How Do Supernovae Impact the Circumgalactic Medium? I. Large-scale Fountains around a Milky Way–like Galaxy

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Received 2019 October 30; revised 2020 June 22; accepted 2020 June 22; published 2020 August 3

Abstract

Feedback is indispensable in galaxy formation. However, lacking resolutions, cosmological simulations often use ad hoc feedback parameters. Conversely, small-box simulations, while they better resolve the feedback, cannot capture gas evolution beyond the simulation domain. We aim to bridge the gap by implementing small-box results of supernovae-driven outflows into dark matter halo-scale simulations and studying their impact on large scales. Galactic outflows are multiphase, but small-box simulations show that the hot phase ($T \approx 10^6$–$10^7$ K) carries the majority of energy and metals. We implement hot outflows in idealized simulations of the Milky Way halo, and examine how they impact the circumgalactic medium. In this paper, we discuss the case when the star formation surface density is low and therefore the emerging hot outflows are gravitationally bound by the halo. We find that outflows form a large-scale, metal-enriched atmosphere with fountain motions. As hot gas accumulates, the inner atmosphere becomes “saturated.” Cool gas condenses, with a rate balancing the injection of the hot outflows. This balance leads to a universal density profile of the hot atmosphere, independent of mass outflow rate. The atmosphere has a radially decreasing temperature, naturally producing the observed X-ray luminosity and column densities of O VI, O VII, and O VIII. The self-regulated atmosphere has a baryon and a metal mass of $(0.5–1.2) \times 10^{10} M_{\odot}$ and $(0.6–1.4) \times 10^{8} M_{\odot}$, respectively, small compared to the “missing” baryons and metals from the halo. We conjecture that the missing materials reside at even larger radii, ejected by more powerful outflows in the past.

Unified Astronomy Thesaurus concepts: Galaxy formation (595); Milky Way formation (1053); Galaxy evolution (594); Milky Way evolution (1052); Circumgalactic medium (1879); Hydrodynamical simulations (767); Galactic winds (572); Disk galaxies (391); Supernova remnants (1667); Chemical enrichment (225)

1. Introduction

The circumgalactic medium (CGM) is the battlefield between cosmic accretion and galactic feedback. It is closely related to galaxy formation and the baryon distribution in the universe, where multiple unsolved problems exist. For example, (i) galaxies only contain a small fraction of cosmic baryons (Fukugita et al. 1998; Bell et al. 2003; Guo et al. 2010; Moster et al. 2010; Planck Collaboration et al. 2018). Why is galaxy formation so inefficient? And (ii) where are the baryons that are not in galaxies (Cen & Ostriker 1999; Bregman 2007; Shull et al. 2012)? (iii) Galaxies only contain a small fraction of the heavy elements (“metals”) they have produced (e.g., Tremonti et al. 2004; Erb et al. 2006; Andrews & Martini 2013; Peeples et al. 2014; Sánchez et al. 2019). Where are the metals? (iv) Galaxies have a bimodal distribution, i.e., star-forming galaxies, and massive quenched systems (e.g., Blanton et al. 2003; Kauffmann et al. 2003). How do galaxies stop forming stars? The dynamical, thermal, and chemical states of the CGM contain vital information about the cosmic baryon cycle and are inextricable from galaxy formation (Cen & Chisari 2011; Shen et al. 2013; Suresh et al. 2015). The mass, energy, and metal contents of the CGM are critical for understanding the cosmic baryon distribution (e.g., Tumlinson et al. 2017; Bregman et al. 2018, and references therein).

The CGM has been a central target for many recent observing programs. It has multiphase components, with cool gas around $10^4$ K, warm-hot phase around $10^5$ K, and hot phase ($> 10^6$ K; e.g., Anderson & Bregman 2010; Chen et al. 2010; Steidel et al. 2010; Tripp et al. 2011; Bouché et al. 2012; Kacprzak et al. 2012; Li & Wang 2013; Zhu & Ménard 2013; Werk et al. 2014; Johnson et al. 2015; Bielby et al. 2019). CGM properties correlate with galaxy properties. For example, O VII has a very high detection rate in star-forming galaxies, but almost no detection in quiescent galaxies (Tumlinson et al. 2011). X-ray luminosities of galaxy coronae scale with star formation rates (SFRs) in galaxies (Mineo et al. 2012; Wang et al. 2016). The motions of the cool CGM increase with the SF intensity in the galaxy (Lane & Mo 2018; Martin et al. 2019; Rudie et al. 2019; Schroetter et al. 2019). For the Milky Way (MW), a relatively quiescent galaxy with an SFR of 1–3 $M_{\odot}$ yr$^{-1}$, the hot and warm-hot phases are seen through O VIII, O VII, and O VI absorption lines along many lines of sight (Sembach et al. 2003; Gupta et al. 2012; Fang et al. 2015; Das et al. 2019); cool CGM phases are prevalent, with a fraction falling toward the galaxy as high-velocity clouds (e.g., Putman et al. 2012, and references therein). Recent theoretical works have provided clues on the working mechanisms of the CGM, through analytic modeling (Maller & Bullock 2004; Faerman et al. 2017, 2020; Voit et al. 2017; Lochhaas et al. 2018; Keller et al. 2020; Stern et al. 2019) and numerical simulations (e.g., Hummels et al. 2013; Shen et al. 2013; Corlies & Schiminovich 2016; Fieling et al. 2017; Hafen et al. 2020).

Energetic feedback from the galaxies plays an essential role in cosmic baryon cycles and galaxy formation. In particular, supermassive black holes and supernovae (SNe) dominate the energy output and can substantially change the CGM, as indicated by recent simulations (e.g., Anglés-Alcázar et al. 2017; Nelson et al. 2019; Oppenheimer et al. 2020; Zhang & Guo 2020). Our focus in this paper is on SNe. SNe produce copious energy and the majority of metals. They maintain a
multiphase interstellar medium (ISM; McKee & Ostriker 1977; Cox 2005), regulate star formation (SF; McKee & Ostriker 2007, and references therein), and drive galactic outflows (Mac Low & Ferrara 1999; Strickland & Heckman 2009; Creasey et al. 2013; Li et al. 2017a; Fielding et al. 2018; Kim & Ostriker 2018; Emerick et al. 2019; Hu 2019). The outflows transport energy, mass, and metals into the CGM and even into intergalactic space (e.g., Songaila & Cowie 1996; Schaye et al. 2003). It is thus important to better understand how the CGM evolves under SNe-driven outflows. Questions of particular interest include: how far can outflows travel? How far can metals go? What fraction of mass/metals are retained in the CGM, break into the intergalactic medium (IGM), or fall back to galaxies?

On the other hand, how SNe feedback works is still an unsolved problem. The energy and metal production of SNe are reasonably well known (Weiler & Sramek 1988; Arnett 1995, and references therein). Yet, it is not known how SN remnants interact with a multephase ISM (Kim & Ostriker 2015a; Li et al. 2015; Martizzi et al. 2016; Zhang & Chevalier 2019), and how much of their energy is used in regulating SF, driving outflows, or is simply dissipated away. Cosmological simulations, due to their general lack of resolution, often use ad hoc models for SNe feedback. While the feedback is tuned so that major galaxy properties match the observations, their CGMs have very different properties and are sensitive to the feedback models used (e.g., Shen et al. 2013; Suresh et al. 2015; Stewart et al. 2017; Davies et al. 2020). We believe that garnering a better understanding of SNe feedback and applying a more physically based feedback model in cosmological simulations are critical next steps to a predictive theory of galaxy formation.

Recently, several groups have simulated how SNe drive galactic outflows from the ISM (e.g., Creasey et al. 2013; Girichidis et al. 2016; Li et al. 2017a; Fielding et al. 2018; Kim & Ostriker 2018; Hu 2019). These simulations cover a kiloparsec-scale domain with parsec-scale resolution, which is generally able to resolve the cooling radius of SNe-driven blast waves. This is essential for convergence on the properties of the multephase ISM and outflows, especially the hot phase (Kim & Ostriker 2015b; Simpson et al. 2015; Hu 2019). The outflows, like the ISM, typically have three phases (McKee & Ostriker 1977): hot (10⁶–10⁷ K), cool (~10⁵ K), and cold (≤100 K). Outflow rates of mass, energy, and metals are quantified from small-box simulations. The hot outflows have a larger volume fraction and are faster, whereas the cooler phases occupy a smaller volume and are slower. Quantitatively, however, the outflow fluxes can be different depending on detailed physics, in particular, where SNe explode—whether in dense clouds or diffuse medium, the spatial-temporal correlation of the SNe (Gatto et al. 2015; Martizzi et al. 2016; Li et al. 2017a; Fielding et al. 2018), the presence of cosmic rays (e.g., Simpson et al. 2016; Girichidis et al. 2018), etc. These complexities appear to pose challenges for any simple model of SNe-driven outflows.

However, simple and consistent results seem to emerge when different phases of outflows are counted separately. Li & Bryan (2020) compiled recent results from multiple small-box simulations of SNe-driven outflows. They use different numerical codes, and the physics included also vary, such as self-gravity and star formation, other stellar feedback, etc.¹ Intriguingly, however, Li & Bryan (2020) find consensus that the majority of outflow energy is carried by the hot phase. The energy flux of hot outflows is 2–20 times greater than that of the cool phases. The cooler phases usually dominate the mass fluxes. Seemingly, cool outflows carry mass outside the galaxies. However, the specific energy, i.e., energy per unit mass, of the cool outflows is small. Most cool outflows seen in small-box simulations cannot escape dark matter (DM) halos of $M \geq 10^{11} M_\odot$, whereas hot outflows can escape halos up to $10^{13} M_\odot$ (Li & Bryan 2020). The former is confirmed by recent observations (Schroetter et al. 2019). For an MW-mass galaxy, most cool outflows will travel only a few kiloparsecs above the disk before falling back due to gravity (Li et al. 2017a; Kim & Ostriker 2018). In contrast, the hot outflows have a specific energy 10–1000 times larger than the cool phases (Li & Bryan 2020, and references therein), and can therefore travel much farther away from the galaxy. Hot outflows should thus have a much greater impact than the cool outflows for halos with $M \geq 10^{10} M_\odot$. Furthermore, hot outflows also carry a great amount of metals (Creasey et al. 2015; Li et al. 2017a; Hu 2019), which can be transported large distances. Consequently, it is necessary to study how hot outflows impact the thermal, dynamical, and chemical states of the CGM. Besides the power of hot outflows, the fluxes of mass, energy, and metal mass of hot outflows have tight correlations, essentially reducing the three parameters into one. These findings make it promising to implement hot outflows into large-scale simulations.

To see the impact of outflows on larger scales, one needs a much larger volume and a much longer timescale than what small-box simulations can cover. Because of computational expense, this means sacrificing resolution and thus the ability to resolve individual SN remnants. In other words, the launching of the outflows cannot be captured simultaneously while covering their domain of impact (though it is now possible for small galaxies for a short duration; e.g., Schneider et al. 2018; Emerick et al. 2019; Hu 2019).

Our approach is to take the small-box results, i.e., the averaged outflow rates of energy, mass, and metals, and add hot outflows as a source term to a large simulation box. We then focus on the evolution of the hot outflows on scales of kiloparsecs to hundreds of kiloparsecs, and investigate how they impact the CGM over cosmic time.

We organize our paper as follows. In Section 2, we briefly present the small-box results that we will use in the global simulations. In Section 3, we introduce the setup of the global simulations. In Section 4, we use a fiducial run to illustrate the basic picture of the evolution of the simulated CGM. In Section 5, we examine how varying input parameters affects the results and discuss the emerging universal density profile. In Section 6, we discuss the observational signatures from the simulated CGM and how they relate to the underlying physics. We discuss the implications of our findings in Section 7 and conclude in Section 8.

2. Results from Small-box Simulations

In this section, we will first introduce the parameterization of the outflows, i.e., the loading factors. Then we will summarize the results from small-box simulations, which will be used in our global CGM simulations.

To quantify the ability of SNe to launch outflows, three dimensionless loading factors $\eta_m$ (mass loading), $\eta_e$ (energy

¹ These simulations do not include cosmic rays, which, according to recent studies, can change the ISM structure significantly (e.g., Farber et al. 2018; Girichidis et al. 2018).
loading), and $\eta_Z$ (metal mass loading) are defined,
\begin{align}
\dot{\Sigma}_m & = \eta_m \dot{\Sigma}_{\text{SF}}, \\
\dot{\Sigma}_E & = \eta_E \frac{\dot{\Sigma}_{\text{SF}}}{m_*}, \\
\dot{\Sigma}_Z & = \eta_Z \frac{m_{Z,\text{SN}} \dot{\Sigma}_{\text{SF}}}{m_*},
\end{align}

where $\dot{\Sigma}_m$, $\dot{\Sigma}_E$, and $\dot{\Sigma}_Z$ are the outflow rates per area of mass, energy (thermal + kinetic), and metal mass measured from the simulations; $\dot{\Sigma}_{\text{SF}}$ is the SF surface density, $m_*$ is the mass of stars formed to produce one SN, and $m_{Z,\text{SN}}$ is the metal mass released per SN. From these definitions, $\eta_E$ is the fraction of SN energy that is carried by the outflows, and $\eta_Z$ is the fraction of metals released by SN that is carried in the outflows (note that in this definition of $\eta_Z$, the metal flux does not include metals that are in the ISM before SNe explode).

We use the results from Li et al. (2017a), which include runs over a wide range of $\dot{\Sigma}_{\text{SF}}$. The fiducial runs assume a Kennicutt–Schmidt relation for $\dot{\Sigma}_{\text{gas}}$ and $\dot{\Sigma}_{\text{SF}}$. The loading factors are measured for each run at a height of 1–2.5 kpc from the midplane, i.e., above the ISM and SNe explosion sites, and are temporally averaged over the last 40% of the simulation time (160 Myr) when the system reaches a semi-steady state. Note that unlike the cool phases, the fluxes of hot outflows change little with the height within the simulation domain, due to their large specific energy compared to the depth of the gravitational potential of small boxes (e.g., Kim & Ostriker 2018). For the hot outflows, Li et al. (2017a) found
\begin{align}
\eta_{E,h} & = 0.25 \pm 0.1, \\
\eta_{Z,h} & = 0.5 \pm 0.1, \\
\eta_{m,h} & \approx 2.1 \left( \frac{\dot{\Sigma}_{\text{SF}}}{1.26 \times 10^{-4} M_\odot \text{yr}^{-1} \text{kpc}^{-2}} \right)^{-0.4}. 
\end{align}

That is, $\eta_{E,h}$ and $\eta_{Z,h}$ are almost constant. This is because the hot phase occupies roughly 50% of the volume in the ISM, for various $\dot{\Sigma}_{\text{SF}}$. These hot bubbles are “holes,” where metals and energy can easily vent out and become outflows. The metal loading $\eta_{m,h}$ decreases with increasing $\dot{\Sigma}_{\text{SF}}$. This is likely because when gas surface density is high, the ISM is dominantly in the dense molecular phase (e.g., Schruba et al. 2011); thus, it is hard for the ISM to be loaded to the outflows (like it is harder for winds to blow away rocks than leaves).

A constant $\eta_{E,h}$ and a decreasing $\eta_{m,h}$ for higher $\dot{\Sigma}_{\text{SF}}$ means that the specific energy of the hot outflows is larger when the SF is more intense. Indeed, this is suggested by X-ray observations (Zhang et al. 2014; Wang et al. 2016) and seen in various small-box works (summarized in Figure 2 of Li & Bryan 2020). Quantitatively, we can use the terminal velocity $\bar{v}_{h,t}$ to represent the specific energy of hot outflows (Chevalier & Clegg 1985),
\begin{align}
\bar{v}_{h,t} & \equiv \left( \frac{2 \dot{\Sigma}_{E,h}}{\dot{\Sigma}_{m,h}} \right)^{1/2} = 548 \text{ km s}^{-1} \left( \frac{\eta_E}{0.3} \right)^{1/2} \left( \frac{1.0}{\eta_m} \right)^{1/2}, \\
& = 1225 \text{ km s}^{-1} \left( \frac{\eta_E}{0.3} \right)^{1/2} \left( \frac{0.2}{\eta_m} \right)^{1/2}. 
\end{align}

The above equation assumes $E_{\text{SN}} = 10^{51}$ erg and $m_* = 100 M_\odot$. The first example uses $\eta_{m,h}$ for a low $\dot{\Sigma}_{\text{SF}} = 6.3 \times 10^{-3} M_\odot \text{yr}^{-1} \text{kpc}^{-2}$, which is the approximate mean $\dot{\Sigma}_{\text{SF}}$ for the MW, and the second example uses $\eta_{m,h}$ for a larger $\dot{\Sigma}_{\text{SF}} = 0.15–0.71 M_\odot \text{yr}^{-1} \text{kpc}^{-2}$. The terminal velocity of outflows can be compared to the escape velocity of DM halos $v_{\text{esc}}$ to evaluate whether hot outflows can potentially leave the halo. For the MW halo where $v_{\text{esc}} \approx 600 \text{ km s}^{-1}$, $\bar{v}_{h,t} < v_{\text{esc}}$ for the smaller $\dot{\Sigma}_{\text{SF}}$ case while $\bar{v}_{h,t} > v_{\text{esc}}$ for the larger $\dot{\Sigma}_{\text{SF}}$. So the MW-mass halo is of special interest since changing $\dot{\Sigma}_{\text{SF}}$ can lead to a transition of escape for hot outflows.

This paper will focus on the case that has $\bar{v}_{h,t} < v_{\text{esc}}$ for an MW-mass halo. In a companion paper, we discuss the case when $\bar{v}_{h,t} > v_{\text{esc}}$. We find that the above two cases result in fundamentally different CGMs.

Note that small-box simulations by other groups have somewhat different loading factors, but intriguingly, the three loading factors differ by a similar factor (see discussions in Li & Bryan 2020). This makes the global results easily scalable. We will discuss this point in Section 7.

3. Global Simulation Setup

In this Section, we describe the setup of our global simulations of CGM, using the small-box results for modeling the launch of hot outflows.

3.1. Simulation Code and Cooling

The hydrodynamic equations are solved by the Eulerian code Enzo (Bryan et al. 2014), using the finite volume piecewise parabolic method (Colella & Woodward 1984). The fiducial box size is 800 kpc on each side. We use a static refinement throughout the simulation. The spatial resolution is progressively higher toward the center of the box, which is 0.5 kpc for the inner (50 kpc), 1.0 kpc for the inner (100 kpc), and so on. The dependence of global CGM properties on the resolution is discussed in Appendix C.

We use the Grackle library to calculate the cooling rate of the gas (Smith et al. 2017). We assume the extragalactic UV background from Haardt & Madau (2012) at redshift 0 in Grackle when determining the ionization levels from equilibrium calculation. The cooling is metallicity dependent. Throughout this paper, we adopt a solar metallicity $Z_\odot = 0.01295$, which is the default value in Grackle.

3.2. Gravitational Potential

The galaxy is located at the center of the box, with the disk in the $x$–$y$ plane. We use a static gravitational potential. (We simulate the CGM for 8 Gyr, over which the halo mass changes by less than a factor of two, e.g., McBride et al. 2009, so a static halo potential is a reasonable approximation.) The potential includes a DM halo, a stellar disk, and a stellar bulge. The parameters of the potential follow those of the MW. The DM halo is assumed to have a Burkert (1995) profile, with a central density of $2.71 \times 10^{-2} \text{ g cm}^{-3}$ and a core radius of 10 kpc (Nesti & Salucci 2013). The mass distribution of the stellar disk has a Plummer–Kuzmin functional form (Miyamoto & Nagai 1975), with a mass of $5.5 \times 10^{10} M_\odot$, a scale radius of 50 kpc for the inner (50 kpc), 1.0 kpc for the inner (100 kpc), and so on. The dependence of global CGM properties on the resolution is discussed in Appendix C.

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that from the DM halo, the galactic disk, and the stellar bulge. The exact size does not affect our results component with rotation; but our tests have revealed that its room for a future development of a hot gaseous disk uniform density at equilibrium with the DM halo potential, with an inner core of 3.5 kpc, and a scale height of 0.7 kpc. The galactic bulge is modeled as a spherical Hernquist (1993) profile with a mass of \( 10^{10} M_\odot \) and a scale radius of 1.3 kpc.

The top panel of Figure 1 shows the gravitational potential as a function of radius, \( -\phi(R) = \int_0^R g(R') dR' \) where \( g \) is the gravitational field. The bottom panel shows \( v_0(R) \equiv \sqrt{2(\phi(R) - \phi(3 \text{ kpc})} \), i.e., the velocity of outflows at the launching site in order to reach a radius \( R \) (assuming a ballistic evolution). To escape from the halo \( (R \gtrsim 250 \text{ kpc}) \), the outflow at the galaxy disk needs to have \( v_0 \approx 620 \text{ km s}^{-1} \). This is a simple estimate when there is no gas in the halo. With some preexisting gas, the estimated \( v_0 \) is a lower limit.

### 3.3. Initial Conditions

The initial gas in the simulation box only includes a hot component. We do not include a cool gaseous disk within the galaxy. The gas has a uniform temperature of \( 10^6 \text{ K} \), similar to the virial temperature of the MW-halo mass, and a uniform low metallicity \( 0.2 Z_\odot \). Gas density is set to be in hydrostatic equilibrium with the DM halo potential, with an inner core of uniform density at \( R < 40 \text{ kpc} \). This core is artificial, leaving room for a future development of a hot gaseous disk component with rotation; but our tests have revealed that its exact size does not affect our results (as long as it is small). The normalization factor of initial gas density is parameterized by \( n_0 \), defined as the mean number density of gas within \( R = 200 \text{ kpc} \). This is a free parameter in our simulations, and we vary it from \( 10^{-7} \) to \( 10^{-4} \text{ cm}^{-3} \). Figure 2 shows the initial density profile as a function of radius (solid lines). The enclosed mass is shown by the dashed lines using the right y-axis. The horizontal dashed-dotted line indicates the mean density of the cosmic baryons at redshift 0. The dotted line indicates the total mass of baryons associated with a DM mass of \( 10^{12} M_\odot \), assuming a cosmic baryon fraction (Planck Collaboration et al. 2018). Given the uncertainty of the actual initial condition, our range of \( n_0 \) includes these two limits.

### 3.4. Implementation of Outflows

In our simulations, we do not model star formation in the galaxy disk. In fact, as mentioned before, there is no cool gaseous disk to begin with. Instead, we add outflows by hand at a location above/below the disk. In terms of where and how often to add outflows, we try to mimic the SF process in a disk galaxy. The basic picture is that SF happens in clusters; each star cluster has a life span of a few tens of megayears, during which outflows are launched; the location of the star cluster is random within the galaxy disk. Holding this picture in mind, we add the outflows in the following way: the outflows are injected as discrete events to a small region. The locations of outflows are different each time and are randomly selected within the galaxy. The time intervals between these SF events are constant, \( \Delta t = 9.9 \text{ Myr} \).

For each SF event, the injected region for outflows is two hemispheres above and below the disk whose coordinates \((x, y, z)\) satisfy:

\[
\begin{cases}
(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 \leq R_{sf}^2, \text{ for } z \geq z_0; \\
(x - x_0)^2 + (y - y_0)^2 + (z + z_0)^2 \leq R_{sf}^2, \text{ for } z \leq -z_0,
\end{cases}
\]

where \((x_0, y_0, z_0)\) is the center of this SF event in the disk, which is randomly chosen within a circle of \( R_{sf} \) on the midplane. The hemispheres have a radius of \( R_{hp} \), which is set to be 3 kpc. Note that the outflows are only added at \( |z| \geq z_0 \). We choose to add the outflows at \( z_0 = 3 \text{ kpc} \) above the plane because (1) in small-box simulations, the loading factors are measured at a few kiloparsecs above the plane; (2) later when cool gas forms in the CGM, it will fall to the midplane with a height of a few cell sizes, below where the outflows are added. This prevents adding the outflows to the dense, cool gas layer, and thus avoids the “overcooling” problem commonly seen when applying feedback in coarse-resolution simulations.
As mentioned before, only hot outflows are added. The outflow rates of mass, energy, and metal mass are given by the following equations:

\[ M_{\text{out}} = \eta_{\text{in}} M_{\text{SF}}, \]  

\[ E_{\text{out}} = \eta_{\text{in}} E_{\text{SN}} \left( \frac{M_{\text{SF}}}{m_*} \right), \]  

\[ M_{Z,\text{out}} = \eta_{Z} m_{Z,\text{SN}} \left( \frac{M_{\text{SF}}}{m_*} \right) + M_{\text{out}} Z_{\text{ISM}}, \]  

where \( Z_{\text{ISM}} \) is the metallicity of the ISM that is being "entrained" into the outflows, \( m_{Z,\text{SN}} \) is the metal yield per SN, which we assume to be 1.5 \( M_\odot \), and \( m_* = 100 M_\odot \). For each SF event, the amount of mass, energy, and metal mass added as source terms are simply \( M_{\text{out}} \Delta t \), \( E_{\text{out}} \Delta t \), and \( M_{Z,\text{out}} \Delta t \), respectively. The injected mass, energy, and metals are uniformly distributed within the two hemispheres. Given the insensitivity is because the injection region has a much higher energy than the resolution is not high enough, thermal deposition will result in the overcooling during this momentum-adding procedure, that is, \( \Delta \rho' = \rho + \Delta \rho_z; \) \( \rho_z' = \rho_z + \Delta \rho_z; \) \( p' = p + \Delta p \).

\[ \rho' = \rho + \Delta \rho_z; \]  

\[ \rho_z' = \rho_z + \Delta \rho_z; \]  

\[ p' = p + \Delta p. \]  

For each cell, calculate the current kinetic energy density \( e_k' \). Note that there is a loss of kinetic energy during this momentum-adding procedure, that is, \( \Delta \rho_{\text{k,loss}} = \rho_k + \Delta \rho_k - e_k' > 0 \). (vii) This loss of kinetic energy is then added as thermal energy. That is, for each cell, apply the thermal energy addition as\( e_k = e_k' + \Delta e_k + \Delta e_{\text{k,loss}}, \) (11)

In this way, we preserve momentum and total energy when adding outflows. We show in Appendix A that the outflows are added in simulations at the expected rate.

The SFR and \( n_0 \) for each run are input parameters. We use the nomenclature of \( \left( n_0, \text{SFR}(M_{\text{SF}}) \right) \) to denote each run. For example, "3c-6SFR3" means \( n_0 = 3 \times 10^{-6} \text{ cm}^{-3} \) and an SFR of \( 3 M_\odot \text{ yr}^{-1} \).

4. Results

In this Section, we use a fiducial run, 1e-6SFR3, to illustrate the basic picture of CGM evolution with SNe-driven outflows launched from the disk. The initial density \( n_0 = 10^{-6} \text{ cm}^{-3} \) is relatively small; therefore, the outflow evolution is mostly affected by the gravitational potential. We will discuss the effect of varying \( n_0 \) and SFR in Section 7.

First we estimate that the distance outflows can travel using a simple energy argument. From Equation (5), the terminal velocity of the outflows \( v_{\text{th}} \) is 548 km s\(^{-1}\) given the loading factors we use. By comparing \( v_{\text{th}} \) to the potential (Figure 1),

\[ \frac{1}{2} v_{\text{th}}^2 = \phi(R_{\text{out}}) - \phi(3 \text{ kpc}), \]  

we get

\[ R_{\text{out}} \approx 60 \text{ kpc}. \]  

This means that from a simple energy argument, outflows injected 3 kpc from the galaxy center should go out to a radius of 60 kpc. Note that if \( v_{\text{th}} \) is larger by 13%, the hot outflows can escape from the halo.

4.1. Hot Atmosphere

To give a visual impression, Figure 3 shows slices of the fiducial run at 2 Gyr. Each slice is taken at the \( y-z \) plane through the center of the box, i.e., the "galaxy" is viewed edge-on. The horizontal direction of the slice is \( y \), and the vertical is
The length scale of the slices is 400 kpc on each side (the whole box is twice as large). The hot CGM is roughly symmetric around the $z = 0$ plane, which is expected due to the symmetry of the initial condition and the outflow implementation. The metallicity slice shows a clear boundary at $R \approx 140$ kpc, between an enriched inner region and a low-metallicity outer part. This marks the distance that the outflows have reached. Beyond that radius, gas largely remains at the initial condition state, though there are spherical structures seen in temperature, radial velocity, and entropy, which are weak shocks/sound waves that the outflows drive into the preexisting gas. The slice of $z$-velocity indicates that the metal-enriched region is a large-scale fountain flow, with both positive and negative velocity components within each side of the galaxy. The density, temperature, and pressure show a radial decrease when added and undergo an initial expansion; at around 10 kpc, the gas passes through a shock-like jump condition and becomes part of the hot atmosphere.

We use $R_{\text{max}}$ to describe the maximum radius of the metal-enriched gas, which is defined as the radius at which the gas metallicity drops to twice that of the preexisting gas along a given direction. Figure 4 shows how $R_{\text{max}}$ changes over time. The error bars indicate the standard deviation of $R_{\text{max}}$ at different polar angles, which are small compared to $R_{\text{max}}$. This confirms the spherical shape of the outflows. The fiducial run shows that $R_{\text{max}}$ rises to about 140 kpc at $t \approx 1.5$ Gyr, and does not change much after that. There are some fluctuations of $R_{\text{max}}$ over time, which is due to the cooling episode of the hot atmosphere, which we will focus on in the next subsection. The maximum distance the outflows reach, 140 kpc, is larger than the ballistic estimate from Equation (12), which indicates that outflows do not evolve in isolation. We will discuss this more in Section 5.1. The value of $R_{\text{max}}$ is well converged with respect to the numerical resolution, which we show in Appendix C.

The top panel of Figure 5 shows the amount of hot CGM as a function of time. Only gas with $T > 3 \times 10^4$ K is included. The solid line indicates the enclosed mass within $R < 200$ kpc, and the dashed line is the enclosed mass at $R < R_{\text{out}}$ (where $R_{\text{out}} = 60$ kpc). $M_h (R < 200$ kpc) first increases, reaches the maximum at $8 \times 10^9 M_\odot$, and then slightly decreases and settles at $4-5 \times 10^9 M_\odot$. $M_h (R < 60$ kpc) is about 60% of $M_h (R < 200$ kpc), meaning that about 40% of the outflows reach $R > R_{\text{out}}$. The hot outflows are being injected into the box at a constant rate throughout the simulation. Why does the total

\[ t = 2.0 \text{ Gyr} \]

\[ \text{Number Density} \]

\[ \text{Temperature} \ (\text{K}) \]

\[ \text{Pressure} \]

\[ \text{Entropy} \ (\text{cm}^2 \text{s}^{-2} \text{keV}) \]

\[ \text{Metallicity} \]

\[ \text{Z-Velocity} \ (\text{km/s}) \]

\[ \text{Figure 3.} \] Edge-on slices of the fiducial run 1e-6SFR3 at $t = 2$ Gyr. The plot is sliced through the center of the box. The horizontal direction is $y$, and the vertical direction is $z$. The slices are 400 kpc on each side. The hot outflows form a nearly spherical, metal-enriched atmosphere, which has fountain motions.

\[ \text{Figure 4.} \] Maximum radius metals reach, $R_{\text{max}}$, as a function of time for the fiducial run 1e-6-SFR3. The error bars indicate the standard deviation of $R_{\text{max}}$ at different polar angles. $R_{\text{max}}$ first rises to reach about 140 kpc and stays roughly constant after that.

\[ 4^* \text{In this paper “hot gas” denotes gas with } T > 3 \times 10^4 \text{ K, which is volume-filling. Gas with } T \lesssim 2 \times 10^4 \text{ K is defined as “cool gas.”} \]
mass of hot gas in the CGM not keep increasing? It is because as gas accumulates, gas density increases, and so does the cooling rate. At some point, the inner hot CGM has a large enough cooling rate that the cool phase starts to condense out of the hot atmosphere. That is, the hot atmosphere is “saturated.”

The bottom panel of Figure 5 shows the ratio between the formation rate of the cool phase, \( M_{\text{cool}} \), and the injection rate of the hot outflows, \( M_{\text{out}} \). The cool phase starts to form at around 2 Gyr. The ratio \( M_{\text{cool}}/M_{\text{out}} \) quickly rises to around unity within less than 1 Gyr. After that, the ratio stays close to unity. As a result, the amount of hot gas in the CGM remains roughly constant.

### 4.2. Cool Gas Condensation

Figure 6 shows the projected density of cool gas \((T < 3 \times 10^4 \text{ K})\) at \( t = 3.2 \text{ Gyr} \). The projection is in the x-direction, i.e., the “galaxy” is viewed edge-on. Most of the cool gas is at \( R < 50 \text{ kpc} \). In contrast to the smooth hot flows, the cool gas is lumpy and shows filamentary structure. The cool gas has a larger covering fraction at smaller impact parameters.

Figure 7 shows the radial velocity versus radius, color coded by gas mass for the fiducial run. The top panel is for the cool gas, and the bottom panel shows the hot gas. The snapshot is taken at \( t = 3 \text{ Gyr} \). Outward motions are positive. The hot gas has both outward and inward motions, confirming a fountain flow. In contrast, the cool gas has only negative radial velocities. The inflow velocity increases with decreasing radius. The overplotted solid lines indicate trajectories of freefall beginning at a few radii, given the gravitational potential (Figure 1). Unlike the hot gas, the cool clumps are not pressure-supported, and fall nearly ballistically toward the center of the potential well. At \( R = 10 \text{ kpc} \), the velocity of the cool gas is \( 100-350 \text{ km s}^{-1} \). This is similar to the observed intermediate- or high-velocity clouds in the MW (Putman et al. 2002; McClure-Griffiths et al. 2009; Lehner & Howk 2010) or infalling gas for external galaxies (Zheng et al. 2017).

The lack of a positive-velocity component in cool gas indicates that cool gas does not form when hot outflows are expanding outward. This is different from the picture that Thompson et al. (2016) and Schneider et al. (2018) propose about forming cool outflows en route from hot winds. The main difference is that the density (related to mass loading factor) of our outflows is not large enough; thus, the cooling time of the hot outflows is much longer than their dynamical time. Instead, the formation of cool gas in our simulations happens significantly later, when the hot CGM has accumulated enough mass to be saturated, i.e., when the inner halo has a sufficiently short cooling time of \( \sim 1 \text{ Gyr} \).

Cool gas dropping out of the hot atmosphere is a natural way to explain the high-velocity clouds in the MW (Field 1965; Shapiro & Field 1976; Bregman 1980; Maller & Bullock 2004; Voit 2019). If they drop out of an atmosphere formed from SNe-driven hot outflows, they would have the same high metallicity as these outflows, which in our case is \( 1.4 Z_\odot \). Observationally, some of these high-velocity clouds are highly enriched, with near solar or super-solar metallicity (e.g., Zech et al. 2008). This highly enriched cool phase should originate from the galaxy, since accreted materials would have low metallicities. From small-box simulations, the cool outflows launched from the disk typically cannot go very far, \(< 10 \text{ kpc} \) (Li et al. 2017a; Kim & Ostriker 2018), and the fall-back velocity is limited by the launching velocity, which is a few
mixing with low-metallicity preexisting halo gas. The mixing with preexisting gas is not a significant effect for hot outflows in this paper, because their entropy is lower than that of the preexisting gas. As a result of little mixing, there is a clear division between the inner atmosphere formed almost completely from the hot outflows, and an outer layer of preexisting gas. This division is clearly seen from the metallicity slice in Figure 3.

5. Effects of Varying Parameters

In this section, we discuss how CGM properties change when we vary input parameters, specifically $n_0$ and SFR, while the loading factors are the same. We discuss the fountain height, formation of cool gas, and density profile of the hot CGM.

5.1. Fountain Height $R_{\text{max}}$

As discussed above, $R_{\text{max}}$ quantifies how far outflows can reach and spread metals. The top panel of Figure 8 shows how $R_{\text{max}}$ changes with time for different $n_0$. The SFR for all three runs is $3 \, M_\odot \, \text{yr}^{-1}$. Like the fiducial case, $R_{\text{max}}$ reaches a constant value after a dynamical time. The final $R_{\text{max}}$ is smaller when $n_0$ is larger. This is expected since larger $n_0$ means a heavier weight of preexisting gas. For a sufficiently small $n_0 \lesssim 10^{-6} \, \text{cm}^{-3}$, $R_{\text{max}} > R_{\text{out}}$, that is, outflows reach farther than the simple energy argument dictates (see Equation 12). This implies that each parcel of outflow does not evolve in isolation, but energy transfers from small radii to large, through, for example, (weak) shocks.\footnote{In fact, if we do not have a sustaining outflow injection, but only allow a few SF events, then $R_{\text{max}} \sim R_{\text{out}}$.} But note that even though $R_{\text{max}}$ can be larger than 200 kpc, i.e., outflows occupy a very large volume, the mass outside $R_{\text{out}}$ is limited. For example, Figure 5 shows that only 40% of the outflow mass is beyond $R_{\text{out}}$.

When $n_0$ is large, $\gtrsim 10^{-5} \, \text{cm}^{-3}$, and $R_{\text{max}} < R_{\text{out}}$. This means that the preexisting gas is sufficiently heavy that outflows are confined by its weight. The thermal pressure of preexisting gas also plays a role in confining outflows, but one can prove that this is minor compared to its weight.

The bottom panel of Figure 8 shows the final $R_{\text{max}}$ (values after reaching plateau) as a function of SFR for different $n_0$. The error bars indicate the standard deviation of $R_{\text{max}}$ over time and polar angles. For a given $n_0$, the final $R_{\text{max}}$ does not depend on SFR. This may seem counterintuitive: the outflow rates of energy and mass scale linearly with SFR, so why do larger fluxes of outflows not have a stronger effect? This is because of radiative cooling. The cooling time is short compared to the dynamical time over which $R_{\text{max}}$ increases. Note that with the loading factors unchanged, the runs with high SFRs, 10 or $50 \, M_\odot \, \text{yr}^{-1}$, probe an unrealistic parameter space, but are important for understanding the evolution of outflows in the halo. In reality, such a high SFR generally means a much larger $\Sigma_{\text{SF}}$; thus, the loading factors would be different.

5.2. Cool Phase Formation and Hot CGM Mass

As in the bottom panel of Figure 5, Figure 9 shows $M_{\text{cool}}/M_{\text{out}}$ as a function of time for runs with various $n_0$ and SFR. Once the cool phase starts to form, its formation rate is roughly equal to that of hot outflow injection rate. This is true...
for all \( n_0 \) and SFR we have tried. For a given \( n_0 \), runs with lower SFRs have later onsets of cool phase formation. This is understandable since it takes longer for the hot CGM to saturate when the mass injection rate is small. For the same SFR, the larger \( n_0 \) is, the earlier the cooling starts. This is because less outflow mass is needed for the saturation of the CGM when there is already some mass in the halo.

Figure 10 shows \( M_h(R < 200 \text{ kpc}) \) for various simulations. When \( n_0 \lesssim 10^{-6} \text{ cm}^{-3} \), the evolution is similar to what we have seen for the fiducial run. \( M_h(R < 200 \text{ kpc}) \) increases initially, until the total mass reaches \( 7-8 \times 10^9 M_\odot \). Then the cooling happens, taking away some mass from the hot atmosphere; after that, \( M_{\text{out},200\text{ kpc}} \) stays at around \( 5 \times 10^9 M_\odot \). Different SFRs only affect the time it takes to reach the maximum mass, but do not affect the value of this mass. For the runs with \( n_0 = 10^{-5} \text{ cm}^{-3} \), the mass remains almost unchanged throughout the simulation, at \( 1.2 \times 10^{10} M_\odot \). This is a factor of two to three larger than the steady state of the hot CGM with \( n_0 \lesssim 10^{-6} \text{ cm}^{-3} \). When

\( n_0 = 10^{-4} \text{ cm}^{-3} \), the outflows barely reach a few kiloparsecs, and the mass of the CGM stays close to the initial condition.

5.3. Universal Density Profile of the Hot Atmosphere

Because the mass of the hot atmosphere reaches a constant value, it is interesting to examine the density profile. In this section, we first use one example run to show the time evolution of the density profile. Then we show that that the density profile up to \( R_{\text{max}} \) is independent of SFR and \( n_0 \). Lastly we quantify the density profile and compare to observational constraints from the MW.

Figure 11 shows the time evolution of the density profile for the run 1e-7SFR3. Since this run has the lowest \( n_0 \), it is easier to see the filling process of the CGM. The density at a certain radius is the spherically averaged value weighted by volume. Overall, the density profile does not change much after \( t \gtrsim 1.5 \text{ Gyr} \). The subtle evolution after that (within a factor of two) is similar to the evolution of the enclosed mass (Figure 10), that is, first an increase, followed by a slight decrease. Large radii (\( R \gtrsim 100 \text{ kpc} \))
reach their maximum density first. The error bar indicates \( n_h \approx (1.1 \pm 0.45) \times 10^{-4} \text{ cm}^{-3} \) at \( R \approx 50 \text{ kpc} \). This is constrained for the MW from the leading arm of the Large Magellanic Cloud (Salem et al. 2015). Our density profile naturally evolves to and stays around this value at \( r > 1.5 \text{ Gyr} \).

Figure 12 shows the radial profiles of density of the hot CGM for various runs. The top panel shows the runs with three different SFRs: 1, 3, and \( 10 M_\odot \text{ yr}^{-1} \), but with the same \( n_0 = 10^{-7} \text{ cm}^{-3} \). The bottom panel shows the runs with different \( n_0 \) but with the same SFR of \( 1 M_\odot \text{ yr}^{-1} \). The snapshot of each run is taken when \((6-7) \times 10^{9} M_\odot \) outflows have been injected into the CGM. We use this criteria for comparison because these outputs are shown slightly after the saturation state is reached (Figure 10), after which point there is little change in the density profile in any run. The vertical dotted lines indicate the final \( R_{\text{max}} \) for each run of the same color. For reference, the run 1e-7SFR1 (magenta line) is shown on both panels.

In the top panel of Figure 12, the resultant density profiles of the three runs look very similar. Since the only difference among the three runs is how fast the mass is being injected into the CGM, the similarity of the results indicates that the density profile does not depend on the mass injection rate (for a given set of loading factors). As long as the same amount of mass of outflows is added, the density profiles are very similar. In the bottom panel, the density profiles are the same up to their respective \( R_{\text{max}} \). The only exception is when \( n_0 \) is extremely large, \( 10^{-4} \text{ cm}^{-3} \), in which case outflows reach only a few kiloparsecs, and the density profile stays at the initial condition. This large density, as shown in a later section, is excluded by X-ray observations.

We plot the power-law profiles \( n \propto R^{-\beta} \) to compare with the universal density profile (i.e., after the saturation is reached). Our density profile can be well approximated by a broken power law with a “knee” at \( R_{\text{out}} \approx 60 \text{ kpc} \), i.e.,

\[
 n_h \approx 9 \times 10^{-5} \text{ cm}^{-3} \left( \frac{R}{R_{\text{out}}} \right)^{-\beta},
\]

where

\[
\beta \approx \begin{cases} 
1.5, & R \leq R_{\text{out}}, \\
3.5, & R_{\text{out}} < R \leq R_{\text{max}}.
\end{cases}
\]

The density profile drops steeply beyond \( R_{\text{out}} \). We show in Appendix C the resolution test for \( n_h \) at a few radii, which has good convergence.

The density profile of hot gas for the MW CGM is well constrained at \( R \lesssim 50-70 \text{ kpc} \) (see recent summaries by Miller & Bregman 2013; Faerman et al. 2017; Bregman et al. 2018).
The density at $R \gtrsim 50–70$ kpc has a power law with an index of $-1.5$, as constrained from the emission measure of O VII (e.g., Henley & Shelton 2013; Miller & Bregman 2015), dispersion measure of pulsars in the Magellanic Clouds (Anderson & Bregman 2010), and absorption lines of O VII and O VIII (Gupta et al. 2012; Fang et al. 2015; Bregman et al. 2018). The density at a radius of 50 kpc, as mentioned before, is inferred to be $(1.1 \pm 0.45) \times 10^{-2}$ cm$^{-3}$ (Salem et al. 2015). Our density profile is in excellent agreement with these constraints. At $R \gtrsim 50–70$ kpc, the constraints are mainly from the inferred pressure of cool phases, which are likely model dependent; different models sometimes give conflicting results (e.g., Stanimirović et al. 2002; Fox et al. 2005; Werk et al. 2014). Theoretical models also differ greatly at these large radii (Maller & Bullock 2004; Faerman et al. 2017, 2020; Fielding et al. 2017; Qu & Bregman 2018; Kauffmann et al. 2019; Stern et al. 2019; Voit 2019; Davies et al. 2020; Huscher et al. 2020).

Our model, having a steep slope at $R > R_{out}$, gives a lower density compared to other models. Future observations of MW-mass halos, such as X-ray emission/absorption from large impact parameters and measurement of the Sunyaev–Zel’dovich effect, are necessary to robustly constrain the outer part of the diffuse CGM.

6. Observational Signatures

In this section, we discuss the observational signatures of the CGM, focusing on the warm-hot/hot ($T > 3 \times 10^4$ K) component. We will show that the observables are closely related to the underlying physical properties of the CGM.

6.1. X-Ray Luminosity

X-ray emission is observed from the “coronae” around disk galaxies, and the luminosity increases with the SF activity in galaxies (e.g., Mineo et al. 2012; Li & Wang 2013). In this subsection, we discuss the X-ray luminosity $L_X$ of the CGM in our simulations, and find that it traces the total amount of diffuse gas in the halo.

Figure 13 shows the evolution of $L_X$ for runs with different $n_0$ and SFR. $L_X$ includes the X-ray emission in the energy range of 0.5–2 keV, for all gas located at $10 \leq R \leq 30$ kpc. Most emission comes from $R \lesssim 30$ kpc where the density is highest; $R < 10$ kpc is excluded due to its proximity to the injection regions and large temporal variations (see Appendix B for details). $L_X$ is calculated using the yt module with the APEC emissivity model.

The evolution of $L_X$ resembles that of $M_b$ in Figure 10. When $n_0$ is small, $\lesssim 10^{-6}$ cm$^{-3}$, $L_X$ first increases, followed by a peak at $t \approx 3–4$ Gyr, and then becomes a constant at several $10^{56}$ erg s$^{-1}$ thereafter. When $n_0 \gtrsim 10^{-5}$ cm$^{-3}$, $L_X$ stays at nearly the initial value throughout the simulation. The observed $L_X$ for MW-sized galaxies with an SFR of 1–3 $M_\odot$ yr$^{-1}$ is $1.5–8 \times 10^{56}$ erg s$^{-1}$ (Mineo et al. 2012; Wang et al. 2016, and references therein), which is shown by the gray shaded region in the plot. $L_X$ settles to the observed value if $n_0 \lesssim 10^{-5}$ cm$^{-3}$; when $n_0 = 10^{-4}$ cm$^{-3}$, $L_X$ is too large to be consistent with the observations. The observed $L_X$ corresponds to $M_b(R < 200$ kpc) $\sim (0.5–1.2) \times 10^{10} M_\odot$. We also show in Appendix C the resolution check for $L_X$, which shows little dependence on the numerical resolution.

In summary, $L_X$ is highly indicative of the evolution of hot diffuse CGM in the halo. The rising curve of $L_X$ corresponds to when the hot atmosphere is being filled. The peak of $L_X$ occurs when the hot atmosphere has the largest mass and becomes saturated. After that, the hot envelope reaches a steady state, where the density profile of the hot atmosphere settles around the critical point of saturation, and $L_X$ remains unchanged. The saturated hot CGM has an $L_X$ that matches the observed value of $L_X$, if $n_0 \lesssim 10^{-5}$ cm$^{-3}$.

The X-ray luminosity only accounts for a few percent of the energy injection rate carried by the hot outflows. This poses the “missing feedback” problem (Wang 2010). We find that, before saturation is reached, the outflow energy is used to push outflows and preexisting gas to large radii, i.e., the energy released from the galaxy converts into potential energy of the CGM. After saturation, most of the outflow energy is radiated away at $T < 2 \times 10^8$ K. The X-ray emission at 0.5–2 keV band is mainly from gas $T \gtrsim 3 \times 10^8$ K, which is the temperature of most of the CGM. The temperature distribution of the CGM will be discussed in the next section.

6.2. Absorption Lines

Observational studies of the CGM have relied heavily on absorption lines against background quasars (e.g., Chen et al. 2010; Steidel et al. 2010; Tumlinson et al. 2011). This is especially useful at large radii, where the emission is too weak to detect due to the low density.

In order to gain physical intuition, we will first show the radial profiles of specific entropy, temperature, and Mach number, and their differences before and after CGM saturation. Then we use the oxygen as an example and show the column density of oxygen at different ionization states, namely O VI, O VII, and O VIII, as a function of impact parameter. We emphasize how the column density distributions of these ions relate to the underlying temperature profile. We make predictions for a few other highly ionized ions, Ne VIII, Ne IX, and Mg X.

6.2.1. Radial Profiles of the CGM

Figure 14 shows the radial profiles of specific entropy, local Mach number, and temperature for the run 1e-SFR3. We use the lowest density run where $R_{max}$ is largest. Simulations with larger $n_0$ have the same profiles up to their $R_{max}$. The snapshot on the left column is at 2 Gyr, prior to the saturated state, and the right column is at 5.5 Gyr, after saturation is reached. The black dashed line in each plot indicates the fountain problem (e.g., Chen et al. 2012; Li & Wang 2013).

Before the saturation state, the radial profile of specific entropy is mostly flat up to $R_{max}$ at $80 \pm 20$ cm$^2$ keV. In other words, the fountain flows have maintained an isentropic atmosphere. Beyond $R_{max}$, the entropy is that of the preexisting gas, which has a value higher than the fountain flow. At $R \lesssim 100$ kpc, there is some low-entropy gas, which is also seen in the temperature profile as gas at about $10^7$ K. This is the gas that has already started to cool, and is the “precursor” of the upcoming cooling event at $t = 3–4$ Gyr. The flat entropy profile means that buoyancy is not at work to suppress the thermal instability in this stratified atmosphere (Field 1965; Balbus & Soker 1989; Binney et al. 2009; Voit et al. 2017).

The middle panel shows the profile of the local Mach number, defined as the velocity of each cell divided by its sound speed. The majority of the gas between 10 and 200 kpc has a Mach number at 0.5–1.2, with a mean value of 0.8. This
indicates that there are considerable motions in the hot CGM. The motions can also serve as “pressure” support of the CGM against gravity.

The bottom panel shows the temperature profile, which decreases with increasing radius. It has a broad range of $7 \times 10^5$–$5 \times 10^6$ K in the inner 20 kpc, and drops to $\lesssim 10^5$ K at $R > 180$ kpc. To understand the decreasing profile of the temperature quantitatively, we first model it as an isentropic gas in quasi-hydrostatic equilibrium with the gravitational potential. There is a simple correlation between temperature and the potential in this case. The main equations are as follows:

(i) a quasi-hydrostatic equilibrium

$$\frac{1}{\rho} \frac{dP_{\text{tot}}}{dr} = -\frac{d\phi}{dr}.$$  

(ii) a constant Mach number $\mathcal{M}$, so that

$$P_{\text{tot}} = P_{\text{th}} + P_{\text{dyn}} = P_{\text{th}}(1 + \mathcal{M}^2),$$

(iii) a constant specific entropy $K$,

$$P_{\text{th}} \rho^{-\gamma} = K,$$

where $\gamma$ is the adiabatic index. Using the above three equations, we have

$$\frac{\gamma(1 + \mathcal{M}^2) k_B}{\gamma - 1} T(r) = -\phi(r) + C,$$  

where $C$ is a constant. This means that the radial profile of the temperature follows that of the potential.

In the bottom panel of Figure 14, we plot the potential $-\phi(r)$ using a black line, with an arbitrary normalization. The temperature follows $-\phi(r)$ up to $R_{\text{out}} \sim 60$ kpc. Beyond that, the temperature drops faster than the potential up to $R_{\text{max}}$.

For an isentropic profile,

$$n \propto T^{\gamma/(\gamma - 1)} \propto \phi^{1/(\gamma - 1)}.$$  

For $R >$ the core radius of the DM (10 kpc in our case), $\phi \propto R^{-1}$; thus, $n \propto R^{-3/2}$ for $\gamma = 5/3$. This is consistent with the universal density profile $n \propto r^{-3/2}$ up to $R_{\text{out}}$ (Figure 12).

The fact that beyond 60 kpc, $T(r)$ deviates from Equation (19) indicates that the above condition (i) quasi-hydrostatic equilibrium is not satisfied (since the other two conditions are true from the simulations). Both density and temperature drop quickly with radius at $[R_{\text{out}}, R_{\text{max}}]$. This radial range seems to be the transitional region between the bulk of the fountain to the low-density IGM space. Interestingly, some cosmological simulations also see a decreasing temperature profile in the halo to various degrees (e.g., Hummels et al. 2013; Kaufmann et al. 2019; Huscher et al. 2020), though the exact reason is not clear.

After the CGM saturates, the profiles of entropy and temperature have interesting shifts compared to the pre-saturation state, as seen in right column of Figure 14. The inner 30 kpc of the entropy profile is flat for the hot phase, at 10–20 cm$^2$ keV. This is the region where the cool phase forms, evidenced by the low-entropy patches on the lower-left part of the diagram. This is consistent with the conjecture of Maller & Bullock (2004), that the cooling instability leaves a constant entropy for the remaining hot atmosphere, and is also seen in cosmological simulations (e.g., Huscher et al. 2020). The flat entropy profile allows future thermal instability to proceed. The
Figure 14. Radial distribution of specific entropy, Mach number, and temperature for the run 1e-7SFR3. The black dashed line in each plot shows $R_{\text{max}}$. The left column is at 2 Gyr, prior to the saturation, and the right column is at 5.5 Gyr, after the saturation. For the left column, the specific entropy and Mach number are radially flat, and the temperature decreases with increasing radii. On the left temperature panel, we plot the gravitational potential $-\phi(r)$ with an arbitrary normalization (black line). The temperature follows $-\phi(r)$ up to $R_{\text{out}} \sim 60$ kpc. For the right column, the specific entropy increases with radius, and the temperature profile is less steep. These are because of the reverse shocks induced by the collision of cool clumps at the center. The Mach number remains flat.

The temperature profile becomes less steep at large radii. The rising profile of entropy and the less steep profile of temperature are due to outward shocks. These are reverse shocks induced by collisions of cool gas after they fall into the center of the halo with velocities of several hundred kilometers per second, as a result of the colliding cool clumps at the center of the halo. In fact, some shock fronts are visible on the temperature profile, e.g., a temperature jump at about 160 kpc. These shocks increase the entropy and temperature at larger radii. Our simulations do not have an ISM to start with, but if one was included, the reverse shock should still be present, since cool CGM gas falling at several hundred kilometers per second...
would collide with the ISM in the galaxy and induce strong reverse shocks into the CGM.

The radial profile of the Mach number, on the other hand, only shows minor changes over time. The majority of the gas has \( M = 0.6 \pm 0.3 \) after the condensation, in comparison to \( 0.9 \pm 0.3 \) before the condensation. The motions are maintained by the constant injection of the energy from outflows. The high-Mach number (\( \gtrsim \frac{1}{4} \)) patches at \( R \lesssim 30 \) kpc are from the cool clumps falling toward the galaxy ballistically.

While Figure 14 shows two representative snapshots, we note that there is little time evolution of the profiles in the time windows of \( 1\,\text{--}\,3.5 \) Gyr (after the outflows reach \( R_{\text{max}} \) and before the saturation) and \( \gtrsim 4.5 \) Gyr (after the reverse shocks propagate through the CGM), respectively. The temperature of the medium determines the ionization state of ions when the ionization is caused by collision. The temperature decreases radially, meaning that ions are at progressively lower ionization states at larger radii. We now discuss column densities of \( \text{OVI} \), \( \text{O VII} \), and \( \text{O VIII} \), and connect them to the underlying physical properties of the CGM, i.e., the radial profiles discussed above.

### 6.2.2. \( \text{OVI} \)

When calculating the column densities, we assume a number density ratio \( \text{O/H} = 4.9 \times 10^{-4} \) for the solar metallicity (Asplund et al. 2009). Note that there is a factor of two for the uncertainty of the ion abundances. An additional but smaller uncertainty comes from our model input of the ISM metallicity, which is \( 0.8Z_{\odot} \), though this value evolves across cosmic time. In this paper we also assume collisional ionization equilibrium (CIE), and use the ionization table from Mazzotta et al. (1998). We recognize that nonequilibrium effects and photoionization can leave the ionization states different from what CIE dictates, particularly in low-density regions (e.g., Breitschwerdt & Schmutzler 1994; Oppenheimer & Schaye 2013; Corlies & Schiminovich 2016; Stern et al. 2018). But since the cosmic ionizing background is redshift dependent (e.g., Haardt & Madau 2012), has great uncertainties (Kollmeier et al. 2014; Shull et al. 2015), and can also be stochastic (e.g., Oppenheimer et al. 2018b), we postpone the inclusion of these effects to future work. While presenting results under CIE, we will estimate the possible effects when relevant, which are generally small except for at large radii. In the plots, we mark the radius at which the density is below \( 10^{-3.5} \) cm\(^{-3} \), where these effects can be important.

Figure 15 shows the column densities \( N \) of \( \text{OVI} \), \( \text{O VII} \), and \( \text{O VIII} \) as a function of impact parameter \( d \) from the galaxy, viewed from outside the halo. The points are from randomly selected sight lines. Due to the spherical nature of the fountain, the viewing angle does not make a difference. The snapshot is taken at 2.5 Gyr for the run 1e-7SFR3. We choose 2.5 Gyr because it is shortly before saturation of the halo (which occurs at \( \sim 3.5 \) Gyr). However, the difference between the unsaturated state and saturated one is only significant for \( \text{OVI} \), which we will discuss in Figure 16.

\( N (\text{OVI}) \) is flat at \( d \lesssim 120 \) kpc and drops sharply beyond that. The Cosmic Origins Spectrograph (COS)-Halos survey has observed \( \text{OVI} \) around MW-mass galaxies (log \( M_\odot/M_{\odot} \approx 9.5\,\text{--}\,11 \)) at redshifts \( = 0.1\,\text{--}\,0.36 \), out to \( d \sim 150 \) kpc (Tumlinson et al. 2011). The detection rate around star-forming galaxies is very high, in contrast to quiescent galaxies. The observed range of \( N (\text{OVI}) \approx 10^{14.2\,\text{--}\,15.1} \) cm\(^{-2} \) is marked by the shaded region in the top panel of Figure 15 (Tumlinson et al. 2011). The eCGM...
Figure 16. Evolution of $N$ (O VI) at impact parameter 50 < $d$ < 150 kpc for the run 1e-7SFR3. The solid line and the error bars indicate the mean and standard deviation, respectively, of $N$ (O VI) from different sight lines. The gray shaded region indicates the Cosmic Origins Spectrograph (COS)-Halos observations at redshifts 0.1–0.36 (a few gigayears in look-back time; Tumlinson et al. 2011), whereas the pink shaded region indicates the observed $N$ (O VI) from the MW halo (Sembach et al. 2003). Our simulation reproduces this evolution.

The Astrophysical Journal, 898:148 (23pp), 2020 August 1

Li & Tonnesen

The calculation includes sight lines at 50 < $d$ < 150 kpc, which covers galaxy masses of log $M_\star/M_\odot$ ~ 9–11, extended to much larger $d$, and found that beyond about 160–200 kpc, $N$ (O VI) is much smaller with only upper limits (Johnson et al. 2015). Our results show remarkable agreement with these observations.

We can gain insight into O VI observations by examining the physics of O VI–bearing gas in our simulations. O VI exists in a very narrow range of temperature $10^{5.5} \pm 0.1$ K. Given our temperature profile, the O VI–bearing gas is located in a shell at $R = 100–150$ kpc. This relatively low-temperature shell forms as the hot outflows expand in the gravitational potential. Gas at $R = 100–150$ kpc has a low density of about $10^{-5}$ cm$^{-3}$ (Figure 12). This means that the O VI–bearing gas has a long cooling time of $\approx 5$ Gyr. Therefore, the O VI shell is a relatively long-lasting structure, in contrast to the common assumption that O VI–bearing gas is cooling rapidly (e.g., Heckman et al. 2002; Faerman et al. 2017).

Indeed, we find the $N$ (O VI) remains at the state in Figure 15 for about 3 Gyr, until after the cooling begins. Figure 16 shows the mean $N$ (O VI) as a function of time. The error bars indicate the standard deviation of $N$ (O VI) from different sight lines. The calculation includes sight lines at 50 < $d$ < 150 kpc; the inner 50 kpc is excluded because after cool clumps form, there is O VI cospatial with the cool gas (which exists in the inner 50 kpc). Some of the O VI comes from the interface between the cool phase and hot surroundings and is not well resolved in the simulations; thus, we do not consider O VI at $R < 50$ kpc as predictive results. The mean $N$ (O VI) reaches above $10^{14}$ cm$^{-3}$ at $t \approx 0.8$ Gyr, when $R \gtrsim 100$ kpc is filled to $10^{-5}$ cm$^{-3}$ (Figure 11). It lasts until $t \approx 4$ Gyr, after which the mean $N$ (O VI) decreases by a factor of a few to $10^{13.5–13.9}$ cm$^{-3}$. The decrease is because of the reverse shock, which happens after cool clumps fall to the center, heat the outer CGM (right panel of Figure 14).

The gray shaded region in Figure 16 again indicates the COS-Halos observations (Tumlinson et al. 2011), whereas the pink shaded region indicates the observed $N$ (O VI) from the MW halo (Sembach et al. 2003). For the MW, we use the column density from the O VI category with no cool gas counterpart (Table 3 of Sembach et al. 2003), because O VI can also arise from the interface between the cool gas and the hot gas. The shaded regions indicate upper limits since these are values of $N$ (O VI) for detected sight lines. In addition, because the sight lines originate from within the galaxies, the column densities would be approximately half compared to the sight lines from outside the halo passing through the center. We therefore multiply the observed $N$ (O VI) of MW by a factor of two for a fairer comparison with the the COS-Halos results (this, of course, assumes that the O VI distribution is spherically symmetric). In general, sight lines from the galaxy can only be compared to external sight lines, which also pass through the galaxy. But since the COS-Halos reveals a flat $N$ (O VI) as a function of the impact parameter, it makes little difference whether sight lines pass through the halo center or not. Overall, the COS-Halos observations, which are at redshifts 0.1–0.36, i.e., a few gigayears in look-back time, have an $N$ (O VI) a factor of a few larger than the MW values. If indeed there is such a time evolution of O VI column density for the MW, our simulation interestingly reflects this evolution.

Including photoionization from the cosmic ionizing background would not change our results significantly. Gas at $10^{5.5}$ K has a density of about $10^{-5}$ cm$^{-3}$, which means the photons can lower the fraction of O VI at this temperature (e.g., Faerman et al. 2020); but at the same time, gas at lower temperatures will have a non-negligible fraction of O VI. Using the ratio of O VII due to photoionization versus collisional ionization from Faerman et al. (2020, their Figure 5), we estimate that including photoionization would change the results by no more than a factor of two. Another effect that can contribute to the O VI fraction is a dynamical nonequilibrium effect: since the $10^{5.5}$ K gas comes from the expansion of hotter outflows, the ions can be frozen at higher ionization states for a recombination timescale. The radiative recombination timescale for O VII at $10^{−5}$ cm$^{-3}$ is $\approx 1$ Gyr, smaller by factor of a few than the “lifetime” of O VI in our simulation. So this nonequilibrium effect would not change the results significantly.

So far we have discussed the example case of 1e-7SFR3. We now address how the input parameters of SFR and $n_0$ affect $N$ (O VI) and its evolution. When the SFR is lower, the pre-saturation O VI shell lasts longer, since it takes more time for the condensation and reverse shock to happen. On the other hand, if the SFR is even larger, the pre-saturation O VI shell would last for too brief a time. If the initial density is large, $n_0 > 10^{-6}$ cm$^{-3}$, hot outflows will not reach $R > 100$ kpc (Figure 8), and thus the CGM beyond $R_{\text{max}}$ has a temperature of $10^9$ K as the initial condition. Therefore the temperature at all radii is $>10^{5–6}$ K, and $N$ (O VI) does not exceed $10^{14}$ cm$^{-3}$. So to have $N$ (O VI) $10^{14}$ cm$^{-3}$ as the COS-Halos survey indicates, one needs a relatively small $n_0 \lesssim 10^{-6}$ cm$^{-3}$ and an SFR $\lesssim 3 M_\odot$ yr$^{-1}$.

We caution that O VI may occur at different types of locations. One is the large-scale volume-filling gas. This is the case for our O VI shell. The others are generally in thin layers, such as interfaces between the hot ($\gtrsim 10^6$ K) and cool ($\lesssim 10^4$ K) gas due to mixing and/or thermal conduction (e.g., Gnat et al. 2010; Kwak & Shelton 2010; Li et al. 2017b; Ji et al. 2019), or cooling of hot gas that passes the intermediate
temperature (e.g., Heckman et al. 2002). While the latter cases usually occur on small scales associated with (the formation of) cool gas, the first scenario can be a large-scale feature independent of the cool clumps. To be clear, O VI shown in this paper is from the volume-filling $10^{5.5}$ K gas. The small-scale O VI should exist in nature but cannot be robustly quantified from our macroscopic simulations, since the interface is not resolved.

From recent cosmological simulations, O VI production is sensitive to the feedback prescription used (e.g., Hummels et al. 2013; Nelson et al. 2018). $N$(O VI) for the halos of MW-like galaxies is generally under-produced compared to the COS-Halos survey by a factor of two to three (Hummels et al. 2013; Gutcke et al. 2017; Suresh et al. 2017; Oppenheimer et al. 2018a). These simulations also show considerable variations of the radial profile of $N$(O VI), ranging from a centrally peaked configuration (Suresh et al. 2017; Nelson et al. 2018) to a flatter profile (Ford et al. 2016; Gutcke et al. 2017; Oppenheimer et al. 2018a). We note that Oppenheimer et al. (2018a) find that, in EAGLE simulations, $N$(O VI) in the MW-like halos mainly comes from warm-hot gas at large radii, similar to our results.

6.2.3. O VII and O VIII

In this subsection, we focus on the higher ionization states of oxygen, O VII, and O VIII. Their column densities as a function of the impact parameter are shown in the lower two panels of Figure 15. $N$(O VII) declines with increasing $d$; at $d > 100$ kpc, the decline becomes much steeper. Because O VII exists for a broad temperature range of $10^{5.5}$–$10^{5.5}$ K, O VII–bearing gas actually fills the volume at $R \approx 100$ kpc. The decline at $d > 100$ kpc is mainly due to the decline of density with increasing radius. In contrast, O VIII only exists at small radii below tens of kiloparsecs since it requires the largest temperature at $10^{6.2}$–$6.7$ K.

O VII and the O VIII absorption lines are detected thus far only for the MW (from many sight lines), and we show the observed values using the error bars in Figure 15 (Gupta et al. 2012; Fang et al. 2015). Since we show the simulation results using sight lines from outside of the halo, the same as for O VI, we apply a factor of two increase of the observed range to account for the location of observers from inside the MW. For O VIII, we use the column densities given in Faerman et al. (2017), which were converted from the equivalent width reported in Gupta et al. (2012). For external galaxies, only upper limits are available for $N$(O VII) and $N$(O VIII) from X-ray stacking (Yao et al. 2010) at large impact parameters, which are shown by the arrows in the figure. Our results show excellent agreement with these observational constraints.

For the time evolution, both $N$(O VII) and $N$(O VIII) change little with time, unlike O VI. This is because they are from higher-temperature gas, which is located in the inner halo, where the temperature profile does not change much over time. For the same reason, $N$(O VII) and $N$(O VIII) distributions are not sensitive to SFR nor to $n_0$ (except when $n_0$ is very large $\geq 10^{-4}$ cm$^{-3}$, in which cases outflows barely get into the CGM). Also, including photoionization will have a very minor effect on $N$(O VII) and $N$(O VIII) since the gas has higher densities.

We comment briefly on the velocities of the gas that bears O VI, VII, and VIII, which are reflected in the nonthermal broadening of absorption lines. We have found a flat radial profile of Mach number of $0.8 \pm 0.3$, which only shows a slight decline over several gigayears, so we will use these numbers as a simple estimate for the velocities. For O VI, a Mach number of 0.8 and a temperature of $10^{5.5}$ K gives a 3D velocity of $52$ km s$^{-1}$. This is consistent with the observed nonthermal broadening of $\approx 40$–$50$ km s$^{-1}$ found in COS-Halos surveys (Werk et al. 2016). For O VII and O VIII, there are no observational constraints on the line widths yet. We therefore predict them to be $110 \pm 20$ km s$^{-1}$ and $180 \pm 30$ km s$^{-1}$, respectively. With future X-ray missions such as Athena, Lynx, and HUBS, which have unprecedented spectral resolution at the electronvolt level, the motions of the hot gas can be constrained. Note that we do not have CGM rotation in our modeling, which can contribute to the velocities as well (Hodges-Kluck et al. 2016).

Finally, we checked that the numerical resolution does not change the results for the column densities of O VI, VII, or VIII, since they are all well-resolved structures (see Appendix C). This is, however, generally not true for O VI located at the interface between hot and cool phases, which is not resolved.

The above observables, $L_X$, column densities of O VI, O VII, and O VIII are the currently available observational constraints for the (warm-hot) CGM of MW-like galaxies. Before we move on to predictions for future observations, we would like to first summarize how these observables place constraints on our model inputs, i.e., $n_0$ and SFR (we do not regard the loading factors of outflows as free parameters since they are taken from small-box simulations). First we note that the initial conditions cannot simultaneously match all four constraints. In particular, $N$(O VI) is significantly under-produced since all of the halo gas is at $10^6$ K. It is then not surprising that $N$(O VI), among the four observables, puts the tightest constraints on the model inputs. Successfully reproducing $N$(O VI) requires $n_0 \lesssim 10^{-6}$ cm$^{-3}$ and SFR $\lesssim 3 M_\odot$ yr$^{-1}$, whereas reproducing $L_X$, $N$(O VII), and $N$(O VIII) only requires the initial $n_0 \lesssim 10^{-5}$ cm$^{-3}$. The small initial density $n_0 \lesssim 10^{-6}$ cm$^{-3}$ implies a tenuous halo as an initial condition ($\lesssim 1\%$ of the cosmic baryons are in the halo). How such a condition can be satisfied and its implications for the MW formation will be discussed in Section 7. Also note that in the runs that yield a CGM matching all four constraints, the observables come from gas at $R < R_{\text{max}}$, that is, within the outflow-turned-fountain region, rather than from the outer layer, which remains the initial condition. This means that these observables are the model outputs rather than inputs.

6.2.4. Ne VIII, Ne IX, and Mg X

We show predictions for various ions in the warm-hot regime, Ne VIII, Ne IX, and Mg X, for which data has begun to be collected and will be plentiful with future X-ray and UV telescopes (Tripp et al. 2011; Meiring et al. 2013; Qu & Bregman 2016; Burchett et al. 2019; Das et al. 2019). A further motivation is that recent analytic models for the MW CGM by Voit (2019) and Faerman et al. (2020) produce the observed $N$(O VI), $N$(O VII), and $N$(O VIII) and $L_X$, with similar underpinnings of a radially decreasing temperature profile to our simulation results. Their separate quantitative assumptions accounting for such a temperature profile are a bit different; Voit (2019) assume the CGM is in the precipitation limit (with
additional local temperature fluctuations), whereas Faerman et al. (2020) assume an isentropic CGM. Nevertheless, we all find that ions with higher ionization states are more concentrated in the center, and that O VI exists mainly at large radii. They both make predictions for \( N(\text{Ne VIII}) \), and Faerman et al. (2020) also include \( N(\text{Mg X}) \). So for a more robust comparison, we do the same exercise.

We use the chemical abundances in Asplund et al. (2009) and the CIE table for ion fractions from Mazzotta et al. (1998). Figure 17 shows column densities of these ions. Consistent with what we have found for oxygen, Ne IX is more concentrated in the center than Ne VIII; Mg X has the highest ionization temperature and is the most centrally concentrated of the three. Also, similar to O VII and O VIII, the time evolution of the column density distributions are insignificant since they all come from the inner CGM. Notably, Das et al. (2019) recently reported a detection of Ne IX in the MW halo, with \( N(\text{Ne IX}) = 9.3^{+4.7}_{-3.0} \times 10^{15} \text{ cm}^{-2} \). At the smallest impact parameter, our result is consistent with this detection.

Our predictions for \( N(\text{Ne VIII}) \) and \( N(\text{Mg X}) \) agree well with Faerman et al. (2020) at \( d \lesssim 75 \text{kpc} \). Our \( N(\text{Ne VIII}) \) also agrees with the values at \( d = 50 \text{kpc} \) predicted in Voit (2019). This corroborates the similarities of our radially decreasing temperature profiles in the inner halo. Differences exist at large radii, which is mainly because they have a larger density than ours at large radii, and also because Faerman et al. (2020) includes photoionization effects. We will discuss the comparisons in more detail in Section 7.

7. Discussion

In this Section, we discuss the implications of our results, possible effects of missing pieces, and comparisons to other work.

7.1. Sensitivity to Variations of Loading Factors

In this paper, we use a specific set of loading factors of mass, energy, and metals for hot outflows. Different modeling of small-box simulations sometimes leads to different results. How would the CGM change if we used a different set of loading factors from small-box simulations?

First, we point out that from the small-box simulations, the three loading factors of hot outflows are tightly correlated (Li & Bryan 2020). Note that the simulations compiled by Li & Bryan (2020) use different numerical codes, and detailed physics included are not the same, either. Nevertheless, consistent results emerge. Specifically,

\[
\frac{\eta_{E,h}}{\eta_{m,h}} \sim 0.8^{\pm 0.2} \frac{\Sigma_{\text{SF}}}{\Sigma_{\text{Z},h}}, \quad \frac{\eta_{E,h}}{\eta_{Z,h}} \sim 0.5, \tag{21}
\]

where \( \Sigma_{\text{SF}} \) is in units of \( M_\odot \text{ yr}^{-1} \text{kpc}^{-2} \). These correlations hold for over four orders of magnitude in \( \Sigma_{\text{SF}} \). The tight correlation indicates that for simulations that have modeled similar SF conditions but obtained different loading factors, the three loading factors differ by a constant factor. For example, Kim & Ostriker (2018) modeled the solar neighborhood condition, and have \( \eta_{m,h} = 0.18, \eta_{E,h} = 0.044, \) and \( \eta_{Z,h} = 0.078 (\eta_{Z,h} \text{ is from C.}-G. \text{ Kim et al. 2020, in preparation, 2020 private communication}). \) These loading factors are lower than what we use in this paper by factors of 5.6, 6.8, and 6.4, respectively. Since the outflow fluxes scale with SFR times the loading factors, adopting their loading factors is essentially similar to using our loading factors but with an SFR six times lower. From Section 5.3, we see that this would make the filling of the CGM slower by a factor of six, but does not make a qualitative difference on the CGM properties.

Cosmic rays can also help launch galactic outflows. Recent simulations show that cosmic rays can significantly change the phase structure of the ISM and outflows, driving outflows that are predominately in the cool phase and are at lower speeds than the SNe-driven hot outflows (Simpson et al. 2016; Girichidis et al. 2018). That said, the studies of cosmic rays are still at early stages, and many questions and issues need to be addressed. For example, the ability of cosmic rays to drive outflows depends sensitively on the detailed physics/parameters, such as transport mechanism, diffusion coefficient, etc. (Salem & Bryan 2014; Wiener et al. 2017; Farber et al. 2018), which have large uncertainties. Notably, including cosmic rays generally leads to an ISM and outflows that are short of hot gas, which is unsupported by X-ray observations (Peters et al. 2015). Hence, while we acknowledge that cosmic rays may play a role in affecting loading factors of outflows, their true impacts remain to be understood and quantified.

7.2. Missing Baryon Problem

Most of the cosmic baryons are not in galaxies (e.g., Fukugita et al. 1998; Bell et al. 2003; Guo et al. 2010; Moster et al. 2010). For the MW, if assuming the baryon to DM ratio is the cosmic value, the baryonic mass within a \( 10^{12} M_\odot \) halo is around \( 1.5 \times 10^{11} M_\odot \).

Roughly half of this baryonic mass does not reside in the MW or its satellite galaxies. These missing baryons are likely to be in the CGM and/or IGM with a temperature of \( 10^{5–7} \text{K} \), which cannot be observed very easily (Bregman 2007; Shull et al. 2012; Nicastro et al. 2018; de Graaff et al. 2019). The

\[^{6}\text{For those curious about a factor of six difference, this is mainly because of the different SN scale heights adopted, which have little observational constraints. A larger scale height leads to more SNe exploding above the ISM layer and thus larger loading factors of hot outflows. See Li et al. (2017a) and Kim & Ostriker (2018) for more detailed discussions.} \]
The Astrophysical Journal, 898:148 (23pp), 2020 August 1

Li & Tonnesen

7.3. Missing Metals Problem

Besides the missing baryon problem, there is also the missing metals problem. Most metals do not reside in galaxies (Ferrara et al. 2005; Bouček et al. 2007; Peeples et al. 2014; Telford et al. 2019). Peeples et al. (2014) estimated that only 30% of metals ever produced are in galaxies in a mass range of $10^{10.5} M_\odot$. Like the missing baryon problem, the metals missing from galaxies are very likely in the CGM and/or IGM.

We first show that the metals associated with the CGM in our simulations are small compared to the missing metals. Figure 18 shows the total metal mass in the hot CGM, $M_{Z, \text{hot}}$. Metals from the preexisting gas in the halo are excluded. In other words, we only count metals from the hot atmosphere formed out of the SNe-driven outflows. The evolution of $M_{Z, \text{hot}}$ is very similar to that of $M_h$. That is, the mass first increases and then reaches a plateau once the CGM is saturated. The final $M_{Z, \text{hot}}$, $(0.6-1.4) \times 10^8 M_\odot$, depends little on $\eta_0$ or SFR. Observationally, the mass of metals in MW-mass galaxies is around $6 \times 10^4 M_\odot$, while the total metals ever produced are about $2 \times 10^8 M_\odot$ (Peeples et al. 2014; but note that there is at least a factor of two uncertainty related to the metal yield and the value of the solar metallicity). Our atmosphere thus does not contain a significant fraction of the missing metals.

The maximum metal mass due to saturation in our simulations is for the late stage of the MW evolution, i.e., when the SF surface density is low and outflows are gravitationally bound by the halo. Metals that are still missing are likely carried away by galactic winds that are strong enough to leave the DM halo. The unbound winds can arise from earlier phases of galaxy formation, when the star formation and feedback are more intense (e.g., Pettini et al. 2001; Bouček et al. 2007; Oppenheimer et al. 2010; Steidel et al. 2010; Cen & Chisari 2011; Keller et al. 2015; Rudie et al. 2019). Metal-enriched winds are also necessary to explain the observed metals in the IGM (e.g., Songaila & Cowie 1996; Ellison et al. 2000). In other words, we view the formation of the MW CGM as a two-step process: an early stage with unbound winds and a late stage with fountain flows, separated by the intensity of SF. With this picture in mind, the metals retained in the CGM only come from the later stage modeled here when outflows remain bound to the halo.

We will discuss the case of unbound winds in detail in a separate paper, but here we present a crude estimate of the total energy released by an MW-like galaxy in the form of SNe-driven hot outflows over cosmic time. From this estimation, the energy is sufficiently large to push metals out of the halo and suppress cosmic accretion, which will leave a low-density halo. This low-density halo would then be the initial conditions for our current simulation.

The estimation utilizes a tight correlation, found from small-box simulations, between the energy and metal loading factor for the hot outflows, $\eta_{E, h}/Z_{h} \sim 0.5$ (Li & Bryan 2020). This means that the missing metals from galaxies can be used to estimate the energy associated with these metals. For the MW, 30% of metals residing in galaxies means that $\eta_{Z, h} \sim 0.7$ over cosmic time, which gives $\eta_{E, h} \sim 0.35$ from the above equation. The total amount of energy associated with these missing metals is then

$$E_{\text{out}} = 2.1 \times 10^{59} \text{ erg} \left( \frac{\eta_e}{0.35} \right) \left( \frac{N_{\text{SN}}}{10^9} \right) \left( \frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right) \left( \frac{\alpha}{0.6} \right),$$

where $N_{\text{SN}}$ is the total number of SNe exploded over the lifetime of the galaxy, and $\alpha$ is the fraction of hot outflows that have $v_{\text{h}, l} > v_{\text{esc}}$ over cosmic time. (If $v_{\text{h}, l} < v_{\text{esc}}$, the amount of metals retained in the CGM is not very large, as is the case in this paper.) The value of $\alpha$ is uncertain. Since $\phi \sim 2 \times 10^{15}$ erg g$^{-1}$ for the MW halo (from the galaxy to $R \sim 250$ kpc), this means that $M \sim E_{\text{out}}/\phi \sim 5.5 \times 10^{10} M_\odot$ mass can be expelled out of the halo. The available energy from outflows is sufficient to keep the majority of the missing baryons, together with the missing metals, outside of the DM halo. Note that this is a conservative estimate since the galaxy potential is shallower in the past, and not all baryons fall to the center of the potential.

7.4. Cosmic Inflows

Cosmic inflows are not modeled explicitly in our simulations. Gas can come into the halo in two forms: hot, nearly spherical accretion (Rees & Ostriker 1977; Silk 1977), and cool, filamentary inflows along cosmic webs (e.g., Birnboim & Dekel 2003; Kereš et al. 2005). The former is more important in massive halos and at low redshifts, which is the case for the
MW in the recent past. In our simulations, the preexisting gas exerts weight on the outflows, mimicking the effects of the hot-mode accretion to some extent. Future work will include modeling this hot-mode accretion explicitly (e.g., Fielding et al. 2018). That said, we want to point out that hot outflows, when powerful enough, can suppress the spherical inflows (e.g., Somerville & Davé 2015; Zinger et al. 2020). As discussed in the previous subsection, based on the current metal mass in the halo, at early times, outflows were so strong that they drove gas into the IGM. The low \( n_0 \) required in our simulations to reproduce the observed CGM properties, especially \( L_X \) and \( N (\text{O VI}) \), does imply that suppression of inflows happened in the past (unless significant mass is ejected in the form of a low volume-filling cold phase).

We thus conjecture that the “assembly” of the hot halo around the MW is a two-step process: first the strong hot outflows have left a halo with a relatively low mean density, \( \lesssim 10^{-3} \text{ cm}^{-3} \), and for the more recent past, less powerful hot outflows have led to the formation of a fountain atmosphere. Note that the strong outflows with \( v_{\text{rel}} > v_{\text{esc}} \) do not necessarily need a very large SFR; a mild SFR in the inner part of the galaxy where the gravitational field is large can also lead to a strong outflow (Li et al. 2017a; Armillotta et al. 2019). The switch could have happened a few gigayears ago, as the thin disk of the MW is formed from the inside out (e.g., Bovy et al. 2016; Goddard et al. 2017; Telford et al. 2019).

On the other hand, hot outflows cannot suppress the cold-mode accretion as efficiently. Observationally, cool CGM exists at both inner and outer parts of the halo, and has a wide range of metallicities (e.g., Lehner et al. 2013; Prochaska et al. 2017). The latter may point to different formation channels of cool CGM. In our simulations, cool gas only forms in the inner halo and has a large metallicity; it does not form at larger radii because the cooling time there is very long. The observed cool CGM that has a low metallicity or exists at large radii can be related to the cold-mode accretion and/or the stripping of satellite galaxies (e.g., Afruni et al. 2019; Hafen et al. 2020; Hummels et al. 2019). Indeed, the similarity of cool CGM around star-forming and quiescent galaxies at large radii (e.g., Chen et al. 2010; Tumlinson et al. 2013; Lan et al. 2014) may indeed point to this cool gas relating to the cosmic accretion, rather than to feedback.

### 7.5. Comparison to Other Work

There are two recent analytic works by Faerman et al. (2020) and Voit (2019) that have radially decreasing temperature profiles, broadly consistent with our simulation results. Both models reproduce the observed \( \text{O VI} \) and \( L_X \) of the MW. And their predicted \( \text{Ne VIII} \) and \( \text{Mg X} \) are very similar to ours (except at large radii where photoionization would make a difference). Here we comment on the comparisons between their models and our simulation. One difference is that while they assume a steady-state CGM, our simulations have time evolution. One key assumption Faerman et al. (2020) made is that the atmosphere is isentropic. In our dynamic model, it is naturally the case within \( R_{\text{max}} \) before saturation; after saturation, the CGM starts to deviate from isentropic. The evolution of \( N \) (\( \text{O VI} \)) reflects this transition. Their model is tuned so that \( N \) (\( \text{O VII} \)) and \( N \) (\( \text{O VIII} \)) match the observations, whereas our simulations self-consistently produce the observed \( N \) (\( \text{O VII} \)) and \( N \) (\( \text{O VIII} \)). Voit (2019) presents a precipitation-limited model of the CGM by assuming \( t_{\text{cool}}/t_{\text{freefall}} = 10-20 \) and hydrostatic equilibrium for all radii. In our simulations, the precipitation limit is reached, but only in the inner halo \( R \lesssim 50 \text{ kpc} \). Beyond that, the ratio \( t_{\text{cool}}/t_{\text{freefall}} \) is larger than 20 throughout, i.e., the outer halo never reaches the precipitation limit. Similar results are seen in simulations by Fielding et al. (2017).

In terms of the hot CGM mass, our results are very similar at \( R \lesssim 60 \text{ kpc} \), which is \( (2-4) \times 10^9 M_\odot \) (this is also well constrained from observations, see Section 5.3). The difference is more obvious at large radii: our mass within 200 kpc is \( 0.5-1.2 \times 10^{10} M_\odot \), compared to their mass of \( 3 \times 10^{10} M_\odot \). This is mainly because the density in our simulation drops quickly with radius due to the confinement of outflows by gravity. By assuming nonthermal pressure support (Faerman et al. 2020), or a precipitation limit (Voit 2019), their density profile drops slower than ours at \( R \gtrsim 60 \text{ kpc} \).

Cosmological simulations have the advantage of modeling the CGM with cosmic inflows and satellite galaxies orbiting within the halo (e.g., Stinson et al. 2012; Ford et al. 2014; Oppenheimer et al. 2018a; Grand et al. 2019). These processes can contribute to the cool CGM phases, especially at large radii, which we do not cover. That said, recent cosmological simulations with enhanced numerical resolution in the CGM region show that the properties of the cool CGM do not converge (Hummels et al. 2019; Peeples et al. 2019; Suresh et al. 2019; van de Voort et al. 2019). In addition, cosmological simulations use ad hoc models for feedback, which likely do not generate outflows with the same properties as ours; thus, the thermal, dynamical, and chemical states of the CGM/IGM would be different, since CGM is sensitive to the feedback schemes and strengths (e.g., Nelson et al. 2018; Davies et al. 2020). A comparison study between idealized simulations and cosmological ones is underway (D. Fielding et al. 2020, in preparation). Since the CGM is where cosmic inflows interact with galactic outflows, a predictive model of the CGM needs both a robust feedback model and a cosmological context. Future endeavors should combine realistic small-scale feedback physics together with a cosmological ab initio condition. Recent zoom-in simulations like Feedback in Realistic Environments are approaching this goal for small galaxies (Hopkins et al. 2013; Muratov et al. 2017).

### 8. Conclusions

From small-box simulations, the hot phase of SNe-driven outflows is found to be the dominating phase, which carries the majority of outflow energy and metals, and can travel much further than the cooler phases. In this paper, we investigate how the hot outflows emerging from an MW-like galaxy (in terms of gravitational potential and star formation) evolve on large scales. The loading factors of hot outflows are taken from small-box simulations for the current SF surface density of the MW. From the loading factors, the specific energy of the hot outflows is not sufficient for them to escape from the halo. Indeed, a large-scale fountain is formed. Our main findings are as follows:

1. The hot SNe-driven outflows form a metal-enriched, warm-hot atmosphere in the halo, with fountain motions. The maximum radius the outflows reach, \( R_{\text{max}} \), can be larger than the radius from a simple energy argument \( R_{\text{out}} \) (defined in Equation (12)), indicating that outflows from different SF episodes do not evolve in isolation.
2. For a given set of loading factors, $R_{\text{max}}$ is smaller when there is more preexisting gas; however, $R_{\text{max}}$ does not depend on the rate at which the outflows are injected (Figure 8).

3. As more mass accumulates in the halo, the inner CGM is saturated, i.e., the mass of hot gas reaches a maximum. This steady state is maintained because cool clumps condense out of the hot atmosphere and fall toward the galaxy ballistically (Figure 7). This is a natural way of forming the highly enriched “high-velocity” clouds.

4. After the saturation is reached, the condensation of cool gas balances the hot outflow injection (Figure 10).

5. The balance leads to a universal density profile up to $R_{\text{max}}$, which has a break at $R_{\text{out}}$ (Figure 12). This universal density profile does not depend on the SFR.

6. The hot CGM has a radially decreasing temperature profile, due to the expansion of hot outflows (Figure 14). Together with the density profile, several important CGM observables are naturally reproduced, including the X-ray luminosity and column densities of OVI, O VII, and O VIII, assuming CIE (Figures 13, 15, and 16).

7. The collisionally ionized O VI is located in a shell at 100–150 kpc, which cools inefficiently. The formation of an O VI shell requires a small mean density of preexisting gas $n_0 \lesssim 10^{-6}$ cm$^{-3}$, which allows $R_{\text{max}} \gtrsim 100$ kpc.

8. Saturation determines the maximum masses of baryon and metals in the hot atmosphere, which are about $(0.5-1.2) \times 10^{10} M_\odot$ and $(0.6-1.4) \times 10^{9} M_\odot$, respectively. These are not significant amounts compared to the “missing baryons” and “missing metals.” We conjecture that the missing metals reside at even larger radii and were ejected from an unbound galactic wind at earlier epochs of galaxy formation.

The CGM is known to be complex and likely many processes are ongoing, but we hope to better understand it by starting with fewer assumptions and by isolating the number of processes involved. Our simulations have simple inputs: hot outflows and hot preexisting halo gas. The resultant CGM is multiphase: a hot atmosphere ($>10^6$ K), a warm-hot shell ($\sim10^5$ K) from the expansion of hot outflows, and cool clumps ($\sim10^4$ K) precipitating due to the condensation of the hot atmosphere. Despite its simplicity, the CGM reproduces many aspects of observations. We also make predictions for intermediate and high ions such as Ne VIII, Ne IX, and Mg X, which can be compared against future observations. Finally, feedback from supermassive black holes can also impact the CGM, as evidenced by the Fermi bubble (Su et al. 2010). It will be interesting to investigate in future how black holes and SNe together affect the CGM.

We thank the referee for the comments provided for this paper. M.L. thanks the insightful discussions with many colleagues, including Chris McKee, Crystal Martin, Cameron Hummels, Daniel Wang, Eve Ostriker, Yuan Li, Greg Bryan, Mark Voit, Taotao Fang, Mary Putman, Josh Peek, Jason Tumlinson, Joel Bregman, Yakov Faerman, Smita Mathur, Drummond Fielding, Filippo Fraternali, and Amiel Sternberg. Computations were performed using the publicly available Enzo code, which is the product of a collaborative effort of many independent scientists from numerous institutions around the world. Their commitment to open science has helped make this work possible. Data analysis and visualization are partly done using the yt project (Turk et al. 2011). The simulations are performed on the Rusty cluster of the Simons Foundation. We thank the Scientific Computing Core of the Simons Foundation for their technical support.

Appendix A
Outflow Rate

To check that the outflow rates agree with our inputs from the small-box simulations (Li et al. 2017a), we run a test of 1e-6SFR3 with cooling turned off, and show the outflow rates of mass and energy (including kinetic and thermal forms) as a function of radius in Figure A1. The expected rates at the inner boundary are $3 M_\odot$ yr$^{-1}$ and $9 \times 10^{48}$ erg yr$^{-1}$, respectively, which are taken from the small-box simulations. The simulation shows good agreement. Time variations are expected since injections are discrete events. The mass outflow rate is flat and then drops at the turn-around radius of 130 kpc. The energy outflow rate declines gradually with radius as a fraction of gas energy is converted into gravitational energy.

Figure A1. Mass outflow rate (left panel) and total energy outflow rate (right) as a function of radius, for a test run of 1e-6SFR3 with cooling turned off. This is to show that the injection rates of mass and energy are as expected, which are $3 M_\odot$ yr$^{-1}$ and $9 \times 10^{48}$ erg yr$^{-1}$, respectively, at the inner boundary.
Appendix B
X-Ray Luminosity

In Figure B1, we show the radial dependence of the X-ray luminosity. This illustrates why we choose $10 < R < 30 \text{kpc}$ as the region to calculate the X-ray luminosity $L_X$ in Figure 13. The left panel shows that most X-ray emission comes from $R < 30 \text{kpc}$. The right panel shows $L_X (0 < R < 30 \text{kpc})$ as thin lines and $L_X (10 < R < 30 \text{kpc})$ as thick lines. $L_X (0 < R < 30 \text{kpc})$ is biased toward higher luminosity because of the temporal sampling of data outputs: the time interval of data output (every 10 Myr) is close to that of the outflow injection (every 9.9 Myr); therefore, more snapshots are taken immediately after the outflow injection, when $L_X$ is higher compared to the time-averaged mean, which we deem as the "true value." In contrast, $L_X (10 < R < 30 \text{kpc})$ is less than the true value due to the exclusion of the inner region. In other words, the true time-averaged $L_X$ should be in between these two lines. But since the two curves are closer than the observation scatter (gray shaded region), we use the latter as a proxy in the paper given its smoother feature.

Appendix C
Resolution Test

We verify that our results are robust for the run 1e-6SFR3 because it shows strong agreement with observations. Figure C1 shows the resolution comparison for the masses of the cool and hot gas in the simulation box. The general agreement is very good. The largest difference is when the cool gas begins to form, around 3–4.5 Gyr. The normal-resolution run has an earlier onset of cooling. This is expected since the the higher-resolution run, with eight times more cells, samples a broader distribution of cooling time. After that the agreement is good. Other properties of the CGM, such as $R_{\text{max}}$, the radial profiles of density, temperature, entropy, and observables such as the column densities of different ions, show little change with resolution.

We show other quantities for the resolution check in Figure C2. The quantities, except $N(\text{O VI})$ in panel (e), are calculated by averaging over $t = 3–8 \text{Gyr}$, after the CGM reaches the saturated state, and these quantities show quasi-steady values. As we show in Figure 16, $N(\text{O VI})$ has two evolutionary states, with a higher value before the reverse shocks heat the outer radii than after. We therefore check the resolution effect on $N(\text{O VI})$ at these two states, respectively. The error bars show the standard deviation of the temporal variations for $n_0$ and $L_X$, while showing that of the temporal and sight-line variations for $R_{\text{max}}, N(\text{O VI}), N(\text{O VII}),$ and $N(\text{O VIII})$. From the figure, a factor of two change in resolution leads to little difference on these quantities. This is not surprising since these quantities come from well-resolved gas structure in the simulation.

Figure B1. Left panel: spherically enclosed X-ray luminosity as a function of radius for 1e-6SFR1. Most emissions come from the inner 30 kpc (dashed line). Right panel: X-ray luminosity at $0 < R < 30 \text{kpc}$ (thin line) and at $10 < R < 30 \text{kpc}$ (thick line).

Figure C1. Resolution check of mass of hot and cool gas in the simulation box as a function of time. The run for comparison is 1e-6SFR3. The top panel shows the mass, where the solid lines represent the fiducial resolution, and the dashed lines are for the run with a resolution coarser by a factor of two. The bottom panel shows the mass ratio between the fiducial run and the low-resolution one. The fiducial run has a slightly earlier onset of cooling, but the overall agreement is good after that.
Figure C2. Resolution checks for 1e-6SF3R. The same as for the previous figure, “normal” is for the fiducial run, and “lr” indicates the run with a resolution two times coarser. Panel (a) $R_{\text{max}}$, panel (b) mean number density of hot gas at a few radii, panel (c) X-ray luminosity $L_X$, panel (d) column density of O VI from sight lines with impact parameters $50 < d < 100$ kpc, and panel (e) column density of O VII and O VIII from sight lines going through the center of the box. The quantities shown in panels (a)–(c) and (e) are averaged over $t = 3$–8 Gyr, after the saturation state of the CGM is reached and the system enters a quasi-steady state. For N(O VI), we show the comparison for the two stages: before saturation (2–3 Gyr), and after saturation (4–5 Gyr). The error bars indicate the standard deviation of the temporal variations for panels (b) and (c), while showing the temporal and sight-line variations for panels (a), (d), and (e). All quantities show little changes with respect to the resolution.

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Li & Tonnesen
