GAS ACCRETION IS DOMINATED BY WARM IONIZED GAS IN MILKY WAY MASS GALAXIES AT $z \sim 0$

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ABSTRACT

We perform high-resolution hydrodynamic simulations of a Milky Way mass galaxy in a fully cosmological setting using the adaptive mesh refinement code, Enzo, and study the kinematics of gas in the simulated galactic halo. We find that the gas inflow occurs mostly along filamentary structures in the halo. The warm-hot (10^5 K < T < 10^8 K) and hot (T > 10^8 K) ionized gases are found to dominate the overall mass accretion in the system (with $M = 3-5 M_\odot$ yr$^{-1}$) over a large range of distances, extending from the virial radius to the vicinity of the disk. Most of the infalling gas (by mass) does not cool, and the small fraction that manages to cool does so primarily close to the galaxy ($R \lesssim 100$ kpc, with more pronounced cooling at smaller $R$), perhaps comprising the neutral gas that may be detectable as, e.g., high-velocity clouds. The neutral clouds are embedded within larger, accreting filamentary flows, and represent only a small fraction of the total mass inflow rate. The inflowing gas has relatively lower metallicity ($Z/Z_\odot < 0.2$). The outer layers of the filamentary inflows are heated due to compression as they approach the disk. In addition to the inflow, we find high-velocity, metal-enriched outflows of hot gas driven by supernova feedback. Our results are consistent with observations of halo gas at low $z$.

Key words: galaxies: evolution – galaxies: kinematics and dynamics – Galaxy: halo – methods: numerical

Online-only material: color figures

1. INTRODUCTION

Chemical evolution models and analysis of the color–magnitude diagram of the Hipparcos data set indicate that the Milky Way has been forming stars at a nearly constant, yet slowly declining, rate of 1–3 $M_\odot$ yr$^{-1}$ over the past several gigayears (Hernandez et al. 2000; Chiappini et al. 2001, 2003; Fuchs et al. 2009; Chomiuk & Povich 2011). In addition, a continuous supply of low-metallicity gas coming in at a slightly lower rate is needed to account for the metallicity of the long-lived Galactic stars (the G-dwarf problem; see Tosi 1996 for a review). The source of this fuel has been the subject of decades of research (see Putman et al. 2012b for a review).

High-velocity clouds (HVCs) detected in H$\alpha$ surveys have long been suspected as the source of the star formation fueling spiral galaxies often show a very limited amount of H$\alpha$ gas in their halos (Sancisi et al. 2008; Heald et al. 2011), again suggesting the H$\alpha$ reservoir in halos may not be the dominant fueling source.

Recently there have been suggestions that extraplanar ionized gas may be responsible for maintaining star formation in the Milky Way (Lehner & Howk 2011; Putman et al. 2012a), as well as in other galaxies at intermediate and low redshifts (Bauermeister et al. 2010). Hydrodynamic simulations that model the mixing and recollision of cold clouds at the disk–halo interface (Heitsch & Putman 2009) and the H$\alpha$ emission along the Magellanic Stream (Bland-Hawthorn et al. 2007) also pointed out the potential significance of the influx of warm ionized gas. When combining these results with other findings of substantial amounts of ionized gas in the halos of star-forming galaxies at higher redshifts (Tumlinson et al. 2011; Tripp et al. 2011), it is evident that a self-consistent dynamical model is necessary to connect galaxy fueling mechanisms with the various observational constraints.

On the theoretical front, recent advances have led to an important modification to our understanding of how gas accretion occurs in galaxies. The classical picture posited that the incoming gas would spherically collapse and be shock-heated close to the virial temperature of pressure-supported gas within a galaxy’s halo (Rees & Ostriker 1977; White & Rees 1978; White & Frenk 1991), which is called the “hot-mode” gas accretion. Analytic arguments (Birnboim & Dekel 2003; Dekel & Birnboim 2006; Binney 1977) and smoothed particle hydrodynamic (SPH) simulations (e.g., Katz et al. 2003; Kereš et al. 2005, 2009; Dekel & Birnboim 2006; Ocvirk et al. 2008; Brooks et al. 2009; Agertz et al. 2009; Stewart et al. 2011; van de Voort & Schaye 2012), on the other hand, have shown that some of the gas will never be shock-heated to the virial temperature of the halo and be accreted via a “cold mode,” because a virial shock fails to develop if the gas cooling time is shorter than the local compression time. In this case, the gas can penetrate far inside the halo virial radius without being heated. The cold mode is found to dominate in galaxies at high redshift ($z \gtrsim 2$), as well as in present-day low-mass galaxies ($M_{\text{halo}} \lesssim 5 \times 10^{11} M_\odot$). The Milky Way has a halo mass that is only slightly above this transition mass (Kalberla et al. 2007; Xue et al. 2008; Reid et al. 2009).

In this paper, we describe a high-resolution cosmological simulation of a Milky Way mass disk galaxy using an adaptive mesh refinement (AMR) code and present its key features in terms of the thermal and kinematic distribution of gas in such a halo. We study the detailed way gas accretes in “hot-mode” systems with halo masses not much higher than the transition mass. Classically, such systems were assumed to accrete via smooth, shocking mode. We investigate, for the first time
with high-resolution cosmological simulations, the kinematics and thermal history of the accreting gas as it makes its way to the near-disk region. The high-mass resolution ($m_{DM}$ and $m_a \approx 10^5 M_\odot$) and spatial resolution (136–272 pc physical or better at all times) employed in the simulation allow us to study and track the spatial and kinematical distribution of the multiphase gas in the halo (e.g., White & Frenk 1991; Fardal et al. 2001; Maller & Bullock 2004) in great detail. Our result indicates that, while the morphology of the accreting gas is filamentary, similar to that of the cold-mode accretion, the gas accretion is dominated by warm-hot ionized gas. We describe the simulation in Section 2. The results are presented in Section 3, with the emphasis placed on identifying the gas components responsible for inflow onto the galaxy. Finally, we examine the evolution of the gas in filamentary flows in the simulation and present a new scenario for gas accretion onto Milky Way sized galaxies in Section 4.

2. METHOD

We perform simulations with Enzo, an Eulerian hydrodynamics code with AMR capability (Bryan 1999; Norman & Bryan 1999; O’Shea et al. 2005). It solves the Euler equations using one of the two following schemes: the piecewise-parabolic method (Colella & Woodward 1984) or the solver used in Zeus (Stone & Norman 1992) to handle compressible flows with shocks; we used the latter primarily for numerical stability.

First, we ran a low-resolution simulation with a periodic box of $L = 25 h^{-1}$ Mpc comoving on a side with cosmological parameters consistent with WMAP5: $(\Omega_m, \Omega_{\Lambda}, \Omega_b, h, \sigma_8, n_s) = (0.279, 0.721, 0.046, 0.70, 0.82, 0.96)$. We identified Local-Group-like volumes by using criteria based on the halo mass (mass range $1–2 \times 10^{12} M_\odot$), the mean density (0.60–1.0 times the mean density of the universe), and the relatively low velocity dispersion of the halos ($<200$ km s$^{-1}$) identified within $5 h^{-1}$ Mpc of a given galaxy. We identified four such halos. Then we performed a resimulation for one of the four halos using the multimass initialization technique with four nested levels (five including the root grid), achieving $m_{DM} = 1.7 \times 10^5 M_\odot$, within a ($\sim 5 h^{-1}$ Mpc)$^3$ subvolume. The selected galaxy has a halo mass of $1.4 \times 10^{12} M_\odot$ at $z = 0$ and so contains over 8.2 million dark matter particles within the virial radius. With a maximum of 10 levels of refinement, the maximum spatial resolution stays at 136–272 pc physical or better at all times.

The simulation includes metallicity-dependent cooling extended down to 10 K (Dalgarno & McCray 1972), metagalactic UV background, shielding of UV radiation by neutral hydrogen, and a diffuse form of photoelectric heating (Abbott 1982; Joung et al. 2009). The code simultaneously solves a complex chemical network involving multiple species (e.g., H i, He ii, H2, H i, He ii, He iii, e$^-$) and metal densities explicitly.

Star formation and stellar feedback, with a minimum initial star particle mass of $m_s = 1.0 \times 10^4 M_\odot$, are also included. Star particles are created in cells that satisfy the following two criteria: $\rho > \rho_{SF}$ and a violation of the Truelove criterion (Truelove et al. 1997). The star formation efficiency (i.e., the fraction of gaseous mass converted to stars per dynamical time) is 0.03 (e.g., Krumholz & Tan 2007). Supernova feedback is modeled following Cen et al. (2005), with the fraction of the stellar rest-mass energy returned to the gas as thermal energy, $\epsilon_{SN} = 10^{-5}$, consistent with the Chabrier (2003) initial mass function. The metal yield from stars, assumed to be 0.025, represents metal production from supernovae of both Type Ia and Type II. Feedback energy and ejected metals are distributed into 27 local cells centered at the star particle in question, weighted by the specific volume of the cell. The temporal release of metal-enriched gas and thermal energy at time $t$ has the following form: $f(t, t_i, t_r) = (1/t_i)(t - t_i)/t_r \exp[-(t - t_i)/t_r]$, where $t_i$ is the formation time of a given star particle, and $t_r = m(t_{dyn}, 3 \times 10^5$ yr) where $t_{dyn} = \sqrt{3\pi/(32G\rho_{gas})}$ is the dynamical time of the gas from which the star particle formed. The metal enrichment inside galaxies and in the intergalactic medium (IGM) is followed self-consistently in a spatially resolved fashion.

3. RESULTS

We extracted a spherical volume from the simulation output that extends to the galaxy’s virial radius (250 kpc) at a uniform spatial resolution of 1.09 kpc cell$^{-1}$. In order to examine finer structures, the volume inside 20 kpc in radius was extracted at a higher resolution of 0.272 kpc cell$^{-1}$, the maximum spatial resolution of the simulation, and this replaced the inner volume of the larger sphere. In order to focus on gas accretion in the halo, the cylindrical region defined by $|R| \leq 18$ kpc and $|z| \leq 2$ kpc whose symmetry axis coincides with the rotation axis of the simulated disk was removed from this analysis. Hence, the resulting quantities reflect the properties of the halo region only. We report on our analysis of the simulation result at $z = 0$, unless otherwise specified. The evolution of H i gas in the halo at low redshifts ($z \leq 0.5$) was studied in detail by Fernández et al. (2012).

We find that 70% of the mass influx is concentrated in $\sim 17\%$ of the surface area over a large range of radii. This implies that the gas inflow occurs along continuous, filamentary structures. Figure 1 shows the radial mass influx of gas, projected along the y-axis of the simulation box. It demonstrates that the mass influx is concentrated along filamentary structures in the halo, some of which extend over 100 kpc in length. Before computing the radial gas accretion rate, the mass-weighted mean velocity of all gas within the virial radius was subtracted from all the cells. We find three main filaments of warm gas that feed the galaxy. Further details on the spatial and kinematic properties of these warm filamentary flows will be reported in a forthcoming paper.

3.1. Gas Inflow Velocities

We examine the distribution of radial velocities of the halo gas. The systemic velocity of the galaxy, i.e., the center-of-mass velocity of the dense ($n \geq 0.1$ cm$^{-3}$) cells in the disk, was subtracted from all cells, to focus on the relative motion of the halo gas with respect to the galaxy itself.

Figure 2 displays the radial velocity distribution of gas in various temperature ranges. It shows the curves representing the amount of mass per unit velocity interval in three different temperature ranges, plotted against the radial velocity. The three temperature ranges were selected to be cold ($T < 10^5$ K, blue), representative of H i and Hx emission and Ly$\alpha$ and Mg ii absorbers; warm-hot ($10^5$ K $< T < 10^6$ K, yellow), representative of C iv and O vii absorbers; and hot ($T > 10^6$ K, red), representative of higher level ions such as O viii and O viii as well as X-ray emission. These definitions are used in Figures 3 and 4 as well. The gas associated with the hot component has densities that are usually too low to be detected in current observations,

$^2$ For ease of analysis, we first simplify the data structure by transforming the AMR hierarchy in a given volume into a grid of cells with uniform spatial resolution, a process that we call “extraction.”
except for the region close to the disk. The black curve is the sum of the three solid curves mentioned above.

The warm-hot gas dominates the mass over almost the entire range of radial velocities. Although the hot gas occupies a significant volume fraction, it does not dominate the mass because of the low densities. The only exception is at the highest radial velocities ($v_r \gtrsim 300$ km s$^{-1}$), where the hot outflowing gas contributes $\sim 10^8 M_\odot$.

The gray histogram in Figure 2 shows the amount of cold gas contained within 10 kpc of the four gas-rich satellites identified within the virial radius of the simulated host halo (see below for more details). We picked the radius of 10 kpc because it is at least 40% (and up to 100%) of the virial radii of the satellite subhalos, and so the bulk of the cold gas should reside within this volume, unless it was previously ejected or stripped away (see Fernández et al. 2012). Three of the four satellites have $|v_r| > 100$ km s$^{-1}$, suggesting that at least part of the cold gas with extreme velocities must be associated with gas contained within or stripped recently from the satellite galaxies.

The mean radial velocity increases with gas temperature from more negative to less negative velocities. We find that the cold gas has more negative inflow velocities (the mass-weighted mean radial velocity $\langle v_r \rangle = -82$ km s$^{-1}$) than the warm-hot and hot gases ($\langle v_r \rangle = -41$ and $-16$ km s$^{-1}$, respectively). These values are marked by vertical lines at the top of the figure. The inflowing velocities of cold gas are consistent with observations of HVCs, although we leave the details of the neutral gas structure, projection effects from the position and velocity of the Sun, and obscuration by Galactic disk gas to future work. Note that the radial velocities alone do not tell us which phase is primarily responsible for the gas inflow; we must examine the mass flux in the radial direction to answer that.

### 3.2. Mass Accretion Rate

Figure 3 shows the mass accretion rate of gas as a function of the galactocentric distance. To calculate the mass accretion rate in thin spherical shells centered on the galaxy, we used a formula from Peek et al. (2008):

$$\dot{M}(R) = \sum_{i=1}^{n(R)} \frac{M_i \cdot V_i \cdot (-\hat{r}_i)}{dR},$$

(1)
respectively, and are shown by vertical lines at the top of the plot.

Three of the four satellites have \( |v_r| > 100 \text{ km s}^{-1} \). The warm-hot gas dominates the mass over almost the entire range of radial velocities, except at the highest values (i.e., \( v_r \gtrsim 300 \text{ km s}^{-1} \)), where the hot outflowing gas contributes most significantly with \( \sim 10^6 \text{ M}_\odot \) of mass. The mass-weighted mean radial velocities are \(-82\), \(-41\), and \(-16 \text{ km s}^{-1}\) for the cold, warm-hot, and hot components, respectively, and are shown by vertical lines at the top of the plot.

(A color version of this figure is available in the online journal.)

where \( M_i \) is the gas mass in the \( i \)th cell in a given spherical shell, \( V_i \) is the velocity vector of that cell, \( r_i \) is the radial unit vector, and \( dR \) is the thickness of the spherical shell. Note that this formula gives the mass accretion rate for gas contained in each spherical shell in units of \( \text{M}_\odot \text{ yr}^{-1} \).

Plotted in Figure 3 are the net (i.e., inflow minus outflow) mass accretion rates of all gas (a), of the metals (b), and of the neutral and ionized hydrogen (c). In each panel, the mass accretion rates were divided into the three temperature ranges defined in Section 3.1: cold (blue), warm-hot (yellow), and hot (red).

The net mass accretion rate, \( 3-5 \text{ M}_\odot \text{ yr}^{-1} \), at all radii is comparable to the SFR of the simulated galaxy at \( z \approx 0 \) (\( \sim 5 \text{ M}_\odot \text{ yr}^{-1} \)), and is sufficient to support its current SFR.

The fluctuation in the mass accretion rate is expected from the clumpy and stochastic nature of the accreting mechanisms. The amount of neutral gas mass increases at small distances from the galaxy (Figure 3(c); see also Figure 1 in Fernández et al. 2012), implying some cooling and condensation of gas close to the disk due to increased background pressure.

The primary result of this paper is shown in Figures 3(a) and (c) displaying the mass accretion rates; the overall gas accretion is dominated by warm-hot ionized gas, rather than cold neutral gas, at almost all radii. The bottom panel (Figure 3(c)), which shows the accretion rate of hydrogen gas, demonstrates that the ionized gas is responsible for most of the mass influx with \( dM_{\text{HI}}/dt \sim 2-4 \text{ M}_\odot \text{ yr}^{-1} \), while the neutral gas accounts for only \( 0.1-0.3 \text{ M}_\odot \text{ yr}^{-1} \) (excluding satellites). This is due, in part, to the fact that the filamentary flows responsible for roughly half of the neutral gas in the halo (Fernández et al. 2012) are associated with temperatures between \( 10^4 \) and \( 10^{5.5} \text{ K} \) and are mostly ionized. Closer to the disk (\( R \lesssim 100 \text{ kpc} \)), warm-hot gas is gradually heated, and the accretion of hot gas becomes increasingly important (but see the caveat in Section 4).

The four sharp features in the H\textsc{i} accretion rate at \( R \approx 63, 78, 188 \), and \( 243 \text{ kpc} \) correspond to the four gas-rich satellites (with \( N_{\text{HI}} \gtrsim 10^{16} \text{ cm}^{-2} \)) found within the virial radius at \( z = 0 \). The negative values correspond to those satellites moving away from the galaxy. The feature peaked at \( R \approx 13.5 \text{ kpc} \) is also associated with one of the four satellite galaxies, although in this case the bulk of its mass may come from condensation of gas stripped from the satellite galaxy, which is at \( R = 78 \text{ kpc} \) and moving away from the host galaxy at \( z = 0 \) (“S19” in Fernández et al. 2012).

### Figure 2

Mass contained in unit velocity interval as a function of the radial velocity of gas in three different temperature ranges, as described in the text, at \( z = 0 \): cold (\( T < 10^4 \text{ K} \); blue), warm-hot (\( 10^4 \text{ K} < T < 10^6 \text{ K} \); yellow), and hot (\( T > 10^5 \text{ K} \); red). Positive (negative) velocities correspond to outflows (inflows).

The black solid line is the sum of the three solid curves in color, while the gray solid line indicates the amount of cold gas contained within 10 kpc of the four gas-rich satellites identified within the virial radius of the simulated host halo. The fluctuation in the mass accretion rate is expected from the filamentary flows responsible for roughly half of the neutral gas in the halo (Fernández et al. 2012). The primary result of this paper is shown in Figures 3(a) and (c) displaying the mass accretion rates; the overall gas accretion is dominated by warm-hot ionized gas, rather than cold neutral gas, at almost all radii. The bottom panel (Figure 3(c)), which shows the accretion rate of hydrogen gas, demonstrates that the ionized gas is responsible for most of the mass influx with \( dM_{\text{HI}}/dt \sim 2-4 \text{ M}_\odot \text{ yr}^{-1} \), while the neutral gas accounts for only \( 0.1-0.3 \text{ M}_\odot \text{ yr}^{-1} \) (excluding satellites). This is due, in part, to the fact that the filamentary flows responsible for roughly half of the neutral gas in the halo (Fernández et al. 2012) are associated with temperatures between \( 10^4 \) and \( 10^{5.5} \text{ K} \) and are mostly ionized. Closer to the disk (\( R \lesssim 100 \text{ kpc} \)), warm-hot gas is gradually heated, and the accretion of hot gas becomes increasingly important (but see the caveat in Section 4).

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The low-metallicity gas dominates the inflow in all the phases. Panel (c) shows the temperature distribution of the inflowing gas in each of these metallicity bins. To display the temperature distribution of the inflowing/outflowing gas, the curves are further divided into three temperature bins using the same colors as in, e.g., Figure 3(a). The figure demonstrates that it is the low-metallicity gas at the rate of \( \frac{\Delta M}{\Delta t} \approx 10^{-4} \) \( \text{M}_\odot \text{yr}^{-1} \).

To address this question, we plot in Figure 5 the cooling time (blue) and compression time (red) as a function of the galactocentric radius, for the inflowing hot-mode gas (upper curves) and cold-mode gas only (lower curves). To compute the mean timescales, the inverse of the appropriate time was weighted by the thermal energy density \( T \) in each cell and summed over all inflowing \( \left( v_\parallel \lesssim 0 \right) \) cells in a given spherical shell. For the hot-mode gas, the mean cooling time is longer than the compression time \( t_{\text{cool}} > t_{\text{comp}} \), leading to net heating. For the cold-mode gas, on the other hand, the mean cooling time is shorter than the compression time \( t_{\text{cool}} < t_{\text{comp}} \), resulting in net cooling; note that the difference between the two times increases at small radii. If the same plot is made for all inflowing gas (bottom panel), the two timescales are nearly equal (within a factor of \( \sim 2 \)) over the entire range in radius. Overall, excluding the sites of gas associated with the satellites, the heating should slightly dominate over cooling. The timescales in the top panel are reproduced in light gray in the bottom panel.

This and other \( \text{H} \) features close to the disk may indicate cooling of the inflowing halo gas at the disk–halo interface. We will investigate this issue in more detail in the future, focusing in this paper on properties at \( R > 20 \) kpc. Note that the UV radiation from young stars in the disk, which is not included in the simulation, may photoionize some of the neutral gas in the halo. Hence, our calculated \( \text{H} \) mass is an upper limit.

In Figure 4, each panel corresponds to one of the three metallicity ranges: (a) low \( (Z/Z_\odot \lesssim 0.2) \), (b) intermediate \( (0.2 < Z/Z_\odot \lesssim 0.5) \), and (c) high \( (Z/Z_\odot > 0.5) \). The black solid curves in the three panels represent the accretion rate of gas in each of these metallicity bins. To display the temperature distribution of the inflowing/outflowing gas, the curves are further divided into three temperature bins using the same colors as in, e.g., Figure 3(a). The bottom panel shows a clear gas outflow of high-metallicity gas at the rate of \( \sim 1 \) \( \text{M}_\odot \text{yr}^{-1} \).

The temperature of the outflowing gas decreases gradually from hot at small radii to warm-hot at larger radii (top panel). What is the source of the gas that dominates the inflow at different radii? According to Figure 3(a), the component that dominates the gas accretion changes gradually from cold to warm-hot (at \( R \approx 240 \) kpc) and then from warm-hot to hot (at \( R \approx 50 \) kpc), as the distance decreases. What is responsible for the gradual heating of the inflowing gas?

We showed that the overall gas accretion is dominated by warm-hot ionized gas rather than cold neutral gas in Milky Way sized galaxies at low redshifts. According to Figure 3(a), the component that dominates the gas accretion changes gradually from cold to warm-hot (at \( R \approx 240 \) kpc) and then from warm-hot to hot (at \( R \approx 50 \) kpc), as the distance decreases. What is responsible for the gradual heating of the inflowing gas?

The temperature of the outflowing gas decreases gradually from hot at small radii to warm-hot at larger radii (top panel), presumably due to adiabatic expansion. The metals are carried in hot outflowing gas, as predicted by previous theoretical work (e.g., Mac Low et al. 1989; Strickland & Stevens 2000; Marcolini et al. 2005). This result is consistent with observations finding highly metal-enriched hot gas in the X-ray (e.g., Strickland & Heckman 2007) and in the ultraviolet (e.g., Tripp et al. 2011). Note that the metals have a net outflow rate at almost all radii, although the total gas accretion rate always indicates a net inflow.

4. DISCUSSION

We showed that the overall gas accretion is dominated by warm-hot ionized gas rather than cold neutral gas in Milky Way sized galaxies at low redshifts. According to Figure 3(a), the component that dominates the gas accretion changes gradually from cold to warm-hot (at \( R \approx 240 \) kpc) and then from warm-hot to hot (at \( R \approx 50 \) kpc), as the distance decreases. What is responsible for the gradual heating of the inflowing gas?

To address this question, we plot in Figure 5 the cooling time and compression time versus radius for the “hot-mode” gas (Figure 5, upper curves) and “cold-mode” gas (lower curves),
which are hereafter defined as gas with $T > 10^{5.5}$ K and with $T \lesssim 10^{5.5}$ K, respectively. This is similar to the definition in Keres et al. (2005). To compute the mean timescales, the inverse of the appropriate time was weighted by the thermal energy density $(3/2)nkT$ in each cell and summed over all inflowing $(v_r < 0)$ cells in a given spherical shell. In computing the cooling time, the diffuse photoelectric heating rate was also accounted for.

For the hot-mode inflowing gas, the cooling time (blue) is longer than the compression time (red) at all radii, which suggests that heating dominates over cooling for this component. On the other hand, if we repeat the same calculation for the cold-mode gas, the cooling time is shorter than the compression time at all radii, leading to net cooling and condensation of the densest parts of the inflowing streams, especially at small radii ($R \lesssim 100$ kpc). If we make the same plot for all inflowing gas (bottom panel), the two timescales are nearly equal (within a factor of $\sim 2$) over the entire range in radius, excluding the sites of gas associated with the satellites. Overall, the compression time is shorter than the cooling time, so heating should slightly dominate over cooling.

As the gas flows in, its kinetic energy gets slowly converted to thermal energy due to many weak compressions. The energetics work out since $v_r \approx 100$ km s$^{-1}$ would correspond to $\sim 10^6$ K in gas temperature. The result is consistent with the trend in Figure 2, i.e., the mean inflow velocity decreases as the gas temperature increases. We note that Faucher-Giguère et al. (2011) computed the net cold gas accretion rate based on their SPH simulations (in their work, “cold” and “hot” were defined by gas temperatures at a given snapshot, instead of the maximum temperature reached before accretion onto galaxies). For Milky Way-sized halos at $z = 0$, their Figure 3 shows that only a small fraction ($\lesssim 1/10$) of the cold gas entering the virial radius ($R_{\text{vir}}$) stays cold at $0.2R_{\text{vir}}$, which is consistent with our finding that the accreting gas is gradually heated inside $R_{\text{vir}}$. Murante et al. (2012) also presented a figure from their SPH simulation in which the fractional accretion of the hot gas increases significantly going from $R_{\text{vir}}$ to $0.1R_{\text{vir}}$.

The entropy stays constant unless the gas is shocked, radiatively cooled, or mixed with gas with different entropy. Figure 6 shows the distribution of specific entropy, $s \equiv T\rho^{\gamma-1}$, where $\gamma$ is the adiabatic index, as a function of radius, weighted by gas mass (left panel) and mass flux (right panel). (Although the correct term for $s$ is “adiabat,” we refer to it as entropy following common convention.) This shows that the mean entropy is fairly flat with radius, increasing by only a factor of two from 20 to 250 kpc. In the right panel, blue and red represent inflowing and outflowing fluxes, respectively. The white contour represents zero net mass flux, and the dashed curve shows the mean mass-weighted entropy computed from the left panel. The inflowing gas (blue region in the left panel) has systematically lower entropy than typical gas at that same radius, by a factor of 2–5 at $R \gtrsim 100$ kpc, which is less than the critical cloud overdensity required for cooling (Joung et al. 2012). Note the “beard” in the lower left corners of both panels; they represent the cooling gas in the innermost regions inside the filamentary flows at $R \lesssim 100$ kpc. (A color version of this figure is available in the online journal.)

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Figure 6. Contours showing the distribution of gas mass (left) and the mass flux (right) in arbitrary units in the specific entropy vs. distance plane. The mean entropy is fairly flat with radius, increasing by only a factor of two from 20 to 250 kpc. In the right panel, blue and red represent inflowing and outflowing fluxes, respectively. The white contour represents zero net mass flux, and the dashed curve shows the mean mass-weighted entropy computed from the left panel. The inflowing gas (blue region in the right panel) has systematically lower entropy than typical gas at that same radius, by a factor of 2–5 at $R \gtrsim 100$ kpc, which is less than the critical cloud overdensity required for cooling (Joung et al. 2012). Note the “beard” in the lower left corners of both panels; they represent the cooling gas in the innermost regions inside the filamentary flows at $R \lesssim 100$ kpc.

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\[^5\] In Kereš et al. (2005), the hot-mode accretion and cold-mode accretion were defined based on the maximum temperature attained by a given gas particle. As we cannot follow the history of gas particles in a grid-based code, in order to define the two modes, we use the temperature at a given time slice instead of the maximum temperature. For this reason, the mass of the hot-mode gas that we compute is a lower limit. In particular, some fraction of the gas with $T \lesssim 10^{5.5}$ K at large radii will likely be heated further and so should really count as hot-mode gas. On the other hand, we believe that the distinction between the two modes at small radii ($R \lesssim 100$ kpc) is robust. Also, note that the definitions for the cold-mode and hot-mode gas are to be distinguished from those for the cold, warm-hot, and hot gas in Section 3.
individual cells by the mass influx at a given distance, we find that this cooling gas accounts for only the bottom ~10% of the mass influx. The cooling gas corresponds to the gas located in the central regions of the filaments, which have the highest densities and lowest temperatures—hence the lowest entropies at a given radius. These H\,i clouds, filamentary in shape, correspond to the H\,i features shown close to the disk in Figure 4 of Fernández et al. (2012), and are responsible for the H\,i features at $R < 100$ kpc in Figure 3(c).

The rest of the inflowing gas, with higher specific entropy, has nearly constant entropy as it flows in; in fact, there appears to be a gradual increase in the entropy due to mixing or weak shocks. The temperature of this gas increases as it approaches the disk and is compressed. It might seem surprising that the gas temperature increases as the filaments flow in; however, it is consistent with Figure 5, which shows that the cooling time of the inflowing warm-hot gas is longer than the compression time for the hot-mode gas. This is also a natural consequence of the inflowing gas having nearly constant entropy (since for constant entropy, $T \propto P^{2/5}$, where $P$ denotes the thermal pressure of gas). See Figure 8 of Putman et al. (2012b) for a schematic diagram depicting the thermal evolution of gas in filaments.

Our result is consistent with previous work (e.g., Kereš et al. 2005, 2009; Dekel & Birnboim 2006) that found the broad idea that hot-mode accretion dominates the overall gas accretion in Milky Way mass halos at low $z$. However, the inflowing filamentary gas is not strongly shocked and has lower temperatures than the rest of the halo gas.

The observed neutral gas clouds are only the tip of a much larger “iceberg”: H\,i clouds represent the small densest parts of filamentary flows that are made up of mostly ionized gas, in which they are embedded. Neutral gas accounts for a significant but not a dominant fraction (~1/10) of the accretion rate required to explain the current Galactic SFR. This is comparable to the recent estimate of ~0.1 M\odot yr$^{-1}$ from all the HVC complexes (Putman et al. 2012b). Note that the outer envelope with intermediate velocities will dynamically “shield” the H\,i clouds from the (nearly static) ambient medium and decrease the relative velocity, increasing the Kelvin–Helmholtz growth time and hence the cloud lifetimes. Figure 4, which shows the mass accretion rate broken down by temperature for each metallicity range, demonstrates that the low-Z gas dominates the accretion at all radii for all the phases, which supports the filamentary flow origin of the inflowing gas, since low metallicity would not be expected if the accreting gas came mainly from, e.g., satellites, galactic fountain, or thermal instability in the existing hot halo gas.

The simulation results are consistent with observations of halo gas. The H\,i clouds found in galaxy halos are largely within 20 kpc of galactic disks (Thom et al. 2008; Wakker et al. 2008), while the (largely) ionized component extends throughout the halo (Prochaska et al. 2011; Bowen et al. 2002). In addition, the H\,i component is surrounded by warm and warm-hot gas indicating multiphase flows are present (Putman et al. 2012b; Sembach et al. 2003). Finally, substantial quantities of inflowing warm gas are consistent with the results of Shull et al. (2009) and Lehner & Howk (2011).

We must point out one caveat in our analysis. The stellar mass of the simulated galaxy is too concentrated in the bulge, and so the gravitational potential well has a slope that is too steep compared to the Milky Way. For this reason, the heating of the incoming gas was likely overestimated. However, it will probably introduce only a factor of a few error in gas temperature, and we expect the qualitative results reported in this paper to remain unchanged.

5. CONCLUSIONS

We analyzed a high-resolution AMR cosmological simulation of a Milky Way mass galaxy including star formation and supernova feedback, in a fully cosmological setting. In summary, our key results are as follows.

1. The inflowing gas is filamentary, and the bulk of the inflow is warm-hot ($10^5 \lesssim T < 10^6$ K) and ionized. It has a net accretion rate of $3-5 \times 10^2 \, M_\odot \, yr^{-1}$, and sustains the SFR of the simulated galaxy.
2. Most of the inflowing gas (by mass) does not cool; it has nearly constant entropy and so the temperature increases as the gas approaches the center.
3. Some of the inflowing gas does manage to cool (in the innermost regions of the filaments associated with the lowest entropies), but only inside $R \lesssim 100$ kpc, and mostly within $R \lesssim 20$ kpc.
4. The inflowing gas has low metallicity ($Z/Z_\odot < 0.2$).
5. The typical inflow velocities are 50–150 km s$^{-1}$ and generally decrease with increasing gas temperature.

These results point to a picture in which filamentary gas flows, driven by the cosmic web, continue to be important in Milky Way mass galaxies at low redshifts. This inflow is not “cold-mode accretion” in the sense of Kereš et al. (2005), since the temperatures typically exceed $10^5.5$ K during the passage through the halo, and radiative cooling does not dominate heating. However, it also does not correspond to classic smooth, hot-mode accretion, and the gas in these filaments do not experience a large entropy jump at the accretion shock. Instead, this warm-hot filamentary flow may represent a third mode of accretion—important for galaxies like the Milky Way that are not far beyond the mass and redshift thresholds below which cold-mode accretion dominates. We suggest two areas for future work: the fate of the flows as they reach and enter the galactic disk at the disk–halo interface, and an exploration of how mergers, active galactic nuclei, and feedback may affect the gas while it is still in the IGM.

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REFERENCES

Abbott, D. C. 1982, ApJ, 263, 723
Ageritz, O., Teeyssier, R., & Moore, B. 2009, MNRAS, 397, L64
Bauermeister, A., Blitz, L., & Ma, C.-P. 2010, ApJ, 717, 323
Binney, J. 1977, ApJ, 215, 483
Birnboim, Y., & Dekel, A. 2003, MNRAS, 345, 349
Bland-Hawthorn, J., Sutherland, R., Ageritz, O., & Moore, B. 2007, ApJ, 670, L109
