2017) and Li & Tonnesen (2020). These CGM-focused works include stellar feedback, but this feedback is tied to the gas flow rate through an inner boundary rather than the explicit formation of stars in a gas disk.

This work combines both approaches, modeling star formation and the resulting feedback in the context of both a gas disk and its surrounding nonuniform CGM to create a fully self-consistent picture of how a Milky Way–like galaxy and its CGM interact. This is particularly important for modeling the inner CGM and the disk–halo interface. This combination of features was also used in the simulations of Su et al. (2019, 2020). Those works focused on the suppression of cooling flows more generally, while we focus more specifically on the theoretical process of precipitation. This makes Su et al. (2019, 2020) an interesting point of comparison for our work.

We detail our simulation setup in Section 2. Then, in Section 3, we examine how the galactic disk is affected by our simulation setup and its variations. In Section 4, we follow the movement of gas between the disk and the CGM by tracing inflows, outflows, and the CGM’s gas supply. Section 5 looks at the structure of the CGM in our simulations. We discuss various aspects of our simulations in Section 6. Finally, we summarize and conclude our work in Section 7.

2. Simulation Setup

We perform idealized simulations of isolated, Milky Way–like galaxies and their circumbgalactic media. Our simulations are performed with the Eulerian astrophysical hydrodynamics code Enzo (Bryan et al. 2014; Brummel-Smith et al. 2019). Enzo models stellar populations with particles, and we include feedback from Type II supernova, as will be discussed more in Section 2.2.

---

### Table 1

| Quantity | Name                  | Value         |
|----------|-----------------------|---------------|
| $M_{\text{vir}}$ | dark matter concentration | 1.0 × 10^{12} M_{\odot} |
| $M_{\text{vir}}$ | dark matter virial radius | 10 kpc         |
| $M_{\text{vir}}$ | background stellar mass | 206 kpc        |
| $M_{\text{vir}}$ | effective* initial disk gas mass | 5.8 × 10^{10} M_{\odot} |
| $M_{\text{vir}}$ | initial disk metallicity | 2.3 Z_{\odot}  |
| $R_{\text{disk}}$ | disk radial scale height | 3.5 kpc        |
| $z_{\text{disk}}$ | disk vertical scale height | 0.325 kpc      |
| $M_{\text{CGM}}$ | initial CGM gas mass (fiducial) | 2.3 × 10^{10} M_{\odot} |
| $Z_{\text{CGM}}$ | initial CGM metallicity | 0.3 Z_{\odot}  |

*The actual disk mass ends up being slightly higher than the value of the parameter used in Equation (1), which is $M_{\text{ISM}} = 5.0 \times 10^{5}$. The actual disk mass that results is determined from a temperature cut, as the initial disk is isothermal and distinctly cooler than the surrounding CGM.*

---

The inclusion of $H_{2}$ in our chemistry network is not strictly necessary, and it has little bearing on the simulation results, due to our ISM resolution and chosen star formation algorithm.

A slightly modified version of Cloudy 10 is used, which saves outputs with more precision.
details of our star formation and feedback models. In Section 2.3, we discuss our simulations’ approach to AMR. Finally, Section 2.4 covers the multiple simulation variants we run.

2.1. Initial Conditions

The bulk values used to initialize our simulation can be found in Table 1. Initial mass-averaged profiles are shown in Figure 1. The profiles are split into disk and CGM components at small radii.

Our stellar mass is taken as the uncertainty-weighted average of the observations in Table 6 of Côté et al. (2016). We then use the findings of Peeples et al. (2014) to derive the ISM mass and metallicity based on this stellar mass. The disk metallicity is $Z_{\text{ISM}} = 2.3Z_\odot$, assuming $M_{\text{dust}} = M_{\text{dust}}^{\text{ISM}}$. Peeples et al. (2014) suggests $M_{\text{ISM}} = 9.8 \times 10^6 M_\odot$, but we lower this to $7 \times 10^5 M_\odot$ in order to help minimize the initial burst of star formation experienced by the simulation; see Section 2.2.1 for more discussion.

The CGM is initialized to a constant uniform metallicity of $0.3Z_\odot$. This is the median value from Prochaska et al. (2017). The metallicity of the CGM changes, however, as stellar populations inject supernova feedback and drive outflows (see Section 2.2).

2.1.1. Gaseous Disk

The gas of the disk follows the softened profile of Tonnesen & Bryan (2009):

$$\rho(R, z) = \frac{M_{\text{ISM}}}{8\pi R_s^2 z_s} \sech \left( \frac{R}{R_s} \right) \sech \left( \frac{z}{z_s} \right), \quad (1)$$

where $R$ is the cylindrical radius, and $R_s = 3.5$ kpc and $z_s = 0.325$ kpc are the scale heights of the gas. For $R > 24$ kpc, Equation (1) is multiplied by a smoothing factor of

$$0.5 \left[ 1 + \cos \left( \frac{\pi R - 24 \text{ kpc}}{7.2 \text{ kpc}} \right) \right] \quad (2)$$

that tapers the radial edges of the disk. The disk gas is given a circular velocity prescribed by the combination of our NFW and stellar potentials, with $v_0 = \sqrt{R \cdot g(r, R, z)}$.

The disk is set to an initial uniform temperature of $10^5$ K. In reality, galaxy disks are usually at $10^4$ K or below, but gas cools very efficiently around $10^5$ K. Our disk is initialized at this higher temperature so that gas would be well above our temperature threshold for star formation ($3 \times 10^4$ K; see Section 2.2) but also rapidly cool. The variation in disk density means that the temperature does not change uniformly, which helps spread out the initial burst of star formation across time.

The initial conditions for the disk and CGM are blended together based on density; if $\rho_{\text{ISM}}(r) > \rho_{\text{CGM}}(r)$ in a cell, that cell is considered part of the disk. Otherwise, it is initialized to be part of the CGM.

2.1.2. Circumgalactic Medium

The density and temperature structure of the CGM are set following Voit (2019), who describes an entropy profile that precipitation-regulated galaxies in NFW halos would follow under the assumption of hydrostatic equilibrium. This assumption is reasonable for a $M_{\text{vir}} = 10^{12} M_\odot$ halo (Oppenheimer 2018; Lochhaas et al. 2020). The profile therein assumes

$$(r) = (39 \text{ keV cm}^2) \frac{v_{200}^2}{r_{200}} \left( \frac{r}{r_{200}} \right)^{1/3} + (2\mu m_p)^{1/3} \left[ \frac{2n_e \tau}{3n} \right] \Lambda(T_r, Z_{\text{CGM}}) \left( \frac{r}{r_{200}} \right)^{2/3}, \quad (3)$$

for entropy quantified in terms of $K \equiv kT_{\text{c}} \tau^{-2/3}$. This way we can test halos that deviate from the apparent precipitation limit of $\tau \approx 10$. We assume $n_e = n_i$ such that $2n_e/n = 1$. The initial metallicity is $Z_{\text{CGM}} = 0.3$. The term $\Lambda$ is the cooling rate as a function of of temperature and metallicity, which we calculate with the Grackle chemistry and cooling library (Smith et al. 2017). The term $T_{\text{c}}(r)$ is the gravitational temperature $kT_{\text{c}}(r) = \mu m_p v^2_{\text{esc}}(r)/2$.

To calculate the initial density and temperature profiles of the CGM, we combine Equation (3) with $dP/dr$ from hydrostatic equilibrium. We adopt the boundary condition $kT(r_{200}) = 0.25 \mu m_p v_{\text{esc},\text{max}}^2$ suggested by Voit (2019). Beyond $r_{200}$, the temperature begins to plummet dramatically. To mitigate this, we abandon a functional form for the entropy and instead fix $d\log P/d\log r$ to its value just inside $r_{200}$. We then set the temperature with a sigmoid function that smoothly blends $T(r_{200})$ with a floor of $4 \times 10^5$ K. The resulting mass-weighted profiles for the initial density, temperature, entropy, pressure, cooling time, and enclosed mass are shown in Figure 1. For $\tau = 10$, the actual cooling time deviates slightly from the target...
the circular velocity $v_c$ refers to the power-law index of the initial azimuthal rotation profile. Notes. Variations from the fiducial model are highlighted in bold. The parameter $\beta$ refers to the power-law index of the initial azimuthal rotation profile.

For simplicity, we use a modified NFW profile to calculate the circular velocity $v_c$ used in Equation (3) as was done in Voit (2019). This modification approximates the presence of a galactic disk at the center of the potential well: $v_c^2(r) = v_{c,max}^2$ for $r < 2.163r_s$, where $r_s$ is the scale radius of the NFW profile, and

$$v_c^2(r) = v_{c,max}^2 \cdot 4.625 \left[ \ln \left(1 + \frac{r}{r_s}\right) - \frac{1}{1 + \frac{r}{r_s}} \right]$$

otherwise. Using this modified NFW profile to represent the inner contents of the halo is slightly incongruous with the construction of our gas disk and static stellar potential; however, the modified NFW profile is spherically symmetric, making it easier to calculate the CGM’s density and temperature profiles. This modified NFW profile is only used to set up the initial CGM conditions, while the unmodified NFW potential, the Miyamoto & Nagai (1975) stellar potential, and the gaseous disk’s own gravity are what are actually applied to the simulation during execution. These two potentials differ most strongly in the inner regions of the simulation, where the CGM is most likely to be replaced with the galactic disk.

We give the CGM an initial azimuthal velocity, the strength of which is determined by

$$v_\theta(r, \theta) = v_0 \sin^2 \theta \left(\frac{r}{r_0}\right)^\beta.$$  

Here, $r$ is the spherical radius and $\theta$ is the polar angle. This function replaces the disk’s Keplerian velocity profile wherever the CGM density dominates, as described above. We do not consider Equation (5) when placing the CGM in hydrostatic equilibrium, meaning the CGM may be slightly oversupported against gravity in the cylindrically radial direction. We use Hodges-Kluck et al. (2016) to choose $v_0 = 180$ km s$^{-1}$ and $r_0 = 10$ kpc, which is roughly the radius where their halo model’s specific angular momentum matches that of the disk (see their Figure 5). It should be noted that Hodges-Kluck et al. (2016) adopt a constant $v_\theta$ with their model, which they assume is reasonable within $\sim 50$ kpc. We leave $\beta$ as a free parameter; for our fiducial simulation, $\beta = -1/2$ (see Table 2).

### 2.2. Star Formation and Feedback

Our star formation and feedback algorithms are modified from the implementation of Cen & Ostriker (1992) as described in Section 2.1 of Oh et al. (2020). We require that gas in a grid cell have

1. $\nabla \cdot \mathbf{v} < 0$,
2. either $t_{cool} \leq t_{dyn}$ or $T < 3 \times 10^3$ K,
3. $n \geq 10$ particles/cm$^{-3}$, and
4. $m_\star \equiv \int m_{cell} \Delta x > 10^4 M_\odot$,

where the local gas dynamical time is $t_{dyn} = \sqrt{3\pi/(32G\rho)}$. If all these criteria are met, a “star particle” is created, representing a population of individual stars with total mass $m_\star$. An equivalent amount of gas is also removed from the host cell, and the particle is given a velocity such that momentum is conserved. The minimum stellar mass of $10^4 M_\odot$ is chosen as a balance between resolving the star formation with more particles and the computational expense of tracking and managing these particles. As in Smith et al. (2011), we ignore the Jeans instability criterion because it is always met by the star-forming gas in our simulations. We set $f_{\text{FB}} = 0.2$ and impose a minimum dynamical time of one million years.

Stellar feedback proceeds as described in Section 2.2 of Oh et al. (2020), and it is the same algorithm as used in Peeples et al. (2019). Though a star particle is formed immediately, for the sake of stellar feedback, the accumulation of stellar mass is assumed to be a drawn-out process that peaks in efficiency after one dynamical time (Oh et al. 2020, Equation (3)). The amounts of mass, momentum, and energy that are returned in time step $\Delta t$ are then tied to this extended star formation model through the mass of stars $\delta M_{\text{SF}}$ that would form in that time step; e.g.,

$$\Delta E = \epsilon_{FB} \cdot c^2 \delta M_{\text{SF}}.$$  

We adopt the same efficiencies as Oh et al. (2020) for the returned fraction of total and metal masses. Energy, momentum, mass, and metals are then deposited into the cube of 27 cells centered on the star particle’s host cell.

It should be noted that there are no star particles present in the simulation initial conditions. This means that there are no pre-existing stellar populations affecting the gas in the earliest moments of the simulation. This artificiality has interesting consequences that are discussed in the following subsection.

#### 2.2.1. Ramping Stellar Feedback Efficiency

Idealized galaxies typically need a period of time in which to “settle,” because actual galaxies (including the CGM) are more complicated than can be easily constructed for initial conditions. The settling process may just be as simple as letting the simulation run without any additional physics but starting analysis at a later time, or additional steps may be taken; for example, Jeffreson et al. (2020) speed up their disk-settling time by injecting thermal and kinetic energy into dense gas cells for the first 500 Myr. The goal of settling is for the artificiality of the initial conditions to be erased by physical interactions such that the simulation more closely resembles a real galaxy with complex dynamics.

In our case, we are interested in the settling of the disk and the CGM. We have constructed a CGM profile such that gas should accrete from the CGM and onto this disk, but it must be given time to do so. Through preliminary testing, we found that the disk forms stars and produces stellar feedback on a shorter timescale than an appreciable mass of CGM gas will cool and

| Name          | FB | $t_c/t_g$ | $\beta$ |
|---------------|----|-----------|---------|
| FIDUCIAL      | Y  | 10        | $-1/2$  |
| COOLFLOW      | N  | 10        | $-1/2$  |
| LOWRATIO      | Y  | 5         | $-1/2$  |
| HIGHRATIO     | Y  | 20        | $-1/2$  |
| LINROT        | Y  | 10        | $-1$    |
| NOROT         | Y  | 10        | N/A     |

Table 2

Our Set of Simulations and Their Varied Parameters

Kopenhafer, O’Shea, & Voit

The Astrophysical Journal, 951:107 (25pp), 2023 July 10
accrete onto the disk. In order to give the CGM gas a better chance to establish accretion interactions with the disk, we have implemented a ramp in the efficiency of stellar feedback. The additional scientific advantage of this approach is that we can enforce periods within which the accretion of CGM gas dominates over feedback, and thereby explore how accretion and star formation vary with CGM properties.

The efficiency of stellar feedback is controlled by the dimensionless parameter $\epsilon_{\text{FB}}$ (Equation (6)). This parameter is linearly increased between $t = 1$ Gyr and $t = 2$ Gyr from $\epsilon_{\text{FB}} = 5 \times 10^{-8}$ to $5 \times 10^{-6}$. Our final $\epsilon_{\text{FB}}$ is 0.5 dex lower than both the lowest-efficiency simulations of Oh et al. (2020) and FOGGIE (Peeples et al. 2019). The difference in feedback efficiency between our idealized simulations and these aforementioned cosmological simulations will be important to consider when discussing our results in Section 6. The efficiency ramp begins at 1 Gyr of simulation time in order to give CGM gas with $t_{\text{cool}} \lesssim 1$ Gyr time to interact with the disk before being disrupted by feedback. Adjusting the ramp’s timing—that is, the start and end times—adjusts the overall total mass of the disk, due to this early accretion, but it does not affect simulation properties at late times ($\gtrsim$1 Gyr after the ramp ends). This is demonstrated in Section 6.4, where it is discussed in more detail.

2.3. Resolution

Enzo uses block-structured Cartesian Adaptive Mesh Refinement (AMR; Berger & Colella 1989) to control the resolution of its grid cells. The base grid of our simulation is $128^3$ cells (12.8 kpc per cell side) and the resolution of a region is refined by a factor of two if the cell exceeds a mass threshold of $2.67 \times 10^5 M_\odot \times 2^{-(l-0.5)}$, where $l$ is the zero-based level index. The mass threshold for refinement therefore decreases with level in a super-Lagrangian way, preventing excessive refinement on the lowest levels, which would increase computational cost. The highest levels are concentrated in the galactic disk, which, while not the focus of this study, is important to resolve for the purposes of star formation.

Given the low density of the CGM, a mass-based refinement criterion is not enough for the CGM gas to become well-resolved. The importance of good CGM resolution has been demonstrated by Hummels et al. (2019), Peeples et al. (2019), Suresh et al. (2019), and van de Voort et al. (2019). Smaller clouds are allowed to develop with higher CGM resolution, and turbulent structures are resolved to smaller scales. We therefore also define six nested rectangular regions of fixed minimum resolution (the first four of which are cubic). Cells within these regions are allowed to refine further based on mass. An example of this is shown in Figure 2. We allow up to seven levels of refinement (a minimum spatial resolution of 100 pc). This resolution proves sufficient to resolve the cooling length in the entirety of the CGM. The cooling length is not resolved within the disk, but we leave our ISM resolution lower than, e.g., the FIRE-2 simulations (Hopkins et al. 2018a).

2.4. Simulation Variants

The goal of our simulations is not only to test if we can create a precipitating self-regulating system, but also to explore the robustness of self-regulation. To that end, we explore five variations on our fiducial simulation, as laid out in Table 2. The first variation, COOLFLOW, is identical to the fiducial run in its initial conditions, but it has stellar feedback completely disabled (star formation is still allowed in order to remove cold gas and preserve numerical stability). In this way, it functions as a control to demonstrate the importance of feedback.

The next two variants, LOWRATIO and HIGHRATIO, modify the precipitation limit parameter $\tau$ in Equation (3). Their values of $\tau$ are chosen to be the approximate lower and upper bounds experienced, on average, by a precipitating system (Voit et al. 2017; Voit 2018, 2021). We note that, because the CGM’s radial density profile is defined by the initial $\tau$ through Equation (3), these variants start with CGM masses different by about a factor of 2.6. Compared to the fiducial CGM mass given in Table 1, the HIGHRATIO variant starts with $1.3 \times 10^{10} M_\odot$ of CGM gas and the LOWRATIO with $3.9 \times 10^{10} M_\odot$.

Though the CGM of galaxies likely rotates (Hodges-Kluck et al. 2016; DeFelippis et al. 2020), the shape of its rotation profile is not well-constrained. The LINROT variation modifies the initial rotation profile of the CGM, changing the index $\beta$ in Equation (5), while NOROT is a control for the impact of CGM rotation on the evolution of the system. This latter variant has no initial rotation in the CGM, but it still maintains Keplerian rotation in the disk.

\[ \text{Equation (3)} \]

\[ \text{Equation (5)} \]

\[ \text{Equation (6)} \]

\[ \text{Equation (7)} \]

\[ \text{Equation (8)} \]

\[ \text{Equation (9)} \]

\[ \text{Equation (10)} \]
3. The Galactic Disk

We start by looking at the gas content of the galactic disk and its star formation. In later sections, we will look in detail at the exchange of gas between the disk and CGM, but the effects of CGM accretion are readily apparent within the disk.

3.1. Appearance

Figure 3 compares the disks of our simulation variants at a simulation time of 3 Gyr. We show the density, temperature, and radial velocity within a slice through the disk midplane. The solid white circles represent the average radius within which stars form, which is determined as follows: for each simulation snapshot ($\Delta t = 50$ Myr), we determine the maximum cylindrical radius of star particles formed since the last snapshot. The averages of these maxima over $t = 2$–$4$ Gyr give the white circles in Figure 3. The numerical values of these radii, as well as their standard deviations over time, are reported in Table 3. The dotted circles show the edge of each variant’s initial gas disk. Due to differences in initial CGM structure and the way the disk and CGM are blended together (see Section 2.1.2), the LOWRATIO and HIGHRATIO simulations have slightly different initial radii than the other variants, but all are around 28 kpc.

From these slices, we see that the gas in the disk is around $10^6$ K on average, reaching $10^7$ K and lower in the densest spiral arms and near the center. Star formation is most prevalent in the very center of the disk. There are hotspots of $\sim 10^7$ K gas within the star-forming center of each variant’s disk that are the result of feedback. The exception is the COOLFLOW simulation, which has more prominent hotspots but no feedback. For this variant, the gas heating is due to a “pile-up” of accreting gas. This pile-up will be discussed further in Section 4.1.

The radial velocity slices show us that the hottest gas at $T \sim 10^6$ K is not strictly outflowing. Clear examples of this can be seen in the right side of the fiducial slices, in the bottom corner of the LOWRATIO images, and throughout the NOROT slices. The fiducial simulation, in particular, shows evidence of a radial velocity gradient across a hot, low-density cloud. This, along with the highly variable gas temperature outside the galactic disk, suggests that hot gas is mixing with cooler gas in the disk midplane. The prevalence of radial inflow in hot gas also suggests that gas is cooling as it moves toward the disk. Though highlighted in Figure 3 by LOWRATIO and NOROT, cooling inflow is present for $t > 2$ Gyr in all variations.

The size of the disk’s star-forming region appears impacted by the CGM’s $t_{\text{cool}}/t_\text{ff}$ properties, as seen from the solid white circles in Figure 3 and the values in Table 3. For both of these, we use the average maximum radius within which stars form as a measure of the star-forming region. The LOWRATIO variant has an SF region that is statistically larger than the fiducial and the HIGHRATIO variants (adopting $\alpha = 0.05$ or a 95% confidence interval), though we note that the fiducial’s region is not significantly larger than HIGHRATIO’s. This suggests a small dependence on the simulation’s initial $t_{\text{cool}}/t_\text{ff}$ ratio. Moreover, the fiducial, LINROT, and NOROT simulations are statistically indistinguishable when tested against each other.\(^7\)

\(^7\) A slight difference between the fiducial, LINROT, and NOROT simulations appears when testing each of these simulations against other variants. While the LOWRATIO simulation has a statistically larger star-forming region than the fiducial, it fails to test as significantly larger than the LINROT and NOROT simulations. Additionally, while the fiducial simulation does not test as significantly larger than the HIGHRATIO simulation, the LINROT and NOROT variants do.

These simulations all have the same initial $t_{\text{cool}}/t_\text{ff}$ ratio. The COOLFLOW simulation has a star-forming region that is statistically significantly larger than all the other simulation variants, but this follows from its lack of feedback and aggressive star formation rather than a difference in its CGM.

3.2. Mass Growth

Figure 4 shows the disk mass and star formation rate over the full simulation time (4 Gyr) for each variant. The disk mass is...
split into gaseous and stellar components. The disk gas is defined by a cylindrical region with \( R \approx 5.7 R_\odot = 20 \) kpc and thickness \( \delta z = 2.6 \) kpc. This cutoff in cylindrical radius is somewhat arbitrary, but it corresponds roughly to a transition point in the profiles of density and temperature that is visible from 2 to 4 Gyr. The disk’s stellar mass is defined as the total mass of all stars formed, and neglects stellar mass loss. Including stellar mass loss lowers the stellar masses at \( t > 1 \) Gyr by \( \sim 1.5 \times 10^6 M_\odot \). The accompanying SFR is calculated in bins of \( \Delta t = 50 \) Myr. Vertical dotted lines denote the beginning and end of the feedback efficiency ramp laid out in Section 2.2.1. The fiducial simulation is recreated in all three panels.

In the leftmost panel, the fiducial simulation is compared to the COOLFLOW run. For the fiducial model, the growth in stellar mass slows past 1 Gyr, when the stellar feedback efficiency begins to ramp. In the COOLFLOW model, however, the stellar mass continues to grow significantly as the simulation progresses, depleting the disk’s gas mass more appreciably than in the fiducial variant. The SFR is also generally higher in the COOLFLOW simulation, This behavior is expected, as the COOLFLOW model has stellar feedback disabled. This also indicates the flattening of the fiducial model’s stellar growth is due to feedback, which is confirmation of an expected result.

In the middle panel, variations in the initial \( t_{\text{cool}}/t_{\text{ff}} \) ratio are explored by comparing the fiducial simulation to the LOWRATIO and HIGHRATIO runs. The rightmost panel explores the rotation variants LINROT and NOROT. All of the variants with stellar feedback demonstrate remarkably similar gas mass curves. Stellar growth and gas mass loss flatten out around 1 Gyr, when the feedback efficiency begins to increase. The variants are primarily distinguished by the total amount of stellar mass they form, with the largest difference observed between the \( t_{\text{cool}}/t_{\text{ff}} \) variants.

For the first \( \sim 0.7 \) Gyr, the fiducial and LINROT simulations have the same stellar mass curves. This is also true for the fiducial and COOLFLOW simulations before \( \sim 0.5 \) Gyr. Because these simulations all start with an identical initial disk, deviations in stellar mass can be attributed to gas accretion from the CGM. The NOROT variant has little apparent overlap in stellar mass growth with the fiducial simulation, indicating an earlier deviation in the amount of CGM accretion. We attribute NOROT’s early differentiation to the lack of CGM angular momentum, which should make it easier for gas to settle onto the disk and form stars. The LOWRATIO and HIGHRATIO simulations start with slightly smaller/larger initial disk radii, respectively, due to how the disk and CGM are blended (Section 2.1.1). This has a negligible effect on their disk mass, while their CGM masses deviate from the fiducial by about a factor of two, with LOWRATIO being the most massive. Given that the LOWRATIO simulation goes on to form the most stars (of the variants with feedback), this is further evidence that CGM accretion is a major contributor to stellar growth.

The fiducial model and all other variants with \( \tau = 10 \) start with about \( 8 \times 10^8 M_\odot \) of CGM gas with \( t_{\text{cool}} \ll 1 \) Gyr, which is the timescale on which stellar feedback is kept inefficient. The LOWRATIO variant has \( \sim 4 \times 10^9 M_\odot \) of this short-cooling-time gas (~5 times greater than the fiducial), and forms the most stars before 1 Gyr. On the other hand, the HIGHRATIO variant forms the fewest stars by 1 Gyr, and its CGM only has \( \sim 1 \times 10^8 M_\odot \) of gas with \( t_{\text{cool}} \ll 1 \) Gyr (a factor of 8 lower than the fiducial). These differences support the interpretation that star formation within the first gigayear is fueled not only by disk mass but also by the accretion of gas from the CGM. Because \( \tau \) defines the initial density distribution and therefore the overall CGM mass (Section 4.1.2), these early differences in gas with short cooling times could be due either to a difference in total mass, a shift in the cooling time distribution, or both. The inflow of gas and the evolution of CGM cooling times will be discussed more in Section 4.

Though each variant experiences a different amount of star formation, in particular at early times, their gas masses remain both relatively constant and similar across variants. Additionally, the star formation rates are also quite consistent once stellar feedback reaches its full strength at \( t = 2 \) Gyr. We attribute the constancy of the disk mass among simulation variants to the Toomre criterion \( Q = c_s \kappa / \pi G \Sigma_g \), where \( c_s \) is the sound speed, \( \kappa \) is the epicyclic frequency of the rotating disk, and \( \Sigma_g \) is the gas surface density of the disk’s face (Toomre 1964). Because all of our variant disks were initialized with the same gas density profile (Equations (1) and (2)), dwell within the same gravitational potential, and remain roughly isothermal \((T \sim 4 \times 10^3 \text{ K for the bulk of the gas})\), the quantities \( \Sigma_g, \kappa, \) and \( c_s \) should be similar across variants.

Deviations in \( Q \) across time are most likely driven by changes in \( \Sigma_g \) driven by accretion. As gas is added to an isothermal disk, \( Q < 1 \) and the disk gas is able to fragment and form stars until the surface density falls back below the threshold for instability. Disk stability and structure is a rich field of research (e.g., Krumholz et al. 2018, and references therein) and the original Toomre \( Q \) can be modified to account for more nuanced physics (e.g., Romeo & Falstad 2013). Additionally, our simulations lack the resolution needed for a realistic ISM (e.g., Hopkins et al. 2018a), and our static background potentials do not capture fragmentation effects or the dynamics of spiral arms and bars. Yet this basic framework explains why each simulation variant has a remarkably similar disk gas mass despite differences in stellar mass. The exception is the COOLFLOW variant, where the lack of supernova feedback likely reduces the amount of turbulent driving within the disk—and therefore the effective value of \( c_s \).

In Figure 5, we focus on the late-time (\( t \geq 2 \) Gyr) stellar and gas masses. These quantities are shown relative to each simulation’s gas and stellar masses at \( t = 2 \) Gyr. Once again, stellar mass loss is ignored in order to show the integrated star formation. Including stellar mass loss drops the final stellar mass increase by \( \sim 1 \times 10^8 M_\odot \) for the simulations with feedback and \( \sim 4 \times 10^9 M_\odot \) for the COOLFLOW variant.

The most dramatic stellar mass increase can again be seen in the COOLFLOW simulation, while the variants with feedback
experience more gradual increases in their stellar masses. The fiducial and LINROT simulations grow at a similar rate, while the LOWRATIO and NOROT variants “taper off” in their stellar mass increase after 2.5 Gyr. The HIGHRATIO variant appears to be a “late bloomer,” with stellar mass increases smaller than the other variants with feedback until around 3.6 Gyr. All of the variants with feedback form between $3 \times 10^8 M_\odot$ and $7 \times 10^8 M_\odot$ more stars after $t = 2$ Gyr.

These final increases in stellar mass are partially compensated by overall decreases in gas mass, which, ignoring the NOROT and COOLFLOW variants, are between $1.5 \times 10^8 M_\odot$ and $5.5 \times 10^8 M_\odot$ at $t = 4$ Gyr. Each simulation variant, however, took a very different path to reach this point. Except for the LINROT and COOLFLOW simulations, most variants see an increase in their disk’s gas mass at some point before $\sim 2.3$ Gyr. The NOROT simulation sees the largest increase in disk gas mass, and it is the only simulation to end with more gas at $t = 4$ Gyr than it had at $t = 2$ Gyr. Despite this, it is not the variant with the largest increase in stellar mass. The differences in disk gas mass between the variants highlight that the story of accretion is complex. We will explore it more in Section 4.2.

### 4. Outflows and Inflows

Feedback processes in the disk are able to drive large-scale galactic outflows. In our simulations, these “feedback processes” are limited to Type II supernovae. Indeed, self-regulation requires that infalling gas must balance gas loss through outflows and star formation. Given that our idealized models ignore galaxy mergers, gas filaments, and other cosmological processes, their evolution is a story of inflowing and outflowing CGM gas. Therefore, in this section we examine the exchange of gas between the CGM and the disk as our simulations evolve.

#### 4.1. System Dynamics

Figure 6 shows the evolution of the fiducial simulation in four thermodynamic quantities—density, temperature, entropy, and pressure—as well as radial velocity. Average values along the line of sight are shown at four times (in gigayear intervals) using an edge-on thin slab. These slabs are two radial scale heights ($2R_\text{s} = 7$ kpc) thick and 600 kpc square on their sides, centered on the disk. By averaging through a thin subdomain, we can show a more representative visualization of the domain (as compared to a slice) while not oversmoothing turbulent gas structures. The white circle denotes $r_{200}$. The ramp in stellar
feedback efficiency, as described in Section 2.2.1, occurs from 1 to 2 Gyr.

At 1 Gyr, the initial burst of star formation begins to subside as the feedback efficiency starts to increase. The initial disk is supported radially by velocity but is not sufficiently supported in the vertical direction. This causes it to collapse, pushing out gas in the radial direction. Sound waves were driven by the disk’s initial collapse, including a spherical wave that has propagated beyond the virial radius at 1 Gyr. Gas in the CGM has also largely adopted a positive radial velocity. Gas behind this wave has cooled from its initial temperature profile and started falling inward.

Net inward flow can be seen in blue in the bottom row of Figure 6 and is approximately 50 kpc in radius at $t = 1$ Gyr. Further evidence of sound waves can be seen faintly in the pressure above and below the disk. These intersecting wave patterns will eventually be wiped away by stellar feedback, which we can see starting to happen at 2 Gyr. Even with these wave fronts, the CGM is very smooth, with no apparent multiphase structure.

At $t = 2$ Gyr, we see outflows have disrupted the inflowing gas above and below the disk. A multiphase medium has developed in the cavities left behind the outflow fronts. Some of this multiphase gas has started falling back toward the galaxy. By 3 Gyr, these outflows have expanded past the virial radius. Gas near the edge of older outflows still exhibits some inward radial motion, but it is disrupted by younger outflows. The interiors of these recent outflows have very low densities and pressures; lower than at $t = 2$ Gyr. At both $t = 2$ and 3 Gyr, cold dense gas is feeding the disk along its midplane.

By 4 Gyr, we can see that the history of successive feedback-driven outflows has created a complex shock structure within 100–200 kpc directly above and below the disk. Visible at the very top of the projection is an inflowing front with high temperature and entropy but very low density ($<10^{-32}$ g cm$^{-3}$). Indeed, there is very little gas above and below the disk. Meanwhile, accreting material continues to flow inward along the midplane. There is gas infall at large radii that is outside the disk midplane, but this is prevented from reaching the disk by younger outflows.

In Figure 7, we compare the fiducial simulation at 3 Gyr to each of the variants, still using the line-of-sight average through a thin slab. With no feedback to disrupt its CGM, the COOLFLOW variant has a rough sphere of inflowing gas around its disk. The high-pressure region at the disk’s center steadily grows in radius from the continually inflowing gas. This increase in pressure also drives an increase in temperature. Because it is undisrupted by outflows, the CGM does not develop any multiphase structure but retains its smooth nature from the initial conditions.

All other variants have outflow “plumes” that vary in size and shape. The NOROT variant has a taller, narrower outflow envelope than the fiducial and LINROT models, indicating that rotation in the CGM may be important for distributing outflowing material such as metals evenly through the CGM. Visible in the LINROT model is another high-entropy, low-density front of gas falling back toward the disk. These features develop in many of the simulations, but are prevented from reaching the disk by further feedback.

Consistent throughout all of our simulations with feedback are the wide opening angle of both outflows and the bubbles they leave behind. Inflowing gas is forced to work its way around the bubbles and flow along the disk midplane. The LOWRATIO and LINROT runs exhibit regions of infall that curve to follow the edge of the outflow structures. As noted above, gas can begin infalling from the edges of previous outflows, but it is usually disrupted by successive feedback episodes. These curved inflow regions may be recycling gas that is close enough to the edge of the bubble that it remains undisrupted and is able to funnel into the galaxy along the disk midplane.

Clearly visible in the COOLFLOW variant, but present in all simulations except NOROT, is the remnant of the initial disk’s radial spread due to vertical collapse. This gas has very low entropy, and though not shown, it also has metallicity associated with the initial disk. This initial disk spreads out the least for the NOROT simulation (reaching about half as far as the fiducial simulation at $t = 2$ Gyr), indicating the initial expansion of the disk is encouraged by the CGM’s own angular momentum. For NOROT, this smaller spreading feature is easily disrupted by feedback, which is why this feature is not as prominent in Figure 7 and why hot gas appears much closer to the spiral disk in Figure 3. These features partially align with regions of inflowing gas.

Figure 8 shows the net rate of change in disk mass for $t > 2$ Gyr, which is when stellar feedback is at its full efficiency. The disk is restricted to a cylinder with $R = 20$ kpc and thickness $z = 2.6$ kpc at the center of the simulation domain. Net $M_{\text{disk}}$ is calculated as the sum of the star formation rate $M_*$ and the rate of gas change $M_{\text{gas}}$. If $M_{\text{disk}} = 0$, gas consumption by star formation precisely accounts for all the gas lost from the disk. If $M_{\text{disk}} < 0$, star formation accounts for only part of the gas loss, meaning that outflows have removed some of the disk gas. And if $M_{\text{disk}} > 0$, then consumption of gas by star formation is more than compensated by CGM accretion and the gas shed by stars, although the latter process contributes on the order of $0.1 M_* \text{yr}^{-1}$ or less over $t = 2$–4 Gyr. We compare $M_{\text{disk}}$ to the star formation rate, which has been calculated with bins of $\Delta t = 50$ Myr. Horizontal bars show the average $M_{\text{disk}}$ over 1 Gyr.

This figure makes it clear that the COOLFLOW variant’s persistent star formation (as seen in Figure 4) is accompanied by a persistent inflow of gas. This is the expected behavior for a simulation without feedback. Intriguingly, the NOROT simulation also sees a net growth in its disk gas from 2 to 3 Gyr. This corresponds to the large growth (and then steady decline) in gas mass seen in Figure 5.

The HIGHRATIO variant has the most stable disk mass of the variants, being the simulation with $M_{\text{disk}}$ that is consistently closest to zero. The other variants exhibit much larger fluctuations (even COOLFLOW, though its net $M_{\text{disk}}$ is almost always positive). Yet for the variants with feedback, averaging the net $M_{\text{disk}}$ over Gyr timescales smooths these fluctuations and brings the net rate of change in disk mass closer to zero.

Visually, there is no clear time correlation between net $M_{\text{disk}}$ and SFR. Sometimes, $M_{\text{disk}}$ decreases following a burst of star formation, such as in the fiducial simulation at $t \approx 2.4$ and 3.1 Gyr, LINROT at 2.6 Gyr, NOROT at 2.2 Gyr, and HIGHRATIO at 3.4 Gyr. Other times, a dip in $M_{\text{disk}}$ precedes a burst of star formation, as in NOROT at $t \approx 3.1$ Gyr and LINROT at 3.8 Gyr.
Bursts of high instantaneous SFR and more prolonged periods of steady star formation both tend to be close in time to large changes in $M_{\text{disk}}$, but the sign of this change is not consistent, nor is the magnitude or whether the star formation precedes or follows a $M_{\text{disk}}$ change. This lack of a clear correlation will be discussed more in Section 6.3.

Zooming out to also include the CGM, Figure 9 shows the flux of mass across spherical shells near the disk and in the CGM. These shells are spaced from 6 to 204 kpc in 2 kpc increments. The fluxes are estimated by looking at how much gas will cross the surface (and in which direction) before the time of the next output ($\Delta t = 50$ Myr), assuming its trajectory is unaltered. This style of post-processing flux analysis benefits from finer output sampling than used with our simulations, but it should provide an adequate estimation of the flux for our purposes. Figure 9 shows the evolution of the mass fluxes at
four different times—0.5, 1.5, 2.5, and 3.5 Gyr—for all simulation variants. Each row also shows the flux for gas of a specific temperature: cold ($T < 10^4$ K), cool ($10^4 < T < 10^5$ K), warm ($10^5 < T < 10^6$ K), hot ($T > 10^6$ K), and all gas. The gray band highlights where the $y$-axis scale switches from logarithmic to linear in order to display both positive (outward flowing) and negative (inward flowing) mass flux. A vertical gray line marks $r = 20$ kpc, which we use as the approximate edge of the disk throughout this work.

At $t = 0.5$ Gyr, we can see there is some outflow of cold gas at $r \lesssim 75$ kpc as well as outflow of warm gas at $r \gtrsim 75$ kpc. This is likely due to the initial collapse of the disk and general outward CGM velocity identified above. It should be noted that the disk’s collapse results in gas motion primarily along the plane of the disk, but because the flux is calculated using spherical shells, this motion is picked up alongside the isotropic expansion of the CGM.

By $t = 1.5$ Gyr, we can see that all simulations develop $M_{\text{cold}}(r)$ and $M_{\text{cold}}(r) < 0$ for $r \lesssim 75$–100 kpc, respectively. The magnitude of this flux varies with simulation, with the fiducial and HIGHRATIO variants having the lowest magnitude. Cool and warm gas can be seen to be flowing into the disk, consistent with our observations in Section 3.1 that gases of intermediate temperatures seem to be mixing and cooling as they inflow toward the disk. Warm and hot gas is outflowing just outside the disk, whereas warm, cool, and even cold gas is outflowing in the outer CGM. Indeed, the radii at which cool and cold gas outflow can be seen to increase as time goes by. The radii at which hot and warm gas has positive mass flux also increase as the simulation progresses and the outflow cavities expand farther and farther into the CGM. Curiously, cold gas maintains $M_{\text{cold}}(r) > 0$ within the disk for the entirety of the simulation.

In Figure 7, all simulation variants followed the same general trends as the fiducial simulation. The time evolution of the mass flux $M(r)$ is shown for the fiducial simulation in Figure 10. This flux is shown for three spherical shells: $r = 20$ kpc (the approximate disk boundary), 50 and 150 kpc. As in Figure 9, the gas is divided by temperature as indicated by line style and color. The gray band once again denotes where the $y$-axis transitions from logarithmic to linear scales.

At 20 kpc, the total mass flux is dominated by cold gas. Indeed, at $t \gtrsim 2.4$ Gyr, gases at other temperatures have negligible fluxes. We attribute this to the large cavities that
have formed above and below the disk; previous feedback-driven outflows have cleared away the CGM immediately above and below the disk such that the only material they are able to remove is cold gas within the disk. Notably, cool gas switches from being predominantly inflowing to outflowing around $t = 2.5$ Gyr.

Within the inner CGM at 50 kpc, we see both cold and cool gas inflowing past $t = 1$ Gyr while hot and warm gas is outflowing. During and soon after the feedback efficiency ramp is in effect, the total mass flux switches back and forth from being dominated by cold and warm–hot gas. By the time the simulation ends, outflows at this radius are predominantly driving warm and hot gas. Cold and cool gas continue to flow through the 50 kpc shell. In the outer CGM at 150 kpc, gases of all temperatures are outflowing by $t = 2$ Gyr. Warm gas is outflowing from the start, which we attribute to the general CGM outflow identified earlier. Fluxes at this radius are generally higher and more consistent across temperature.

### 4.2. Gas Availability

In our simulations, there are two major sources of gas for star formation: cold gas that was present in the disk from the initial conditions, and CGM gas that accretes onto the galaxy. Dying stars also return gas to the disk, but their contribution over a $\lesssim 1$ Gyr timescale is negligible in comparison to these other two sources (unlike in ellipticals; see Voit & Donahue 2011). The story of gas accretion can also be thought of as the story of gas availability: what gas can cool and fall inward toward the disk? How much is gas in a rotating CGM able to shed angular momentum? In Figure 4, the differences in stellar mass formed by 1 Gyr are a clear indicator that our simulation variants experience different rates of gas accretion and star formation. In Section 3.2, we noted that these differences depend primarily on the mass of CGM gas with $t_{\text{cool}} < 1$ Gyr and on the presence of rotation. Figure 5 suggests that the simulation variants have unique and variable patterns of gas inflow over time. In this section, we delve more deeply into the ability of the CGM to contribute gas to the disk.

In Figure 11, we look at the cooling time distribution of CGM gas. We define the CGM as a sphere with radius $r_{200} = 206$ kpc, with a cylinder 40 kpc in diameter and 8 $r_{200}$ thick excised to remove the disk. This is consistent with the region used for the disk in Figures 4, 5, and 8. The cumulative mass distributions are presented in intervals of 1 Gyr, starting from the initial conditions. The stellar feedback efficiency is ramped from 1–2 Gyr, as explained in Section 2.2.1. The second column therefore represents the cooling time structure of the CGM after it has had a chance to evolve and interact with the disk, but before the impact of feedback. Dashed lines show the cooling time–mass distribution when the disk is not removed (but we still restrict to gas with $r < r_{200}$).

The LOWRATIO and HIGHRATIO variants have higher and lower CGM masses than the fiducial simulation, respectively, as noted in Section 2.4. Indeed, the initial $t_{\text{cool}}/t_{\text{ff}}$ ratio is the only thing that affects the initial cooling time distribution—both its overall mass and its shape as seen in Figure 12.

The overall mass of the CGM drops over time in all variants, irrespective of feedback. The majority of the mass loss (all but $\sim 2 \times 10^5 M_\odot$) is an artifact of the initial conditions: as explained in Section 4.1, the collapse of the initial disk pushes back on the CGM, inflating it and pushing gas beyond $r_{200}$. Indeed, by 4 Gyr, the CGM mass within $r_{200}$ has dropped by over an order of magnitude, with the fiducial CGM mass dropping to $\sim 1.8 \times 10^5 M_\odot$.

At 1 Gyr, we can see that each variant has increased its amount of CGM gas with $t_{\text{cool}} \sim 0.4$ Gyr. Given the difference between the solid and dashed lines at $t_{\text{cool}} \lesssim 0.4$ Gyr and the relative flatness of the disk-included profile in this region, most of the low-cooling-time gas has been accreted onto the disk. The NOROT simulation is the one variant with notably more gas with $t_{\text{cool}} \lesssim 0.4$ Gyr left in its CGM at 1 Gyr. This is intriguing, given its rapid growth in stellar mass as seen in Figure 4.

From 2 to 3 Gyr, the COOLFLOW simulation has less CGM gas at short cooling times ($t_{\text{cool}} < 1$ Gyr) than in the fiducial, but a roughly equivalent amount of gas at longer cooling times. This is the imprint of the COOLFLOW simulation’s constant inflow of gas (Figure 8), which depletes gas with short...
cooling times. The fiducial simulation experiences gas inflow as well, of course, but in a reduced capacity thanks to stellar feedback: at the 0 and 1 Gyr snapshots—before the feedback efficiency is increased—the fiducial and COOLFLOW variants have essentially identical cooling time–mass distributions. The distributions (both with and without the disk) deviate at 2 Gyr after feedback has become effective. This also means that any variations in cooling time distribution before 2 Gyr are due to CGM differences. Interestingly, the fiducial and COOLFLOW CGM distributions come roughly back into agreement.
agreement at 4 Gyr (though the fiducial simulation has a more massive disk).

Figure 12 highlights the differences in shape between the CGM cooling time–mass distributions of our variants by normalizing them. On the left, we show the $t_{cool}/t_{ff}$ variants: the fiducial, LOWRATIO, and HIGHRATIO simulations. On the right are our rotation variants: the fiducial, LINROT, and NOROT runs.

We first focus on the $t_{cool}/t_{ff}$ variants. As noted above, changing the initial $\tau$ parameter changes both the shape of the cooling time distribution in addition to overall mass of the CGM. The LOWRATIO variant has a cooling time distribution that is generally skewed toward lower cooling times, as is expected, given that $\tau$ should be close to the median $t_{cool}/t_{ff}$ ratio for the CGM by construction.

At 1 Gyr, we see the distribution’s shape starts to evolve. The fraction of gas with $t_{cool} < 1$ Gyr has largely equalized between the three $t_{cool}/t_{ff}$ variants. We ascribe this equalization to the accretion of gas with initial $t_{cool} < 1$ Gyr; the same accretion responsible for the differing stellar masses at $t = 1$ Gyr in Figure 4. The LOWRATIO variant continues to have proportionally more gas with moderate cooling times of $1 < t_{cool} < 10$ Gyr. This continued excess may explain the large, positive $M_{disk}$ exhibited by the LOWRATIO simulations from $t = 2$ to 2.5 Gyr in Figure 8. The fiducial simulation also has positive $M_{disk}$ during this time, though of less magnitude than LOWRATIO. Correspondingly, the fiducial simulation has an intermediate proportion of CGM gas with moderate cooling times.

By 3 Gyr, we see that the three simulations in the left of Figure 12 have evolved cooling time–mass distributions with the same general shape. These similarities are, for the most part, retained by 4 Gyr. This suggests that, despite initial differences in the CGM’s structure and continued differences in total mass, feedback has impacted their cooling time–mass distributions in a similar manner. This is despite the morphological differences in their feedback (Figure 7).

The similarity between the fiducial and COOLFLOW simulations in Figure 11 tells us that the LOWRATIO, HIGHRATIO, and fiducial cooling time distributions have the same shape because feedback does not affect the cooling time–mass distribution much at all. This seems strange, given the dramatic outflows in Figure 7, but most of that outflowing gas has $t_{cool}$ longer than a Hubble time and therefore should not be expected to return to the disk. The gas that is visible in Figure 11, in particular that with $t_{cool} \lesssim 10$ Gyr, is gas that has necessarily not been heated by outflows. This is likely gas near the disk midplane, which avoids being heated.

What does have an impact on the CGM’s cooling-time structure is rotation, as seen in the right side of Figure 12. Not only is there a difference between NOROT and the other variants with rotating CGMs, but there are also variations due to the different rotation profiles. We adopt a very straightforward prescription for the CGM’s rotation (Equation (5)), but these differences highlight the importance of understanding the angular momentum of the CGM.

5. The Circumgalactic Medium

The CGM has a complex, multiphase structure that can be difficult to encapsulate. The digestibility of information must be balanced against the loss of detail. This is especially important considering that, while precipitation can be characterized via global properties such as the median $t_{cool}/t_{ff}$ ratio, the actual condensation of gas occurs due to local variations in $t_{cool}/t_{ff}$. We can see in Figures 6 and 7 that our simulations do not have a spherically symmetric CGM and are instead closer to having cylindrical symmetry. Trying to encapsulate the structure of the CGM with, e.g., mass-weighted spherical profiles therefore constitutes a loss of information. Furthermore, averages are biased toward the highest values, even when mass-weighted.

Therefore, in an attempt to encapsulate the radial structure of the CGM, we subdivide the gas within the virial radius based on its polar angle $\theta$. This creates a set of cones (at the poles) and

---

**Figure 10.** Evolution of the fiducial mass flux over time. The mass flux is calculated at spherical shells of varying radii (from top to bottom): 20, 50, and 150 kpc. The gas is broken into the same temperature ranges as Figure 9: cold (blue dashed), cool (green dotted-dashed), warm (orange double dotted-dashed), hot (red dotted), and all gas (magenta solid). The gray band and y-axis scales are as in Figure 9. A gray dashed line marks $\eta = 0$. [Image of mass flux graphs with different radii and temperature categories indicated.]

---

**Figure 12.** Highlights the differences in shape between the CGM cooling time–mass distributions of our variants by normalizing them. On the left, we show the $t_{cool}/t_{ff}$ variants: the fiducial, LOWRATIO, and HIGHRATIO simulations. On the right are our rotation variants: the fiducial, LINROT, and NOROT runs. [Diagram showing mass flux over time with different radii and temperature categories.]
θ will refer to these regions based on their central polar angle, encompasses the disk midplane. To keep our notation concise, the cumulative mass distribution of CGM gas as a function of cooling time at five simulation times: 0, 1, 2, 3, and 4 Gyr. The CGM is defined by $r < r_{200} = 206$ kpc, with a cylinder $40$ kpc in diameter and $8_c = 2.6$ kpc thick excised to remove the disk. The top row compares the FIDUCIAL model (blue) with the COOLFLOW variant, the middle row with LOWRATIO (green) and HIGHRATIO (orange), and the bottom row with LINROT (purple) and NOROT (brown). The initial distribution (leftmost column) is identical for all but the $t_{cool}/t_{ff}$ variants.

Figure 11. Cumulative mass distribution of CGM gas as a function of cooling time at five simulation times: 0, 1, 2, 3, and 4 Gyr. The CGM is defined by $r < r_{200} = 206$ kpc, with a cylinder $40$ kpc in diameter and $8_c = 2.6$ kpc thick excised to remove the disk. The top row compares the FIDUCIAL model (blue) with the COOLFLOW variant, the middle row with LOWRATIO (green) and HIGHRATIO (orange), and the bottom row with LINROT (purple) and NOROT (brown). The initial distribution (leftmost column) is identical for all but the $t_{cool}/t_{ff}$ variants.

Figure 11. Cumulative mass distribution of CGM gas as a function of cooling time at five simulation times: 0, 1, 2, 3, and 4 Gyr. The CGM is defined by $r < r_{200} = 206$ kpc, with a cylinder $40$ kpc in diameter and $8_c = 2.6$ kpc thick excised to remove the disk. The top row compares the FIDUCIAL model (blue) with the COOLFLOW variant, the middle row with LOWRATIO (green) and HIGHRATIO (orange), and the bottom row with LINROT (purple) and NOROT (brown). The initial distribution (leftmost column) is identical for all but the $t_{cool}/t_{ff}$ variants.

Within each region, we radially bin quantities of interest from $r = 2$ to $r = 206$ kpc using 51 bins. This gives a bin width of $\Delta r \approx 4$ kpc. For each radial bin, we find the 16th, 50th, and 84th percentiles. These percentiles assist in assessing more localized variations. This analysis is done for each simulation output (whose cadence is $\Delta t = 50$ Myr). Figures 13 and 14 show the time average of these percentiles from $t = 3$ to $t = 4$ Gyr. We restrict the average to the last gigayear, as the feedback ramp is at its full strength and the profiles are visually the most stable over time.

Figure 13 shows the radial profiles of entropy, pressure, $t_{cool}/t_{ff}$, gas mass, and radial velocity for the fiducial simulation. A vertical dashed line at $r = 20$ kpc marks the rough edge of the disk used throughout our analysis. The horizontal dashed lines in the $t_{cool}/t_{ff}$ panel indicate the $5$–$20$ range predicted for the median $t_{cool}/t_{ff}$ ratio by precipitation (Voit et al. 2017; Voit 2018, 2021), while the dashed line on the $v_r$ panel marks $v_r = 0$ km s$^{-1}$. For $\theta_{cen} = 90^\circ$ (the disk midplane), the 16th percentile of entropy is cut off at $r \sim 30$ kpc, reaching values of $\sim 10^{-3} \text{ keV cm}^{-2}$ at the smallest radii. This is the influence of the galactic disk, which, unlike in much of our analysis, we do not excise. The disk is also evident in the 84th percentile of the mass profile.

It is clearly visible that all four quantities vary with polar angle: entropy and $t_{cool}/t_{ff}$ decrease toward the disk midplane at $90^\circ$, while cell mass, pressure, and radial velocity rise. The simulation is roughly symmetric about the disk plane. The higher entropy, lower pressure, and lower mass near the poles are consistent with the bipolar outflows seen in Figure 6, as gases at these extreme polar angles exhibit the highest outward radial velocities. An exception is the 16th percentile for the $\theta_{cen} = 0^\circ/180^\circ$ bin, which exhibits inflowing radial velocities near $r = 200$ kpc. This corresponds to the inflowing gas seen in Figure 6 that is prevented from reaching the disk by further outflows (Section 4.1). Gas entropy, pressure, and mass near the disk midplane—especially for the 16th percentile—share the properties of the gas inflows in Figure 6. The radial velocity panel shows a mixture of inward and outward velocities at $90^\circ$, with the median radial velocity being positive. The opening angles of our bins are larger than the opening angle of gas inflow, so they naturally capture more outflowing gas, which raises the median. This mixture of inflowing and outflowing gas contributes to the large spread in values, with the range between the 16th and 84th percentiles increasing toward the midplane.

All simulation variants demonstrate the above trends. Near the poles (far from the disk midplane), the time-averaged $t_{cool}/t_{ff}$ ratio tends toward a smoothly declining profile. At these high angles, the time-averaged cooling time is approximately constant at $t_c \sim 2 \times 10^3$ Gyr. The shape of $t_{cool}/t_{ff}$ is set
primarily by the freefall time—and by extension, the NFW halo profile. On the other hand, only the $t_{\text{cool}}/t_{\text{ff}}$ profile centered on $90^\circ$ (the plane of the disk) is remotely consistent with the median $t_{\text{cool}}/t_{\text{ff}}$ range of 5–20 predicted by precipitation. For $r \gtrsim 40$ kpc, the 16th percentile falls within this range while the 50th percentile does not. The most generous interpretation of this feature is that precipitation could be occurring only within the $\theta_{\text{cen}} = 90^\circ$ wedge, with this 16th percentile representing the local median on scales much smaller than the wedge. The $\theta_{\text{cen}} = 90^\circ$ wedge is also the polar angle with the highest cell mass, and it is the angle at which most of the cold gas inflow is located.

The mass dominance of the $\theta_{\text{cen}} = 90^\circ$ profiles, as well as their association with the inflowing gas along the disk midplane in Figure 7, motivates isolating these profiles for comparison across the simulation variants. This is done in Figure 14, where the time-averaged profiles of entropy, $t_{\text{cool}}/t_{\text{ff}}$, and radial velocity for the $\theta \in (75^\circ, 105^\circ)$ wedge are shown for all of the simulation variants. The time averaging is again restricted to the last 1 Gyr of simulation evolution. A vertical line at 20 kpc again marks the nominal edge of the disk, and horizontal dashed lines mark $t_{\text{cool}}/t_{\text{ff}} = 5$–20 and $v_r = 0$ km s$^{-1}$. The initial entropy profiles are shown as dotted gray curves. Colored dotted lines are used to highlight the 16th percentile of the radial velocity, which is predominantly negative. The entropy profile within the disk is once again cut off, to better demonstrate the CGM.

The first column compares our fiducial model to the COOLFLOW variant that lacks stellar feedback. Both of these models share the same initial entropy profile, which is the entropy profile expected for a precipitation-regulated system (Voit 2019). We can clearly see that, in the absence of feedback, the CGM loses entropy and becomes approximately isentropic. With stellar feedback, the median entropy profile begins to rise, especially at $r \gtrsim 100$ kpc. Gas in the midplane of the COOLFLOW simulation has a much greater inward velocity than inflowing gas in the fiducial simulation, and this inflow is nearly uniform among the three percentiles measured. Most notably, the median $t_{\text{cool}}/t_{\text{ff}}$ ratio between the fiducial and COOLFLOW simulations is very similar within $r \lesssim 100$ kpc.

For all simulations with stellar feedback, the spread in entropy and $t_{\text{cool}}/t_{\text{ff}}$ between the time-averaged 16th and 84th percentiles crosses several orders of magnitude. Though this spread is still less than the overall dependence on polar angle (Figure 13), we can see from the radial velocity that our wedges encompass both inflowing and outflowing gas. Figures 6 and 7 show that the inflow region is very thin. We chose a large $\Delta \theta$ in order to capture potential warping of this region (most evident in the fiducial simulation; see the third and fourth columns of Figure 6), and so we inevitably capture a mix of gas phases.

Focusing on the $t_{\text{cool}}/t_{\text{ff}}$ ratio in the variants with feedback, we see that the median of gas near the midplane is predominantly higher than predicted from precipitation theory, though the 16th percentile does extend into the 5–20 range for all but the NOROT simulation. As mentioned above, a generous interpretation may be that the 16th percentile represents the local median of precipitating gas, given that the $\theta_{\text{cen}} = 90^\circ$ wedge contains a mixture of inflowing cool gas and outflowing hot gas. Yet as noted earlier, the COOLFLOW simulation has median $t_{\text{cool}}/t_{\text{ff}}$ in the $\theta_{\text{cen}} = 90^\circ$ wedge, which is similar to the fiducial simulation. Because feedback is a necessary component of precipitation-regulation, the COOLFLOW simulation cannot be precipitation-regulated. Therefore, the $t_{\text{cool}}/t_{\text{ff}}$ seen in this Figure are strong evidence that our simulated galaxies are not being regulated by precipitation, even if we search for precipitation only in the disk midplane.

6. Discussion

We simulated a suite of idealized galaxies that are similar to the Milky Way in order to explore the conditions under which
In light of the results from Prasad et al. (2020), the question motivating our work is: can we also create a self-regulating galaxy–CGM system but with feedback coupled to star formation instead of AGN and older stellar populations? We broadly take self-regulation to mean that feedback tunes the net inflow of CGM gas to match the disk’s time-averaged star formation rate. Because our only feedback mechanism is Type II SNe, this also implies that the star formation rate of self-regulated systems would be tuned to the inflow of cold gas.

Ultimately, we do not consider the galaxies we have simulated to be self-regulating. Instead, the CGM in our simulations experiences large-scale disruption due to outflows. Only gas along the disk midplane is of low enough entropy to be able to cool and accrete onto the disk. Even this limited accretion mode does not appear to be precipitation-regulated, based on the most general measure, i.e., the median ratio of cooling and freefall times. Our star formation rates drop to very low values of order $0.1 M_\odot$ yr$^{-1}$ after the onset of our feedback efficiency ramp. This limited gas accretion and star formation keep the average disk growth, $M_{\text{disk}}$, near zero. Rather than creating a system that maintains a moderate SFR, we have created a system in which feedback essentially shuts off star formation.

At this point, it is worth re-examining our choice of feedback algorithm. While a method based on Cen & Ostriker (1992) is by no means the most sophisticated among today’s subgrid models, the algorithm as it exists in Enzo (described in detail by Oh et al. 2020) has been used with good success in the FOGGIE cosmological simulations (Peeples et al. 2019; Simons et al. 2020). Though this kind of feedback model has in the past been prone to catastrophic radiative losses (e.g., Katz 1992), with modern simulation resolution it is able to produce galactic phase structures that are similar to more detailed feedback algorithms (Rosdahl et al. 2017; Smith et al. 2018). Methods based on Cen & Ostriker (1992) have historically not had issues with overly aggressive outflows; indeed, they have typically struggled to drive outflows. Therefore, at the outset of this project, we presumed that the algorithms described in Oh et al. (2020) would be sufficient for our investigation.

As described in Section 2.2.1, we adopt a final feedback efficiency value that is half a dex lower than the efficiency used in the cosmological simulations of both Oh et al. (2020) and Peeples et al. (2019). This decision was made during early testing in an attempt to minimize feedback outflows. The fact that our simulations use the same feedback algorithm—with a lower feedback efficiency—as cosmological simulations that do not see the same dramatic outflows is indicative of missing or incorrectly captured physics in our simulations. Such physics could be an alternative feedback algorithm, as perhaps the shortcomings of Cen & Ostriker (1992) are more pronounced in an idealized simulation as opposed to a cosmological one, or it could be one of the factors we will discuss in Section 6.4.

In Section 6.4, we will also discuss the structure of our CGM. As noted in Section 4.1, the bulk of our CGM experiences an overall expansion shortly after the simulation begins. This lowers the density and pressure of the medium, which certainly does not contribute to the containment of outflows. We constructed our CGM using an analytic model for a precipitation-regulated CGM (Voit 2019), which we believe gives the methods in Section 2.1.2 a reasonable theoretical

Figure 13. Radial profiles of entropy, pressure, $t_{\text{cool}}/t_{\text{ff}}$, gas mass, and radial velocity in the fiducial CGM at late times ($t = 3–4$ Gyr) as a function of polar angle $\theta_{\text{cen}}$. The disk midplane corresponds to $\theta = 90^\circ$. Solid lines are the time average of the 50th percentiles (medians), and shaded regions are of the 16th and 84th percentiles; see text for more details on our analysis. The vertical dashed line at 20 kpc represents the approximate extent of the disk adopted throughout this text, while the horizontal dashed lines show the $t_{\text{cool}}/t_{\text{ff}}$ range of 5–20 predicted by precipitation theory as well as where $v_r = 0$ km s$^{-1}$.

self-regulating feedback might arise. Our hypothesis was that these galaxies would naturally regulate their star formation rates according to the predictions of precipitation theory if initialized with a CGM having $t_{\text{cool}}/t_{\text{ff}} \sim 10$ (Voit 2019). This work therefore complements that of Prasad et al. (2020)—who studied the precipitation-regulation of larger AGN-dominated systems with SNIa feedback (i.e., massive central elliptical galaxies in groups and clusters)—in that it explores the ability of less massive galaxies to regulate themselves through stellar feedback alone.
justification. Yet the results of our simulations—in particular the bulk outward motion—have called this grounding into question. Yet before considering possible future improvements to our simulations, we will first discuss in depth the features of our current simulations. In Section 6.1, we examine the impacts of variations in the simulation parameters. Then, in Section 6.2, we compare the structural features of our simulations to other works, both observational and theoretical. Our simulations do not have self-regulated star formation, but their failure to self-regulate is illuminating. In Section 6.3, we interrogate the definition of self-regulation and highlight the ambiguity as to the expected timescales involved. Finally, in Section 6.4, we discuss the physical effects missing in our simulations that could better couple gas accretion and stellar feedback.

### 6.1. Impact of CGM Variations

The overall behavior of our simulations is unaffected by variations in the CGM: once stellar feedback is at its full strength, the CGM becomes disrupted by wind-driven bubbles and the SFR drops by an order of magnitude. The exception is, of course, the COOLFLOW variant, which completely lacks stellar feedback. Yet despite observing no impact on the overall behavior, we do see important differences manifest in our simulation variations. The variations in initial conditions exert their biggest influence at $t < 1$ Gyr, when feedback is made artificially weak. In the following subsections, we will discuss the differences resulting from changes to the initial $t_{\text{cool}}/t_{\text{ff}}$ ratio (Section 6.1.1) and from alterations to the CGM’s initial rotation profile (Section 6.1.2).

#### 6.1.1. Variation in Precipitation Limit Parameter

The LOWRATIO and HIGHRATIO variants are distinguished by modifying the condensation criterion $\tau$ in Equation (1). This parameter is essentially the initial $t_{\text{cool}}/t_{\text{ff}}$ ratio of the CGM, though as discussed in Section 2.1.2, the actual $t_{\text{cool}}/t_{\text{ff}}$ ratio deviates slightly. Including the fiducial simulation, we sample $\tau \in [5, 10, 20]$. Because the CGM’s density structure is set by $\tau$, these variants have different starting CGM masses. The LOWRATIO...
variant has the most mass at $3.9 \times 10^{10} M_\odot$, followed by the fiducial with $2.3 \times 10^{10} M_\odot$ and the HIGHRATIO with $1.3 \times 10^{10} M_\odot$. Therefore, a higher $\tau$ results in an overall less massive CGM.

Moreover, a higher $\tau$ lowers the relative amount of gas with initial $t_{\text{cool}} < 1$ Gyr. This is shown in Figure 12. For a real multiphase CGM, this can be understood via the framework of Voit (2021): the median $t_{\text{cool}}/t_{\text{ff}}$ of the CGM defines the center of a distribution in $t_{\text{cool}}/t_{\text{ff}}$. Moving the median to higher values means that less of the distribution covers low cooling times, and therefore less gas is able to efficiently cool, condense, and reach the galaxy. Our simulations, however, do not start with a multiphase CGM; rather, the temperature and density are smooth, spherically symmetric functions of radius. In fact, the initial temperature profile is very similar between the fiducial, LOWRATIO, and HIGHRATIO simulations. The differing masses of gas with $t_{\text{cool}} < 1$ Gyr are then a result of both variations in the initial density profiles and the different initial $t_{\text{cool}}/t_{\text{ff}}$.

Differences in the initial mass of gas with $t_{\text{cool}} < 1$ Gyr easily describe the different initial stellar mass growth of the HIGHRATIO and LOWRATIO simulations. This is seen in Figure 4, where at $t < 1$ Gyr the LOWRATIO simulation has the highest disk gas mass, greatest growth in stellar mass, and highest SFR. Conversely, the HIGHRATIO variant has the least growth in stellar mass and lowest SFR, although its gas mass is not as distinct from the fiducial simulation as the LOWRATIO simulation is.

The difference in low-cooling-time gas also seems to have a slight impact on the physical size of the disks, as seen in Figure 3 and Table 3. The LOWRATIO simulation has the most gas with $t_{\text{cool}} < 1$ Gyr, and correspondingly it has the largest radius within which star formation occurs. The converse is not quite true for the HIGHRATIO simulation, whose average radius of star formation is not statistically significantly different from the fiducial simulation’s. The average star formation radii in Table 3 are determined over $t = 2$–4 Gyr, after the feedback ramp has ended and the bulk of star formation has occurred. This therefore suggests that the initial differences in CGM gas accretion between the LOWRATIO, HIGHRATIO, and fiducial simulations have lingering effects on the structure of the galactic disk. This effect would appear to be on the same scale as natural variation in the maximum radius of star formation. These differences are likely not a result of the difference in initial disk radius, as the initial LOWRATIO disk is about 1 kpc smaller than the fiducial’s gas disk.

Feedback does not generally seem to have much impact on the $t_{\text{cool}}$ distribution function for CGM gas. This is seen between the $t_{\text{cool}}/t_{\text{ff}}$ variants in Figure 12. Though the $t_{\text{cool}}/t_{\text{ff}}$ variants have different star formation histories and stellar masses, feedback neither amplifies nor diminishes any pre-existing differences in the $t_{\text{cool}}$ distribution function. The similarity between the fiducial and COOLFLOW distributions at $t = 4$ Gyr further indicates that feedback has minimal impact on the CGM’s overall availability of low-cooling-time gas.

Even though the cooling time distribution is largely unaffected by feedback, the $t_{\text{cool}}/t_{\text{ff}}$ variants do not evolve identically. In Figure 7, we can see that outflows in the LOWRATIO simulation have traveled less far than in either the fiducial or HIGHRATIO simulations. For $t < 1$ Gyr, the LOWRATIO simulation has the highest CGM pressure of the $t_{\text{cool}}/t_{\text{ff}}$ variants, and HIGHRATIO has the lowest. This generally tends to remain true for the outer CGM ($r \approx 150$–200 kpc), even as outflows drop the overall CGM pressure.

The $M_{\text{disk}}$ in Figure 8 also shows interesting differences. The HIGHRATIO variant experiences the smallest $M_{\text{disk}}$ fluctuations of the simulations considered here, suggesting that relatively little mass is involved in the cycle of accretion and star formation. The fluctuations of $M_{\text{disk}}$ in the LOWRATIO simulation are on par with and occasionally larger than those experienced by the fiducial simulation. Generally, the fluctuations in $M_{\text{disk}}$ get smaller as the simulations go on, as shown by the average from $t = 3$ to 4 Gyr.

It may be that the LOWRATIO simulation, being able to accrete more cool gas initially, was set into a cycle of large amounts where gas accretions were followed by productive periods of star formation, rather like an oscillator with a large initial perturbation. Also like most oscillators found in nature, the LOWRATIO simulation experiences damping in its cycle of accretion and star formation. Though it is the simulation with the highest stellar mass, Figure 5 shows that it had only moderate gains in stellar mass after 2 Gyr. This figure also shows that the LOWRATIO simulation continued to accrete gas from $t = 2$ to 3 Gyr, despite the stronger feedback. This may be the LOWRATIO simulation “refueling” in order to maintain a more moderate SFR at the end of the simulation. On the other hand, the fiducial simulation gains the most stellar mass over $t = 2$–4 Gyr in Figure 5, while the HIGHRATIO simulation is with LOWRATIO near the bottom of the pack, although it is something of a “late bloomer.” It may be that the fiducial simulation has the most ideal conditions of these variants for sustained star formation growth. Whether or not we consider it “self-regulating” is a question we defer to Section 6.3.

To summarize, the LOWRATIO, HIGHRATIO, and fiducial simulations all exhibit a number of differences that are a consequence of how the condensation criterion $\tau$ determines both the initial $t_{\text{cool}}/t_{\text{ff}}$ ratio and density structure of the CGM. These density differences result in differences in total mass. The LOWRATIO simulation not only starts with more gas, but a larger fraction of it is able to cool efficiently. The converse is true for the HIGHRATIO simulation. These differences are persistent even in the face of feedback. The structure of the disk and its star formation therefore retain their early differences throughout the simulation runtime.

6.1.2. Variation in CGM Rotation

We now consider variations that arise from the CGM’s rotation. Apparent from Figure 4 is that the presence of rotation as well as its variation with radius both impact the ability of the CGM to supply gas to the disk.

We have indicated throughout this work that the NOROT simulation should be able to accrete gas more efficiently because its CGM gas does not have to shed angular momentum to reach the disk. This is evident in the stellar growth of Figure 4 at $t < 1$ Gyr. It may also explain the large growth in gas mass seen over $t \approx 2$–3 Gyr in Figures 5 and 8. In Section 4.1, we noted a remnant of the initial disk conditions that is present in the CGM: due to insufficient vertical support against gravity, the initial disk collapses and spreads outward into the CGM. The NOROT variant’s initial disk has the smallest amount of radial spread, due to the lack of rotation in its CGM.

9 The CGM is defined as a sphere with $r = r_{200} \approx 206$ kpc with a cylinder excised for the disk. This disk has height $z = 4z_d = 1.3$ kpc from the midplane and radius $R = [27.5, 28.5, 29]$ kpc for the LOWRATIO, fiducial, and HIGHRATIO variants, respectively.
The Astrophysical Journal, 951:107 (25pp), 2023 July 10

Kopenhafer, O'Shea, & Voit

The mere inclusion of rotation in the CGM has a large effect on gas accretion and simulation evolution, but the radial profile of that rotation also has an impact. The LINRO simulation forms more stars than the fiducial model within the first 1 Gyr, before stellar feedback has much effect. The LINRO simulation also has lower angular momentum at all CGM radii, making it easier for gas to accrete than in the fiducial simulation. Rotation is also able to change the shape of the cooling time–mass distribution in Figure 12, affecting the availability of gas that can be accreted in addition to the ease of accretion.

Su et al. (2020) also performed isolated galaxy simulations that included a rotating CGM. These simulations targeted cool-core clusters with halo masses between $10^{12}$ and $10^{14} M_\odot$. Rotation followed a $\beta$-profile with $\beta = 1/2$, set to twice the net dark matter spin. Rotation therefore comprised 10–15% of the CGM’s support against gravity, with the rest being supplied by thermal energy. This is in contrast to our simulations, where rotation was not considered in the calculation of hydrostatic balance. The simulations of Su et al. (2020) were included in the Fielding et al. (2020) meta-analysis, where it is noted that these simulations had an enhanced cold phase at $r < 0.2 r_{200}$ compared to the other isolated galaxy simulations in the analysis. This enhancement is attributed to CGM rotation—which was not included in Fielding et al. (2017) and Li & Tonnesen (2020)—in agreement with our results.

DeFelippis et al. (2020) studied the CGM angular momentum of Milky Way–mass galaxies in IllustrisTNG. They split these galaxies into samples based on the stellar specific angular momentum, resulting in high- and low-momentum populations. Both populations have inflowing cold CGM gas near the disk plane. In the sample with high specific angular momentum, this inflow is aligned well with the disk; however, the radial inflow disappears for $r < 0.2 r_{200}$. Much like with our simulations, it is suggested that this is due to the presence of strong rotation. We note that our rotation speeds (derived from Hodges-Kluck et al. 2016) are higher than the rotational speeds measured by DeFelippis et al. (2020).

6.2. Comparison of Structural Features to Other Works

It is worth comparing some of the structures seen in our simulations with those seen or predicted in other works. These works include observations, analytic predictions, and cosmological simulations. We will begin with the gas disk, expand outward to the accretion flows seen along the disk midplane, and finally consider the structure of our feedback-driven outflows.

6.2.1. Extended Gas Disk

Starting with the disk, we can see in Figure 3 that there is cold, dense, rotating gas that extends beyond the average radius of star formation in all of our variants. This is consistent with observations of spiral galaxies in the THINGS survey (Leroy et al. 2008). These observations show that spiral galaxies have high star formation efficiency in their H$_2$-dominated cores. This efficiency declines with radius in the extended neutral hydrogen disk.

The structure of our galactic disk is also consistent with the findings of Lopez et al. (2020) and Tejos et al. (2021). These papers present two instances of extended Mg II disks ($r \sim 20–40$ kpc) that are corotating with the interstellar medium. Our extended cool disks are of order $r \sim 20–30$ kpc. We note that, while an extended cool disk is an emergent feature of our simulations, we purposely aligned the angular momentum vectors of the CGM and the disk. It is unclear what impact misaligned angular momentum vectors might have on our extended gas disk.

6.2.2. Accretion along the Midplane

Figures 6 and 7 make it clear that, while inflowing gas can be found throughout the CGM, only inflowing gas near the disk midplane is able to reach the disk. Inflowing gas not along the midplane is disrupted by outflows. The exception to this is, of course, the COOLFLOW variant, which lacks stellar feedback.

Inflow within the disk plane is not unprecedented in cosmological simulations. Trapp et al. (2022) find this inflow mode in the FIRE-2 simulations and note that it is the dominant source of accretion there, just as it is in our simulations. Gas accretion in the EAGLE simulations is also anisotropic, favoring low heights relative to the disk and inflow speeds of 20–60 km s$^{-1}$ (Ho et al. 2019). This inflow is predominantly cold gas found near the disk or in low-angular-momentum streams, and estimates of the mass rate are enough to meet or exceed the SFR.

Within IllustrisTNG, DeFelippis et al. (2020) also see this inflow structure in $10^{11.75}–10^{12.23} M_\odot$ halos. Truong et al. (2021) see a global anisotropy in the CGM, with density enhanced parallel to the disk plane, and temperature and metallicity enhanced along the orthogonal minor axis. Their anisotropies are more subtle than what we see in our own simulations, being of only 0.1–0.3 dex. These anisotropies peak in Milky Way–like galaxies with $M_s \sim 6 \times 10^{10} M_\odot$, which is the mass at which supermassive black hole feedback turns on in TNG. Generally, the anisotropies are larger in galaxies with SMBH feedback, except for metallicity: the metallicity anisotropy is more pronounced in star-forming and disky galaxies.

The inflowing gas spans a temperature range from $\sim 5 \times 10^3$ to $5 \times 10^5$ K, with the coldest gas living in denser filaments. Gas condenses and cools while being part of a rotating inflow. This is reminiscent of the accretion mode observed in Hafen et al. (2022) and described in detail in Stern et al. (2021). Gas inflow is hot until it reaches $\sim 20$ kpc scales, at which point angular momentum slows its inward motion. Radiative cooling then exceeds heating due to compression, and the gas temperature drops to $\sim 10^5$ K or below. Importantly, Hafen et al. (2022) note that the angular momentum of inflowing gas aligns itself with the galaxy before cooling, but because the angular momentum of our CGM and disk are constructed to be aligned, we cannot make any comparison on this point.

6.2.3. Outflow Structure

Our simulations are dominated by outflows to an unrealistic degree. Very low-density cavities extend out to the virial radius by $t = 4$ Gyr. Outflows have a very wide opening angle of essentially 180°, covering the face of the disk. The CGM essentially becomes obliterated above and below the disk.

That said, the structure of our outflows matches well to analytic models from Lochhaas et al. (2018). These models describe how relatively slow-moving gas bubbles can be inflated by fast galactic winds. In their model, winds drive a forward shock through the CGM. Their interaction leads to the development of a reverse shock, and between these two fronts
lies a contact discontinuity. This discontinuity separates material driven out by the winds from the swept-up CGM gas. Lochhaas et al. (2018) refer to the region between the reverse shock and the contact discontinuity as the “shocked wind.” It is this shocked wind that is responsible for the growth of the gas bubble. Immediately behind this shocked wind (inside the reverse shock) lies cool, unshocked gas, followed by hot unshocked gas immediately next to the galaxy.

We can clearly see the shocked wind in the density projections of Figure 6, often with winds inside winds. The models of Lochhaas et al. (2018) use a continuous wind, while our simulations have multiple discrete winds driven by episodic Type II supernova feedback. At 2 Gyr, a band of shocked winds is visible both above and below the disk. Subsequent winds are able to travel faster due to the evacuated region that follows behind the first (Lochhaas et al. 2018). The thickness of the outermost shocked wind grows as its reverse shock propagates. It travels with speeds on the order of \( \sim 100 \text{ km s}^{-1} \), which is an order of magnitude lower than the feedback-driven winds, corroborating the major result of Lochhaas et al. (2018). The density of the shocked wind is also relatively constant across its width, as assumed by the analytic models, though that density drops as the shocked wind expands.

Instead of a layer of cold unshocked gas, the gas behind the shocked wind is very hot (\( \geq 5 \times 10^4 \text{ K} \)) and chaotic, thanks to successive feedback events. Additionally, these continued outflows prevent the outermost shocked wind from stalling and falling back onto the galaxy, as seen in the additional tests run for Section 5.3 of Lochhaas et al. (2018). They also appear to disrupt any dense, cooling material that may fall inward and falling back onto the galaxy, as seen in the additional tests.

With Figure 8, we attempted to identify by eye correlations between the SFR and the net rate of change in disk mass, \( M_{\text{disk}} \), but ultimately found no consistent relation. Given the “broken thermostat” in our simulations, this may not be surprising. Yet what is concerning is that averaging over 1 Gyr brings \( M_{\text{disk}} \) closer to zero and therefore to apparent balance. While there are certainly rigorous statistical tools for addressing time correlations, this analysis is sufficient to raise questions about what precisely one should be looking for in order to decide if a galaxy is self-regulating its star formation.

The ambiguity over timescale is exacerbated because of the nature of simulations. Because there are limits on resolution and computational power, simulations of Milky Way—mass galaxies must use particles to represent entire stellar populations rather than individual stars. This modeling limitation introduces shot noise into the SFR. It is therefore also worth considering the timescales over which we are concerned with changes in the SFR.

The timescale uncertainties are in large part due to the temporal and spatial separation between gas accretion and feedback. Within our simulations, CGM gas that accretes onto the galaxy is more likely to contribute to a star particle if it reaches the denser disk center. The formation of a star particle obfuscates the physical and temporal scales involved in the actual formation of molecular clouds and protostars, but these are assumed to be below the temporal resolution of the simulation. Connections between inflow and star formation in
simulations seem clearer when made on smaller physical scales, such as gas inflow along dust lanes at the very nucleus of a barred spiral galaxy (Moon et al. 2022). Our efforts to directly explore the self-regulation of galaxy star formation has highlighted the need to refine our questions. Specifically, if we as a community are to define self-regulation as a balance between gas accretion and star formation, we should consider on what timescale we expect this balance to be achieved. This way, we may better identify which physical processes contribute to the self-regulation of galaxies.

6.4. Alternative Model Components

One of the key takeaways from Prasad et al. (2020) and Voit et al. (2020) is that feedback from Type Ia supernovae assists an AGN in self-regulating its own feedback. Similarly, it seems that our simulations are missing one or more important features that work in concert with Type II supernova feedback to regulate a Milky Way–like galaxy. While there may be evidence for weak coupling between gas inflow and star formation, as discussed in Section 6.3, we believe that our simulations are likely not capturing physical features or effects that would make this coupling more obvious and/or tighter.

The biggest evidence for this is the large feedback-driven bubbles that are present in all of our simulation variants with stellar feedback (i.e., excluding the COOLFLOW variant). The ramp in feedback efficiency (Section 2.2.1) merely delays the onset of these bubbles. Figure 15 demonstrates that adjusting the length of the ramp affects the size of the bubbles but does not eliminate them entirely. This figure is similar to Figure 7, except that all simulations presented have the same physics as the fiducial simulation, with only the ramp timing altered from the original 1–2 Gyr period. The modified ramps are SHORT (1.25–1.75 Gyr), LONG (0.50–1.50 Gyr), EARLY (0.50–1.50 Gyr), and LATE (1.50–2.50 Gyr). The images depict the density and entropy of each simulation 1 Gyr after the ramp has ended.

While the SHORT ramp certainly features the smallest cavities, their mere presence is still an issue for our efforts to create a self-regulating system. The other ramp parameters that may be altered are the initial and final feedback values, but as noted in Section 6, the final feedback value is already lower than what is used in cosmological simulations deploying the same feedback algorithm. Indeed, the dramatic cavities seen in at least times in Figures 6 and 7 are due to successive bubbles being blown into the same volume. Earlier feedback winds clear away material, making it easier for later winds to travel faster and farther, and to further remove material from the bubble’s cavity.

These bubbles travel well beyond the virial radius by the end of the simulations at $t = 4$ Gyr, leaving cavities of high-entropy gas that will not cool within a Hubble time. The density of the ambient medium continues to decrease beyond the virial radius (Figure 1), providing nothing for the feedback-driven bubbles to meaningfully collide with and halt against. Additionally, the cooling time at large radii is high enough that material cannot “backfill” the bubble cavities. The behavior of these outflows suggests that we are missing either material that the winds would stall against, a mechanism that would fill the cavities in with low-entropy gas, or both.

The idealized nature of our simulations may be working against us in this regard. Fielding et al. (2020) compared idealized and cosmological simulations of Milky Way–like galaxies and found that the outer CGM structure of the latter ($\gtrsim 0.5 r_{200}$) was highly impacted by cosmological effects such as nonspherical gas accretion and the presence of satellites. No attempt to model cosmological accretion was included in our simulations, but these could address the large wind-driven bubbles in our simulations. This is especially true considering that the FOGGIE simulations (Peeples et al. 2019) use the same feedback algorithm and a slightly higher feedback efficiency but do not see the same long-term disruption due to outflows.

Appropriately modeling inflow in an idealized simulation is a challenge, however. Typically, cosmological accretion in idealized simulations is treated as being spherically symmetric, as in Fielding et al. (2017) (albeit with added density fluctuations), but as stated above, Fielding et al. (2020) emphasized that this spherical treatment is not sufficient. Furthermore, Lochhaas et al. (2023) identified cosmological inflow in the FOGGIE simulations as being filamentary. While Fielding et al. (2020) highlighted the strength of idealized simulations for studying the inner CGM ($\lesssim 0.5 r_{200}$), our work indicates that, for self-regulation, the outer CGM and perhaps the nearby IGM exert an important influence.

Given our discussion at the beginning of Section 6, our approach to constructing the initial CGM is flawed as well. This is most starkly demonstrated by the general expansion experienced by the CGM at very early times. Given that the CGM of Milky Way–like galaxies is primarily observed via absorption features, it can be difficult to infer three-dimensional thermodynamic profiles (as opposed to galaxy clusters, which can more easily infer this information from X-ray emission). The multiphase nature of the CGM further complicates this, as any individual absorber may not represent the median. We elected to adopt a theoretical basis for defining the CGM, but Su et al. (2019) rely on observations of the Milky Way CGM for their simulations of a $1.5 \times 10^{12} M_\odot$ halo. Their simulations are also of isolated galaxies, but they do not experience the same large-scale CGM disruption that we do. Though they also use the FIRE-2 feedback algorithm (Hopkins et al. 2018b), given the “backfill” logic outlined above, we believe that the differences between our two works is due to the structure of the CGM.

Our initial CGM is also smooth and spherically symmetric. A more realistic CGM would be properly multiphase, with fluctuations in density, temperature, and velocity (both radial and tangentially). We initially expected to see such fluctuations develop over the course of the simulation as a result of outflows, but including these from the start would likely have a profound effect. A nonuniform CGM will have a distribution of cooling times at a given radius, as well as better mixing, and it may be better able to disrupt early outflows. In the simulations presented in this work, the earliest outflows are able to expand through the CGM nearly uniformly.

Initial density perturbations are the easiest way to disrupt this spherical symmetry, but they require a choice of power spectrum. A more natural way of introducing perturbations at large radii may occur from adjusting our CGM beyond $r_{200}$. Our current treatment for this “outer” gas was motivated by practical considerations rather than observations. Notably, our entropy initial profile increases monotonically with radius. More realistic halos are likely to have low-entropy gas beyond $r_{200}$, gas that has either not yet passed through a cosmological accretion shock, or has passed through the shock with enough density for its current entropy to be less than the mean at $r_{200}$. The relaxation of the simulation’s initial state could push this.
gas to become Rayleigh–Taylor unstable, and either over time or with the assistance of instabilities seeded in the initial conditions, it could grow dense clumps of gas that may affect the outflows and overall precipitation within our simulations.

Cosmological inflow would further assist in seeding and/or maintaining CGM fluctuations, naturally creating them as infalling material combines with the galaxy. This is true both for filamentary inflow as well as the presence of—and mergers with—small satellites and dwarf galaxies.

The failure of our simulations to “close the feedback loop” is not entirely novel. Prasad et al. (2020) simulated an elliptical galaxy of similar mass ($2 \times 10^{12} M_\odot$), dominated by AGN feedback, and they also saw a highly disrupted CGM emerge. Generally, lower-mass galaxies have a weaker gravitational potential and lower CGM pressure. Outflows can more easily escape the halo. This reinforces our earlier observation that some physical mechanism at the edge of the halo—cosmological inflows or simply more generic density perturbations, to name two candidates—appears necessary for lower-mass halos to maintain their CGM structure.

The simulations of Fielding et al. (2017) and Li & Tonnesen (2020) do not include a cold gas disk, nor do they explicitly model star formation. Instead, they tie outflows to the amount of inflow through an inner boundary. In both cases, outflows do not cause a large-scale disruption of the CGM. Li & Tonnesen (2020) see a clear net balance between gas inflow and outflow in the latter half of their simulation, and both works observe distinct cold gas condensation near the galaxy ($r \lesssim 100$ kpc). Yet tying outflows directly to inflows, without modeling any intermediary star formation, may enforce self-regulation by construction.

Though we suspect the lack of cosmological effects is the biggest missing piece from our simulations, there are other physical processes to consider. Our current simulations use Type II supernovae as their only feedback source. Though our simulations do not currently suffer from a lack of outflows, efforts to counteract their current behavior may highlight the need to include other forms of feedback, such as Type Ia supernovae and AGN. We adopt a fairly straightforward prescription for rotation in the CGM and assume its angular momentum is aligned with that of the disk, but the angular momentum of the CGM is likely quite complicated (Cadiou et al. 2022). This could facilitate better mixing between outflows and the ambient medium, disrupting the structures that develop in our simulations.

Finally, our simulations omit two important plasma components: magnetic fields and cosmic rays. These two influences would significantly alter the behavior of outflows. Magnetic fields can slow outflows and raise the density of the inner CGM, though they also hinder metal mixing (van de Voort et al. 2021). Cosmic rays provide a form of nonthermal pressure support, allowing cold gas to occupy more CGM volume (Ji et al. 2020). Cosmic rays also lead to larger, lower-density cold clouds and keep cold gas in the CGM for longer (Butsky et al. 2020). All of these changes have implications for the galaxy’s accretion of CGM gas.

7. Conclusions

We have run a suite of isolated, idealized Milky Way–like galaxy simulations in order to examine the ability of galaxies to self-regulate their star formation. They were specifically designed to explore the precipitation theory of self-regulation (Voit et al. 2015). The circumgalactic medium (CGM) in our galaxies was initialized in hydrostatic equilibrium with entropy profiles set by expectations from precipitation (Voit 2019). The CGM was also given an initial azimuthal rotation scaled off the estimates of Hodges-Kluck et al. (2016). We explored variations in the entropy profile through the precipitation limit parameter $\tau$ in Equation (3) as well as variations in the rotation profile of the CGM (Equation (5)).

Outflows from feedback quickly disrupt the CGM. This has historically not been a challenge for isolated galaxy simulations (e.g., Benincasa et al. 2016; Kim et al. 2016) because they have often had an essentially nonexistent CGM. To prevent the initial star formation burst from disrupting our CGM before its gas can accrete onto the disk, we implement a ramp in the stellar feedback’s efficiency parameter (Section 2.2.1). This ramp minimizes the impact of feedback for the first 1 Gyr. As a result, the impacts of our CGM variations become apparent.

Our work highlights that including explicit star formation in idealized simulations is crucial to understanding the galaxy–

![Figure 15. Average line-of-sight density and entropy as in Figure 7, but exploring variations in the feedback ramp timing. Each image shows the variant 1 Gyr after the ramp has ended. These alternative simulations are identical to the fiducial except for the ramp timing: FIDUCIAL (1.00–2.00 Gyr), SHORT (1.25–1.75 Gyr), LONG (0.50–1.50 Gyr), EARLY (0.50–1.50 Gyr), and LATE (1.50–2.50 Gyr).](Image)
CGM connection. Alternative solutions, such as tying outflow rates directly to gas accretion rates, obfuscate important steps connecting accretion and feedback. We ultimately fail to produce isolated galaxies that are able to self-regulate their star formation, but this failure is illuminating in several ways. The primary results of our simulations are as follows:

1. Idealized galaxy simulations are highly sensitive to their initial conditions. Our simulation setup is not unusual among isolated disk galaxy simulations, but complications arise when including the CGM. Our CGM initial conditions are based in analytic expectations but experience a general expansion at early times. This early behavior has repercussions throughout the runtime, as it lowers the CGM density and pressure—and therefore limits its ability to constrain outflows.

2. Even after allowing time for the CGM to interact with the disk through our feedback efficiency ramp, our simulations contain outflows that are very disruptive to the CGM. Disruptive feedback seems to be a common feature of isolated galaxy simulations at this halo mass (Prasad et al. 2020), even though the same feedback algorithms with higher feedback efficiency have been used successfully in cosmological simulations (Peeples et al. 2019; Oh et al. 2020; Simons et al. 2020). This indicates that current idealized simulations are missing important features that would constrain, disrupt, or backfill these outflows, such as cosmological inflow and initial perturbations.

3. Our galaxies continue to accrete gas along the midplane of the disk, despite the disruption of the CGM by outflows. Though this accretion channel contains gas with the lowest $t_{\text{cool}}/t_{\text{ff}}$ ratio, it is still higher than expected for a precipitation-regulated system. This accretion is able to maintain low SFRs of $\sim 0.1 M_\odot$ yr$^{-1}$.

4. Rotation in the CGM impacts the ability of gas to accrete onto the disk. This accretion also varies with the rotation profile. Rotation is therefore an important component of idealized CGM studies, and better understanding angular momentum in the CGM is an important prerequisite to informative modeling.

Understanding the balance between accretion rate and star formation first requires an understanding of the timescales over which we expect these processes to balance. While our work is not able to answer this question, we find it important for the community to consider as studies of the CGM’s impact on star formation continue.

Future work will incorporate some of the physical features we have identified as potentially important for mitigating the dominance of outflows in our idealized simulations. We also wish to investigate the importance of magnetic fields and cosmic rays, in particular because the latter can dramatically affect the CGM’s cold gas fraction (Butsky & Quinn 2018; Ji et al. 2020).

Acknowledgments

The authors would like to thank Cassandra Lochhass for the use of her flux tracking code, as well as the reviewer, whose comments improved the message of this manuscript. C.K. was supported in part by a Department of Energy Computational Science Graduate Fellowship under Award Number DE-FG02-97ER25308. C.K. and B.W.O. acknowledge support from NSF grant #1908109, and B.W.O. acknowledges further support from NASA ATP grants NNX15AP39G and 80NSSC18K1105. G.M.V. and B.W.O. acknowledge support from NSF grant #2106575. This work used the Extreme Science and Engineering Discovery Environment (XSEDE) under allocation TG-AST090040, as well as the resources of the Michigan State University High Performance Computing Center (operated by the Institute for Cyber-Enabled Research).

Software: NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020), Matplotlib (Hunter 2007), Pandas (McKinney 2010), yt (Turk et al. 2011), and GNU parallel (Tange 2020).

ORCID iDs

Claire Kopenhafer @ https://orcid.org/0000-0001-5158-1966
Brian W. O’Shea @ https://orcid.org/0000-0002-2786-0348
G. Mark Voit @ https://orcid.org/0000-0002-3514-3083

References

Babiy, I. V., McNamara, B. R., Nulsen, P. E. J., et al. 2018, ApJ, 862, 39
Behroozi, P., Wechsler, R. H., Hearn, A. P., & Conroy, C. 2019, MNRAS, 488, 3143
Benincasa, S. M., Wadsley, J., Couchman, H. M. P., & Keller, B. W. 2016, MNRAS, 462, 3053
Berger, M. J., & Coeulla, P. 1989, JCoPh, 82, 64
Bouché, N., Dekel, A., Genzel, R., et al. 2010, ApJ, 718, 1001
Bromm-Smith, C., Bryan, G., Butsky, I., et al. 2019, JSS, 4, 1636
Bryan, G. L., Norman, M. L., O’Shea, B. W., et al. 2014, ApJS, 211, 19
Butsky, I. S., Fielding, D. B., Hayward, C. C., et al. 2020, ApJ, 903, 77
Butsky, I. S., & Quinn, T. R. 2018, ApJ, 868, 108
Cadiou, C., Dubois, Y., & Pichon, C. 2022, MNRAS, 514, 5429
Cavagnolo, K. W., Donahue, M., Voit, G. M., & Sun, M. 2008, ApJL, 683, L107
Cen, R., & Ostriker, J. P. 1992, ApJL, 399, L113
Chisholm, J., Tremonti, C. A., Leitherer, C., & Chen, Y. 2017, MNRAS, 469, 4831
Corlies, L., Peeples, M. S., Tumlinson, J., et al. 2020, ApJ, 896, 125
Côté, B., Ritter, C., O’Shea, B. W., et al. 2016, ApJ, 824, 82
Davé, R., Finlator, K., & Oppenheimer, B. D. 2012, MNRAS, 421, 98
DeFelippis, D., Genel, S., Bryan, G. L., et al. 2020, ApJ, 895, 17
Di Teodoro, E. M., & Peek, J. E. G. 2021, ApJ, 923, 220
Donahue, M., & Voit, G. M. 2022, PhR, 973, 1
Ferland, G. J., Porter, R. L., van Hoof, P. A. M., et al. 2013, RMxAA, 49, 137
Fielding, D., Quataert, E., McCourt, M., & Thompson, T. A. 2017, MNRAS, 466, 3810
Fielding, D. B., Tonnesen, S., DeFelippis, D., et al. 2020, ApJ, 903, 32
Frisbie, R. L. S., Donahue, M., Voit, G. M., et al. 2020, ApJ, 899, 159
Gaspari, M., Brighenti, F., & Temi, P. 2015, A&A, 579, A62
Gaspari, M., Ruszkowski, M., & Oh, S.-P. 2013, MNRAS, 432, 3401
Gaspari, M., Ruszkowski, M., & Sharma, P. 2012, ApJ, 746, 94
Haardt, F., & Madau, P. 2012, ApJ, 746, 125
Hafen, Z., Stern, J., Bullock, J., et al. 2022, MNRAS, 514, 5056
Harris, C. R., Millman, K. J., van der Walt, S., et al. 2020, Natur, 585, 357
Heckman, T. M., Alexanderoff, R. M., Borthakur, S., Overzier, R., & Leitherer, C. 2015, ApJ, 809, 147
Ho, S. H., Martin, C. L., & Turner, M. L. 2019, ApJ, 875, 54
Hodges-Kluck, E. J., Miller, M. J., & Bregman, J. N. 2016, ApJ, 822, 21
Hopkins, P. F., Wetzelaer, A., Keres, D., et al. 2018a, MNRAS, 480, 800
Hopkins, P. F., Wetzelaer, A., Keres, D., et al. 2018b, MNRAS, 477, 1578
Hummels, C. B., Smith, B. D., Hopkins, P. F., et al. 2019, ApJ, 882, 156
Hunter, J. D. 2007, CSE, 9, 90
Jeffreson, S. M. R., Kruijssen, J. M. D., Keller, B. W., Chevance, M., & Glover, S. C. O. 2020, MNRAS, 498, 385
Ji, S., Chan, T. K., Hummels, C. B., et al. 2020, MNRAS, 496, 4221
Katz, N. 1992, ApJL, 391, 502
Kim, J.-h., Agertz, O., Teyssier, R., et al. 2016, ApJ, 833, 202
Krumholz, M. R., Burkhardt, B., Forbes, J. C., & Crocker, R. M. 2018, MNRAS, 477, 2716
Leroy, A. K., Walter, F., Brinks, E., et al. 2008, AJ, 136, 2782
Li, M., & Tonnesen, S. 2020, ApJ, 898, 148
Li, Y., & Bryan, G. L. 2014a, ApJ, 789, 153
Li, Y., & Bryan, G. L. 2014b, ApJ, 789, 54

24
