Preheating of the Intergalactic Medium by Gravitational Collapse and Ultraviolet Background

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Abstract

The preheating of the intergalactic medium by structure collapse and ultraviolet background (UVB) is investigated in cosmological hydrodynamical simulations. When gravitational collapse is the sole heating mechanism, we find that (1) 60% and 45% of the IGM are heated up to \( S > 8 \) and 17 keV \( \text{cm}^2 \), respectively, at \( z = 0 \), but the fractions drop rapidly to a few percent at \( z = 2 \); (2) the entropy of the circumhalo gas \( S_{\text{crit}} \) is higher than the virial entropy for more than 75% of the halos with masses \( M < 10^{11.5} M_{\odot} \) since \( z = 2 \), but the fraction higher than the entropy, \( S_{\text{pr}} \), required in the preventive model of galaxy formation is only 15%–20% for halos with \( M < 10^{10.5} M_{\odot} \) at \( z = 0 \), and decreases as redshift increases; (3) assuming a metallicity of \( Z \approx 0.03 Z_{\odot} \), the fraction of halos whose circumhalo gas has a cooling time longer than the Hubble time \( t_{\text{cool,cir}} > t_{\text{H}} \) is merely 5%–10% at \( z \gtrsim 0.5 \), and even less at \( z \gtrsim 1 \) for halos with \( M < 10^{10.5} M_{\odot} \); and (4) gas in the filaments undergoes the strongest preheating. Furthermore, we show that the UVB cannot enhance the fraction of the IGM with \( S > 17 \) keV \( \text{cm}^2 \), but can increase the fraction of low-mass halos \( (< 10^{10.5} M_{\odot}) \) having \( S_{\text{crit}} > S_{\text{pr}} \) to \( \sim 70\% \), and having \( t_{\text{cool,cir}} > t_{\text{H}} \) to 15%–30% at \( z \leq 0.5 \). Our results indicate that preheating due to gravitational collapse and UVB is inadequate to fulfill the needs of the preventative model, especially for halos with \( 10^{10.5} M_{\odot} < M < 10^{11.5} M_{\odot} \). Nevertheless, these two mechanisms might cause large-scale galactic conformity.

Key words: galaxies: formation – galaxies: halos – intergalactic medium – large-scale structure of universe – methods: numerical

1. Introduction

Modern galaxy formation and evolution models, with the aid of tools such as semianalytical methods and cosmological \( N \)-body and hydrodynamical simulations, can reproduce the observations well regarding a wide range of galaxies properties (see, e.g., recent review by Somerville \& Dave 2015, and references therein). Despite the tremendous successes that have been made, many details of important baryonic processes involved in galaxy evolution are not well resolved yet, such as the mechanisms regulating the star formation activity (Naab \& Ostriker 2017). Currently, various internal feedback processes are implemented as the primary mechanism to tune the star formation and hence fit the global cosmic star formation rate, as well as prevent the overcooling of gas in low-mass dark matter halos. The environment is also believed to have an important impact on the supply and cycling of gas in the formation and evolution of galaxies (e.g., Kauffmann et al. 2004; Baldry et al. 2006; Peng et al. 2010).

Effects of the large-scale environment on galactic properties are probed in very recent observational studies (e.g., Alpaslan et al. 2016; Chen et al. 2017; Darvish et al. 2017; Kurtma et al. 2017). The anisotropic gravitational collapse of structures in the universe was predicted to form a web-like appearance of matter distribution on a large scale, including voids, walls/sheets, filaments, and clusters, currently referred to as the cosmic web (e.g., Zel’dovich 1970; Ikei 1973; Bond et al. 1996). The observed galactic distribution at low redshifts is basically consistent with this theoretical prediction (e.g., de Lapparent et al. 1986; Colless et al. 2003; Tegmark et al. 2004; Mehmet et al. 2014). Efforts have also been devoted to detecting the intergalactic medium (IGM) in the cosmic web, mostly the filaments, by different observational means (Cappetta et al. 2010; Chang et al. 2010; Cantalupo et al. 2014; Takeuchi et al. 2014). The heating and consequent cooling of gas during the collapse of structures will affect the accretion of gas in galaxies and hence play an important role in their star formation history. The heating due to the virial shocks associated with dark matter halos has been intensively investigated and implemented in galaxy formation models (e.g., Binney 1977; White \& Rees 1978; White \& Frenk 1991). However, more recent studies have suggested that filamentary cold streams could penetrate the shocks and feed galaxies in the dark matter halos that are less massive than a certain threshold (e.g., Dekel \& Birnboim 2006; Keres et al. 2009). Nevertheless, the more recent simulation work in Nelson et al. (2013) showed that there were significant differences between different numerical solvers regarding the thermodynamic history of the accreted gas in halos more massive than \( 10^{10.5} M_{\odot} \). In addition to the virial shock heating, multiple mechanisms could affect the thermal state of the IGM, and some would operate outside of the halos.

The preheating of gas (i.e., gas was heated up to a certain temperature or certain entropy levels before collapse into dark matter halos) has been proposed to suppress the formation of low-mass galaxies (Mo \& Mao 2002; Mo et al. 2005; Lu \& Mo 2007; Lu et al. 2015). Actually, UV photoheating has been shown to be able to prevent the collapse of baryons in halos up to \( M = 10^{10} h^{-1} M_{\odot} \) (e.g., Crain et al. 2007). Gravitational collapse of sheets and filaments can be an additional potential mechanism, as well as early star formation feedback, active galactic nuclei (AGNs), and perhaps dissipation of IGM turbulence (e.g., Mo \& Mao 2002; Lu \& Mo 2007; Zhu et al. 2011). Based on a semianalytical model, Mo et al. (2005) demonstrated that the gravitational preheating due to the
collapse of sheets at $z \lesssim 2.0$ can lift the entropy of circumhalo gas to $\sim 15$ keV cm$^2$. Using a one-dimensional hydrodynamic simulation, Lu & Mo (2007) further showed that preheated gas with entropy $S > 8$ keV cm$^2$ can strongly lessen the baryon accretion and gas cooling in halos with masses $M < 10^{12} h^{-1} M_\odot$, if the mass accretion is smooth. Such a level of preheating can lead to the mass of cooled gas scaling with halo mass, i.e., $M_{\mathrm{cool}} \propto M^2$, and hence matching the observed atomic hydrogen and stellar mass function according to the model given in Mo et al. (2005). Recently, Lu et al. (2015) developed a new semianalytic model of galaxy formation to probe the impact of preheating on disk galaxies and showed that it can reproduce well a number of observational relations if the IGM was preheated up to a certain entropy level, i.e., $S \sim 17$ keV cm$^2$ for halos with $M = 10^{12} h^{-1} M_\odot$.

However, the entropy state of the IGM in filaments and other environments remains less tackled in three-dimensional cosmological hydrodynamic simulations so far. The phase distribution of the IGM in the temperature and density plane has been investigated thoroughly in simulations, focusing on the “missing” baryons at low redshifts (e.g., Fukugita et al. 1998; Fukugita & Peebles 2004). The missing baryon is predicted to have temperature $10^5 K < T < 10^7 K$ and moderate overdensity in simulations, commonly well known as “warm–hot intergalactic medium (WHIM)” (Cen & Ostriker 1999; Dave et al. 2001; Cen & Ostriker 2006); however, that is still missing in the observations (e.g., Shull et al. 2012). The link between gravitational heating of gas and star formation history has been examined only in a few works based on cosmological simulations. Cen (2011) argued that the gravitational heating of gas due to the growth of large-scale structures and collapse of halos in overdense regions on intermediate scales ($\sim 1$ Mpc) should be responsible for several global trends of galaxy evolution at low redshifts. The local mean entropy of gas at the virial radius of halos in the cluster region was found to be higher than those in the void region in Cen (2011). Therefore, a continuous supply of cool gas to galaxies in overdense regions was expected to end earlier than those in underdense regions. However, the environments of filaments and sheets have not been fully probed. Based on $N$-body simulation, Liu & Cen (2017) further proposed a model of gas accretion for galaxies and suggested that gravitational shock heating of gas could be the primary cause leading to the rapid drop of cosmic star formation rate at $z < 2$.

In the past decade, the evolution of the cosmic web has been studied in detail by high-resolution cosmological simulations (e.g., Aragón-Calvo et al. 2007; Hahn et al. 2007; Aragon-Calvo et al. 2010), although most of these are pure $N$-body simulations. Attention was paid to the alignment of filaments with galaxies (e.g., Tempel et al. 2014); the properties of the filaments, such as length, diameter, and mass content (Cautun et al. 2014); and the impact of the cosmic web on star formation (e.g., Snedden et al. 2016). It has been demonstrated that the dominant structures in terms of mass fraction may transit from sheets to filaments at $z \sim 2$–3 for both baryonic and dark matter (Zhu & Feng 2017). Meanwhile, the properties of cosmic shocks associated with structure formation have also been revealed by simulations, showing rapid growth in strength and surface area since $z \sim 3$ (Ryu et al. 2003; Pfrommer et al. 2006; Kang et al. 2007; Skillman et al. 2008; Vazza et al. 2009, 2011; Zhu et al. 2013). Correspondingly, the entropy of the IGM is expected to undergo a significant evolution. It would be interesting to make an investigation of the entropy level of gas heated by collapse of large-scale structures and estimate their contributions to the entropy required in the preventative models. Moreover, the preheating of the IGM might be the cause of galactic conformity extending out to 4 Mpc in gas-poor central galaxies with stellar mass $< 10^{10} M_\odot$ (Kauffmann et al. 2013; Kauffmann 2015), although the significance of the large-scale conformity is under debate (e.g., Berti et al. 2017; Tinker et al. 2017).

In this paper, we track the entropy of the IGM along the evolution of the cosmic web in three-dimensional cosmological hydrodynamic simulations and investigate the corresponding impact of preheating. As a first step, the gravitational collapse and ultraviolet background (UVB) are studied as the heating mechanisms in this work. This paper is organized as follows. We introduce the numerical methodology in Section 2. The entropy distribution of gas in different cosmic structures is investigated in Section 3. We then probe the preheating and cooling of gas within and surrounding dark matter halos in Section 4. In Section 5, we compare our results with other works, estimate the power of gravitational collapse and UVB to fulfill the request by preventative models of galaxy formation, and discuss the numerical convergence, the impact of preheating on low-mass galaxies, and galactic conformity. Then we summarize our findings in Section 6.

2. Methodology

2.1. Simulations and Cosmic Web Classification

To probe the effect of preheating by gravitational collapse, as well as UVB, we run two fixed-grid cosmological hydrodynamic simulations with the Planck cosmology, i.e., $\Omega_m = 0.317$, $\Omega_\Lambda = 0.683$, $h = 0.671$, $\sigma_8 = 0.834$, $\Omega_b = 0.049$, and $n_s = 0.962$ (Planck Collaboration et al. 2014), in a periodic cubic box of side length $25 h^{-1}$ Mpc. One simulation is adiabatic, and the other one includes radiative cooling by assuming a pristine gas composition, i.e., $X = 0.76$, $Y = 0.24$. In the latter one, heating by a uniform UVB (Haardt & Madau 2012, hereafter HM12) is switched on at $z = 11.0$. The two simulations are referred to as “L025-ada” and “L025-uv,” respectively, hereafter. The simulations are run by the hybrid $N$-body/hydrodynamic cosmological code WIGEON, in which the positivity-preserving weighted essentially nonoscillatory (WENO) scheme was implemented to solve the hydrodynamics (Feng et al. 2004; Zhu et al. 2013). The positivity-preserving WENO scheme can guarantee the positivity of density and temperature of gas, tackling the high Mach problem without introducing any floor by hand (Zhang & Shu 2012). All the simulations are evolved from redshift $z = 99$ to $z = 0$ in a $1024^3$ grid with equal number of dark matter particles. The simulations have space resolution $24.4 h^{-1}$ kpc and mass resolution $1.3 \times 10^8 M_\odot$. As a first step, we focus on the heating by gravitational collapse and UVB; processes such as star formation, AGNs, and their feedback are not included.

The classification of cosmic environments, namely, voids, sheets, filaments, and knots, is based on the tidal tensor of density field following Hahn et al. (2007b) and Forero-Romero et al. (2009). More specifically, the number of eigenvalues above a threshold value is used to tag the morphological type of environment that a cell belongs to. The threshold of
eigenvalues is set to 0.8. The same method and threshold were applied in Zhu & Feng (2017), which showed that the dominant structures measured by mass fraction had transited from sheets to filaments at $z \sim 2–3$.

2.2. Gas Entropy and Dark Matter Halos

The gas entropy is an excellent variable to estimate the gas cooling (Scannapieco & Oh 2004). Following Mo et al. (2005), the specific entropy of gas is defined as

$$ S = \frac{T}{n^2/3} = 17 \left( \frac{\Omega_b h^2}{0.024} \right)^{2/3} \left( \frac{T}{10^{5.5}} \right) \times \left( \frac{1 + \delta}{10} \right)^{-2/3} \left( \frac{1+z}{3} \right)^{-2} \text{keV cm}^2, \quad (1) $$

where $\Omega_b$ is the cosmic density parameter at present, $\delta$ is the local overdensity, and the mean molecular weight is taken to be $\mu = 0.6$.

The dark matter halos are identified using the FoF (Friends-of-Friends) method, with a linking length parameter of 0.2. Since the code is based on a fixed grid, less massive halos are poorly resolved. We will investigate the preheating of gas for only those halos consisting of more than 250 dark matter particles in Section 4. The center and radius of halos are defined by the sphere in which the mean density is 200 times the critical density $\rho_{\text{crit}}(z) = 3H(z)^2/8\pi G$ at $z$. The averaged thermal properties of gas within and surrounding the virial radius of the halo, namely, halo gas and circumhalo gas, are probed. We will carry out a brief convergence study on the resolution in Section 5.

3. Entropy of the IGM in Various Environments

In this section, we investigate the entropy of the IGM in different cosmic structures and their redshift evolution. Figure 1 compares the gas distribution in the density–temperature and density–entropy space in our two simulations at $z = 0$. The distributions in the density–temperature space are consistent with the current results in the literature (e.g., Katz et al. 1996; Cen & Ostriker 1999; Dave et al. 2001; Kang et al. 2007; Vazza et al. 2009). Adopting the definition of gas phases in Dave et al. (2010) with the thresholds of $T_{\text{bh}} = 10^5 \text{K}$ and $\delta_{\text{bh}} = 100$, most of the gas in the adiabatic simulation is in the phases of diffuse ($T < T_{\text{bh}}, \delta_b < \delta_{\text{bh}}$), WHIM ($T > T_{\text{bh}}, \delta_b < \delta_{\text{bh}}$), and hot halo ($T > T_{\text{bh}}, \delta_b > \delta_{\text{bh}}$). The inclusion of UV heating and radiative cooling in the L025-uvc brings a slight change to the WHIM phase but has a significant impact on the diffuse and hot halo gas. The UVB effectively heats up the diffuse IGM and leads to a forbidden region in the temperature–density plane with a lower boundary of $T(\rho_b) \propto T_0(\rho_b/\bar{\rho}_b)^{-0.9}$ (e.g., Valageas et al. 2002; Vazza et al. 2009). The radiative cooling in highly overdense regions promotes the collapse and results in a broader density range for the hot halo gas, as well as helping to develop the cold condensed phase ($T < T_{\text{bh}}, \delta_b > \delta_{\text{bh}}$).

Corresponding changes in the density–entropy phase plane can be observed in the bottom panels of Figure 1, reflecting the transformation according to Equation (1). For overdense regions of gas with $\delta_b > 100$, the entropy of gas in L025-uvc shows an evident decrease in comparison to L025-ada due to cooling. Gas with $\delta_b > 100$ would have been heated up to $T > 10^{4.5} \text{K}$ by gravitational collapse and the UVB, at which the cooling will be effective and immediately lead to the decrease of entropy in L025-uvc. With the lower boundary in the temperature–entropy plane, i.e., $T(\rho_b) \sim 10^{4.5}(\rho_b/\bar{\rho}_b)^{0.6}$, the corresponding entropy floor reads $S \sim 13(\rho_b/\bar{\rho}_b)^{-0.07} \text{keV cm}^2$ at $z = 0$, as shown by the bottom right panel of Figure 1. On the other hand, the WHIM gas would undergo mild changes in response to the UV ionizing background. The thermal evolution of the WHIM gas should be governed by gravitational heating.

Figure 2 further displays the phase diagrams of the IGM in the density–temperature space for the four distinct components of the cosmic web. The dashed curve in each plot gives the median values of gas temperature in the corresponding density bin. In L025-ada, the median temperature grows with increasing density, following approximately a power law $T \propto \rho^{\alpha}$ with $\alpha \sim 1.2$ at $z \geq 2$. The mass fraction in filaments shows an evident growth since $z = 2$. A rapid increase in temperature around $\rho = 6–10$ at $z < 2$ is also observed, which is in agreement with Valageas et al. (2002), and has made a primary contribution to the growth of WHIM gas. The associated gravitational heating due to filament formation should be the cause.

The UVB in L025-uvc has heated up the diffuse gas effectively in the sheets and voids since $z \geq 3$ in comparison to L025-ada. The $T-\rho_b$ relation of diffuse IGM at high redshifts is dependent on the UVB model, although shock heating due to collapse would broaden the distribution. We fit the $T-\rho_b$ relation with a power law of $T(\rho_b) = T_0(\rho_b/\bar{\rho}_b)^{-\gamma}$ in the range $10^{-0.5} < \rho_b/\bar{\rho}_b < 10^{0.5}$ and $T < 10^{4.3} \text{K}$. The values of $T_0$ and $\gamma$ are $1.54 \times 10^4 \text{K}$ and $1.55$, respectively, at $z = 2$. The index $\gamma$ is obviously compatible with the previous simulation works.

![Figure 1. Mass-weighted probability distribution of the IGM in the density–temperature (top) and density–entropy (bottom) plane at $z = 0$. The left column shows the adiabatic run L025-ada, and the right column shows the simulation with UV and radiative cooling (L025-uvc). Solid and short-dashed lines indicate $T = 10^5$ and $10^6 \text{K}$, respectively. The long-dashed line indicates $\rho_b/\bar{\rho}_b = 100$.](image)
Figure 2. Mass-weighted distribution in the density–temperature phase diagram of the IGM residing in different environments in simulation L025-ada (left) and L025-uvc (right) at $z = 3.0, 2.0, 1.0, 0.0$ (from top to bottom). Dashed curves indicate the median values of gas temperature in the corresponding density bin.
that had adopted the UVB of HM12 (e.g., Lukic et al. 2015; Bolton et al. 2017). However, the $T_0$ in our simulation is moderately higher. This may be partially caused by the difference in fitted region and the shock heating, especially in sheets and filaments. Nevertheless, this discrepancy would not change our conclusions significantly, as the preheating at high redshifts is ineffective in our simulations, which will be shown in the following sections.

The radiative cooling is efficient for the hot and dense gas with $\delta_0 > 100$ in both filaments and clusters in L025-ucv. The mass fractions of gas in various density–temperature phases in our simulations since $z = 3$ are given in the Appendix. Our results are basically consistent with previous studies (e.g., Cen & Ostriker 2006; Dave et al. 2010; Snedden et al. 2016), but some differences can be observed at $z \lesssim 0.5$. Since we are more concerned about the entropy of gas in different cosmic structures and their evolution, we will go straight to the statistics of entropy in the rest of this paper.

The left column of Figure 3 presents the density–entropy distributions in the four components of the cosmic web in L025-ada from $z = 3.0$ to 0.0. Visually, the median gas entropy is generally increasing from voids to sheets, and then to filaments, and lastly flattened into clusters. The last panel suggests that the gas with $S > 10$ keV cm$^2$ and $\delta_0 < \delta_{\text{HM}}$ is mostly residing in the filaments. A substantial part of this gas should be WHIM. A considerable fraction of the gas in the clusters also has $S > 10$ keV cm$^2$, which should mainly exist in the form of hot halo gas, as judging from their density. In the sheets and voids, there is only a small amount of gas having $S > 10$ keV cm$^2$.

Figure 3 indicates that the major increment of entropy due to gravitational heating occurs after $z = 2$. Only a very small fraction of gas has an entropy higher than 10 keV cm$^2$ at $z > 2$. At $z = 0$, a large amount of the gas in the filaments has built an entropy $S > 10$ keV cm$^2$. In the sheets and voids, however, the entropy of most of the gas still remains below 10 keV cm$^2$ in L025-ada. The entropy evolution of gas in different cosmic web components with a uniform UVB and radiative cooling can be found in the right column of Figure 3.

The heating due to UVB has significantly raised the entropy of the gas with $\delta_0 < \delta_{\text{HM}}$ over 1 keV cm$^2$ since $z > 3$, which happens in all four components of the cosmic web. The cooling process is relatively more effective for the gas with $\delta_0 > \delta_{\text{HM}}$, which mainly resides in filaments and clusters. The distribution of gas with entropy higher than $\sim 15$–20 keV cm$^2$ in the filaments in L025-ucv is mildly changed with respect to the adiabatic simulation. This can be easily understood, as the thermal evolution of the gas in the filaments should mainly be governed by gravitational collapse.

In Figure 4, we plot the mass-weighted probability distributions of the IGM as a function of entropy in our two simulations since $z = 3$. As the mass fraction of gas contributed by the voids is rather small, only the distributions in the other three types of structures are plotted. When the gravitational collapse serves as the sole heating mechanism, i.e., in L025-ada, the entropy of the IGM shows extended distributions over a wide range for each cosmic web component. The peak value of gas entropy has been increasing gradually as the redshift decreases. The probability distributions peak at about 1, 50, and 10 keV cm$^{-2}$ in sheets, filaments, and clusters, respectively, at $z = 0$. Plateaus are found in the probability distribution of gas entropy in filaments within the range $S \sim 1$–100 keV cm$^2$ and in clusters within $S \sim 3$–30 keV cm$^2$. The UVB generally heats up the gas with $\delta < \delta_{\text{HM}}$ in all types of structures, leading to a jump in the probability density function at $S \sim 10, 6, 5, 3$ keV cm$^2$ at $z = 0.0, 1.0, 2.0, 3.0$, respectively. Meanwhile, the radiative cooling makes a larger fraction of gas in the filaments and cluster have $S < 1$ keV cm$^2$ in comparison to L025-ada. The distribution above $S \sim 15$–20 keV cm$^2$ is slightly modified by the UVB and cooling in sheets and filaments.

To quantify the global effect of IGM heating due to gravitation and UVB, we investigate specifically the mass fraction of the IGM with entropy $S > 1$ keV cm$^2$, $S > 8$ keV cm$^2$, and $S > 17$ keV cm$^2$. Lu & Mo (2007) demonstrated that a preheating model with the circumbolo gas heated up to entropy $S = 8$ keV cm$^2$ would lead to the mass of cooled gas $M_{\text{cool}}$ scaling with halo mass $M$ as $M_{\text{cool}} \propto M^2$ in low-mass halos $M < 10^{12} M_{\odot}$, and hence this could help to explain the observed faint-end slope of the galaxy luminosity function. The last threshold value, 17 keV cm$^2$, is the constant entropy value on the right-hand side of Equation (1) and is close to the predicted gas entropy due to the collapse of sheets at $z \lesssim 2$ in Mo et al. (2005), and it is also the typical entropy required for halos with mass $M = 10^{12} h^{-1} M_{\odot}$ in the preventative model given in Lu et al. (2015). Figure 5 gives the mass fraction of preheated IGM since $z = 4.0$. In L025-ada at $z = 0$, about 90%, 60%, and 45% of the IGM has an entropy larger than 1, 8, and 17 keV cm$^2$, respectively. The filaments host about half of the IGM with $S > 8$ keV cm$^2$, and about 70% of those with $S > 17$ keV cm$^2$. The corresponding shares contributed by clusters are $\sim 33\%$ and $20\%$ for $S > 8$ and 17 keV cm$^2$, respectively. In other word, the high levels of IGM entropy produced by gravitational heating are contributed predominantly by the formation of filaments.

The mass fractions of heated IGM drop rapidly as the redshift increases. Around 20% and 10% of the IGM are heated up to $S > 8$ and 17 keV cm$^2$, respectively, at $z = 1.0$, while at redshift $z = 2.0$ these fractions drop further to 3% and 1% only. The dominant role of filaments is slightly more evident at high redshifts. The fractions of gas with $S > 8, 17$ keV cm$^2$ are somewhat altered by the UVB and cooling. This is actually in accordance with the distribution in density–entropy space as shown in Figure 3. The entropy of hot and dense gas in filaments and clusters is reduced by the radiative cooling. The diffuse gas with $\delta_0 < 100$ in voids, sheets, and even filaments is heated up by the UV photos. Consequently, the total mass fractions of the IGM with $S > 8$ and 1 keV cm$^2$ are enhanced since $z = 0.5$ and 3.0, respectively, due to the UV heating.

In summary, about 60% and 45% of the IGM are heated up to $S > 8$ and 17 keV cm$^2$, respectively, at $z = 0$, due to gravitational collapsing. The fractions of IGM heated up to $S > 8.0$ and 17.0 keV cm$^2$drop rapidly while going to high redshifts, and they are only a few percent at $z = 2$, lower than the prediction in Mo et al. (2005). Moreover, the formation of filaments should be the most effective gravitational preheating process, other than sheets. In addition, the ionizing heating from the uniform UVB (Haardt & Madau 2012) has a minor effect on increasing the mass fraction of the IGM with $S > 17.0$ keV cm$^2$.

4. Preheating and Cooling of Circumhalo Gas

In this section, we further explore the preheating of halo and circumhalo gas and estimate the impact on cooling, which is
Figure 3. Mass-weighted distribution in the density–entropy phase diagram of the IGM residing in different environments in simulation L025-ada (left) and L025-uvc (right) at $z = 3.0, 2.0, 1.0, 0.0$ (from top to bottom). Dashed curves indicate the median values of gas entropy in the corresponding density bin.
crucial for understanding the gas accretion of dark matter halos and consequently the star formation in galaxies.

4.1. Entropy of Halo and Circumhalo Gas in Different Cosmic Web Environments

To make a comparison with the preventative feedback models and previous simulations (e.g., Cen 2011), the entropy of halo gas $S_h$ and that of circumhalo gas $S_{cir}$ are used as indicators. More specifically, we calculate the average density and mass-weighted average temperature of gas residing within each dark matter halo, and then we obtain $S_h$ according to Equation (1). Similarly, the average density and temperature of the IGM in the shell with $R_{vir} < r < 2R_{vir}$ that surround each halo are calculated to obtain $S_{cir}$. The latter characterizes the thermal state of gas right before collapsing into halos and hence can serve as a good indicator of preheating. To lower the effect of the limited resolutions in our fixed-grid simulations, we probe only those halos that are composed of more than 250 particles. Figure 6 shows the entropy of circumhalo gas, $S_{cir}$, of 5000 randomly selected dark matter halos in our two simulations at $z = 2.0$, $1.0$, and $0.0$. The circles are color-coded by the ratio of cooling time to the Hubble time, which will be discussed in detail in the next subsection. Only a few halos are more massive than $10^{12} M_\odot$ in our simulations, due to the limited box size. Most of the dark matter halos have been residing in filaments since $z = 2$, which is consistent with previous works based on N-body simulations (e.g., Cautun et al. 2014). The dashed lines in Figure 6 display the virial entropy, $S_{vir} = T_{vir}/n_{vir}^{2/3}$, where $T_{vir}$ is the virial temperature and $n_{vir}$ is the mean gas density within a dark matter halo by assuming that its baryon fraction takes the value of the cosmic mean $\Omega_b/\Omega_m$. The virial entropy indicates the heating produced by the collapse of halos themselves.

To evaluate the strength of preheating in our simulations, we also plot another threshold entropy of circumhalo gas with solid lines given by

$$S_{pr} = 17 \left( \frac{M_{vir}}{10^{12} M_\odot} \right)^{0.2} \frac{1}{1 + (z/1.2)^2} \text{ keV cm}^2,$$

where $M_{vir}$ is the mass of the dark matter halo. A formula like this was first introduced by Lu et al. (2015) to account for various preheating processes in their preventative model of disk galaxy formation. These parameters had been chosen such that their semianalytical model with preheated gas can be capable of reproducing the observed scaling relations of disk galaxies remarkably well. For the sake of simplicity, we use the mass of a halo at particular redshifts, instead of its final mass at $z = 0$, to calculate the $S_{pr}$ at $z = 0$. This modification might lead to a deviation of about 1 keV cm$^2$ from the original formula in Lu et al. (2015). In L025-ada, the average entropy of circumhalo gas, $S_{cir}$, of most halos is generally above the virial entropy $S_{vir}$ at $z = 2$. The excess with respect to $S_{vir}$ could be attributed to the collapse of large-scale structures, i.e., the formation of filaments and sheets. The preheating of circumhalo gas is relatively more significant for halos in filaments than those in sheets, clusters, and voids, in agreement with the density–entropy distribution in different environments. The margin of $S_{cir}$ over virial entropy increases gradually over time for $M_{vir} < 10^{11.0} M_\odot$, compatible with the growth scenario of IGM entropy toward low redshifts reported in the previous section. However, only a few halos are surrounded by gas that has been heated up to $S_{cir} > S_{pr}$ in L025-ada.

The inclusion of UVB in L025-uvc has effectively improved the fractions of halos with $S_{cir} > S_{pr}$ for $M_{vir} < 10^{10.5} M_\odot$, especially in filaments, sheets, and voids. This enhancement should be caused by the heating of gas with $\delta_b < 100$ by the UVB as shown in Figure 3. Gas that was heated by UV at early times will go through further gravitational heating while accreting into more overdense regions at low redshift. In L025-uvc, a shallow trough in $S_{cir}$ is found for halos with mass $10^{10.5} < M_{vir} < 10^{11.0} M_\odot$ in clusters, which should result from the highly efficient radiative cooling. Actually, the radiative cooling function peaks at around $2 \times 10^4$, $10^5$ K (e.g., see Sutherland & Dopita 1993). In the presence of UVB, the temperature of most of the IGM can cross over the first peak, i.e., $2 \times 10^4$ K. However, UV heating can hardly lift the fraction of IGM that can reach the second peak, $10^5$ K, close to the virial temperature of a halo with mass $10^{10.5} M_\odot$. A
Figure 5. Mass fraction of the IGM with entropy $S > 1$ keV cm$^2$ (left), $S > 8$ keV cm$^2$ (middle), and $S > 17$ keV cm$^2$ (right) in simulations L025-ada (solid line) and L025-uvc (dashed line) since $z = 5.0$. The total fraction is shown in cyan, and fractions contributed by gas in clusters, filaments, and sheets are shown in blue, red, and green, respectively.

shallower trough of $S_{\text{vir}}$ with respect to $S_{\text{pr}}$ can also be observed for halos with masses of $M_{\text{vir}} > 10^{10.0} M_{\odot}$ in the filaments.

Figure 7 shows the mass-weighted average entropy $S_{\delta}$ of gas within the dark matter halos. There are only minor differences between $S_{\delta}$ and $S_{\text{vir}}$ in the adiabatic simulation. Once radiative cooling is on, $S_{\delta}$ shows a distinct drop for halos with masses greater than a couple times $10^{10} M_{\odot}$. The drop is more significant in the environment of clusters. For these halos, the baryonic matter would have experienced distinct radiative cooling within the virial radius, and hence the entropy drops away from $S_{\text{vir}}$ dramatically. Once again, this trend matches with the mass distribution in the density–temperature and density–entropy planes shown in Section 3. The cooling is very effective for gas with $\delta \gtrsim 100$ and $T \sim 10^{4.5} - 10^{5.0}$ K, which becomes more violent with the increasing overdensity.

We plot the fractions of halos with $S_{\text{cir}}$ and $S_{\text{pr}}$ higher than $S_{\text{vir}}$ and $S_{\text{pr}}$, respectively, at redshift 2, 1, 0 in Figure 8. The halos are assigned to four mass bins, $10^{8.5 - 10^{9.5}} M_{\odot}$, $10^{9.5 - 10^{10.5}} M_{\odot}$, $10^{10.5 - 10^{11.5}} M_{\odot}$, and $10^{11.5 - 10^{12.5}} M_{\odot}$. The left column shows the halo distributions in different components of the cosmic web. For halos less massive than $\sim 10^{10.5} M_{\odot}$, the primary hosting structure are filaments. Massive halos tend to reside in clusters. A similar trend has been reported in Cautun et al. (2014), but the break halo mass is much higher in their work. The relative smaller box size of our simulations results in smaller collapsed structures, including halos and filaments. Compared to L025-ada, more halos are found in filaments and sheets in L025-uvc. The total number of halos in the last mass bin is small, as well as for halos in sheets that are more massive than $\sim 10^{10.0} M_{\odot}$. Therefore, statistics including fractions would suffer from notable random noise in corresponding bins.

The second and third columns of Figure 8 show the fractions of $S_{\delta} > S_{\text{vir}}$ and $S_{\text{vir}} > S_{\text{pr}}$ in the environments of clusters, filaments, and sheets. At $z = 2$, more than 80% of the halos with $M < 10^{10.5} M_{\odot}$ have an $S_{\text{vir}}$ higher than the virial entropy, and the fraction is lower for more massive halos, falling to $< 30\%$ for $10^{11.5 - 10^{12.5}} M_{\odot}$. The fractions grow with decreasing redshifts and are nearly 100% at $z = 0$ for all the halos. On the other hand, the fraction of $S_{\delta} > S_{\text{vir}}$ is lower than that of $S_{\text{vir}} > S_{\text{pr}}$, about $\sim 75\%$ and $\sim 0\%$ for halos with $10^{10.5 - 10^{11.5}} M_{\odot}$ and $10^{11.5 - 10^{12.5}} M_{\odot}$, respectively. In L025-uvc, the cooling process may have led the fraction of $S_{\delta} > S_{\text{vir}}$ to decrease by $\sim 30\%$ for halos with $10^{10.5 - 10^{11.5}} M_{\odot}$ at $z = 0$.

The fractions of halos with entropy above $S_{\text{pr}}$ are given in the right two columns of Figure 8. When the gravitational collapse is the sole preheating mechanism, the fractions with $S_{\text{cir}} > S_{\text{pr}}$ and $S_{\delta} > S_{\text{pr}}$ are about $\sim 15\% - 20\%$ for halos with $M_{\text{vir}} < 10^{10.5} M_{\odot}$ at $z = 0$ and drop rapidly toward high redshifts. A trough appears in the halo mass range of $10^{10.5 - 10^{11.5}} M_{\odot}$. Some of the most massive halos in our simulations, $M_{\text{vir}} \sim 10^{12.5} M_{\odot}$, are also surrounded by circumhalo gas with entropy higher than $S_{\text{pr}}$. But for these halos, the entropy of gas surrounding halos is close to the virial entropy, which is higher than $S_{\text{pr}}$. Namely, the heating due to the formation of halos themselves should be dominant over the preheating due to the collapse of filaments and sheets hosting those halos. The UVB heating significantly increases the fraction of halos with $S_{\text{cir}} > S_{\text{pr}}$ and $S_{\text{pr}} > S_{\text{vir}}$ to nearly 70% for $M_{\text{vir}} < 10^{10.5} M_{\odot}$ at $z = 0$ and to 50% for $M_{\text{vir}} < 10^{10.5} M_{\odot}$ at $z > 0$.

4.2. Cooling of Halo and Circumhalo Gas

The preheating by gravitational collapse and UVB may delay the cooling and reduce the accretion of baryons in low-mass halos. Lu & Mo (2007) and Lu et al. (2015) investigated the effect of preheated circumhalo gas with a certain entropy level in the semianalytic preventative models of galaxy formation and demonstrated that such models can reproduce well a number of scaling relations of galaxies inferred from observations. The gas surrounding low-mass halos indeed undergoes evident preheating due to gravitational collapsing and UVB in our simulations. We examine the effect of the preheating in our samples by estimating the cooling time of gas surrounding and within halos and comparing it to the Hubble time $t_H$. Following Mo et al. (2005) again, the cooling time
reads as

\[ t_{\text{cool}} \sim 6.3 \Lambda_{-23}^{-1} \left( \frac{0.024}{\Omega_b h^2} \right)^{-1} \left( \frac{T}{10^{5.5} \text{ K}} \right) \times \left( \frac{1 + \delta}{10} \right)^{-1} \left( \frac{1 + z}{3} \right)^{-3} \text{ Gyr}, \]  

(3)

where \( \Lambda_{-23} \) is the cooling function. The radiative cooling implemented in L025-uvc is calculated with the pristine gas composition during the simulation and following the procedures in Theuns et al. (1998). A more realistic treatment should take the gas metallicity into account. Since the star formation and feedback processes have not been included in our simulation temporarily, we made a post-simulation calculation on the cooling time of circumhalo gas and halo gas, using the cooling functions with metallicities of 0.001, 0.01, 0.03 \( Z_\odot \) given by Sutherland & Dopita (1993). More specifically, the mean overdensity and mass-weighted average temperature of gas within \( R_{\text{vir}} < r < 2R_{\text{vir}} \) of 5000 randomly selected dark matter halos, assigned to different cosmic environments, at \( z = 2.0, 1.0, 0.0 \) in L025-ada (left) and L025-uvc (right). Dashed lines indicate the virial entropy, and the solid lines indicate the value given by Equation (2). Halos are color-coded by the ratio of cooling time to the Hubble time.
The circles representing halos in Figures 6 and 7 are color-coded according to their ratio of the cooling time with metallicity $0.01Z_\odot$ to the Hubble time, i.e., $t_{\text{cool}}(0.01Z_\odot)/t_H$. These two figures suggest that the required average entropy should be $\sim 2-3$ times $S_{pr}$, i.e., 30–50 keV cm$^2$, in order to reach $t_{\text{cool}}(0.01Z_\odot) > t_H$. In case of gravitational heating being the sole preheating source, only a small fraction of halos in filaments and sheets meet this level of entropy in L025-ada. Adding UVB will raise this fraction. The left and middle panels of Figure 9 show the fractions of halos that satisfy $t_{\text{cool}} > t_H$ within $r < R_{vir}$ and $R_{vir} < r < 2R_{vir}$ in clusters, filaments, and sheets since $z = 2.0$. We further relax the criterion to $t_{\text{cool}} > 0.5t_H$, and the fractions are given in the right panel. It is reasonable to expect that such a cooling time, $t_{\text{cool}} > 0.5t_H$, can also delay, at least partially, the gas accretion into halos. At $z = 2$, a significant delay of cooling occurs only in a few halos residing in clusters with $10^{11.5} M_\odot < M_{\text{vir}} < 10^{12.0} M_\odot$. This delay effect for halos in this mass bin persists to low redshifts. The preheating can hardly delay the cooling of circumhalo gas for halos with $M_{\text{vir}} < 10^{10.5} M_\odot$. As for halos with $M_{\text{vir}} > 10^{10.5} M_\odot$, the fraction with $t_{\text{cool,cir}} > t_H$ remains only a few percent for all three metallicities considered at $z \geq 1$ and increases to $\sim 5\%-10\%$ at $z \leq 0.5$ in L025-ada. Generally, the fraction in filaments is
the highest, and that in sheets ranks second for low-mass halos, except in $10^{10.5} M_\odot < M_{\text{vir}} < 10^{11.5} M_\odot$. However, the number of halos in sheets in this mass bin is much smaller than that in filaments. The UV heating raises the fraction with $t_{\text{cool, cir}} > t_{\text{H}}$ to $\sim 15\%–30\%$ at $z \lesssim 0.5$. A richer metallicity results in slightly decreased fractions, due to more efficient cooling, and vice versa. The fractions of halos that meet a relaxed condition, $t_{\text{cool, h}} > 0.5t_{\text{H}}$, at different redshifts are $\sim 1.3$ times larger. The fractions with $t_{\text{cool, h}} > t_{\text{H}}$ are relatively lower than that of $t_{\text{cool, cir}} > t_{\text{H}}$ for halos more massive than $10^{10.0} M_\odot$.

5. Discussion

5.1. Comparison with Previous Studies

Using the ellipsoidal collapse model, Mo et al. (2005) proposed that the formation of sheets/pancakes can heat the gas surrounding low-mass halos to $S \sim 15$ keV cm$^2$ at $z \lesssim 2.0$. They further showed that, with such a level of IGM entropy due to preheating, a semianalytical model of galaxy formation can match the H I mass function and stellar mass function at the low-mass end simultaneously. In our adiabatic simulation, the gravitational heating due to structure collapse can heat up about 60\% and 45\% of the IGM to $S > 8$ and 17 keV cm$^2$, respectively, by $z = 0$. However, the fractions drop rapidly toward high redshifts, falling to about 3\% and 1\%, respectively, at $z = 2$. A fraction as low as this would limit the power of gravitational preheating to delay the gas cooling at high redshifts. In addition, our analysis suggests that the collapse of filaments, rather than sheets/pancakes, serves as the dominant process of gravitational preheating, contributing more than half of the IGM with $S > 8$, 17 keV cm$^2$ since $z = 2$. The rapid decrease of gravitational heating toward high redshifts is consistent with the result in Cen (2011, see their Figures 10 and 11), where the gas entropy was explored in a high-resolution simulation run by adaptive grid code ENZO.

Lu & Mo (2007) further showed that if the entropy of IGM were preheated up to comparable to or larger than the virial entropy $S_{\text{vir}}$, the cooling and accretion of gas into dark matter halos would be delayed and reduced. Lu et al. (2015) demonstrated that semianalytic models with preheated gas entropy $S_{\text{pr}}$ in the form of Equation (2) can reproduce many observed relations of disk galaxies. In our adiabatic simulation, the entropy of the circumhalo gas of more than 75\% of low-mass halos is larger than the virial entropy since $z = 2$, due to gravitational preheating. However, the fraction of that larger than $S_{\text{pr}}$ is merely $\sim 15\%–20\%$ for $M_{\text{vir}} < 10^{10.5} M_\odot$ at $z = 0$. The fraction of halos whose circumhalo gas has a cooling time longer than $t_{\text{H}}$ is even less, i.e., grows from a few percent at $z \gtrsim 1$ to $\sim 5\%–10\%$ at $z \lesssim 0.5$, assuming a gas metallicity of $Z \lesssim 0.03 Z_\odot$. Therefore, the gravitational preheating alone is insufficient to sustain the entropy of circumhalo gas urged by the preventative model in Lu et al. (2015).

The inclusion of UVB as an additional preheating source can almost triple the fractions of halos having $S_{\text{cir}} > S_{\text{pr}}$ and of which $t_{\text{cool, cir}} > t_{\text{H}}$ for $M_{\text{vir}} < 10^{10.5} M_\odot$. However, the combination of gravitational and UV heating is still inadequate to reach the level of gas entropy required in Lu et al. (2015) to reproduce observations. The situation for halos with mass $10^{10.5} M_\odot < M_{\text{vir}} < 10^{11.5} M_\odot$ would become more serious, as their virial temperature is close to the peak of the cooling function at $\sim 10^5$ K for gas metallicity $Z \lesssim 0.1 Z_\odot$ (Sutherland & Dopita 1993). Other processes, including preheating by supernovae and AGN winds (Mo & Mao 2002), are speculated to offer partly the rest of the heating energy required by the preventative model in Lu et al. (2015). In Cen (2011), where the star formation and feedback are implemented, the halo gas was found to satisfy $t_{\text{cool}} > t_{\text{H}}$ at $z \lesssim 0.5$ in a considerable fraction of the halos with masses of $10^{10.5} M_\odot < M_{\text{vir}} < 10^{11.5} M_\odot$. However, the preventative feedback alone may be not strong enough to resolve the overcooking in low-mass...
halos, especially for those with masses of $10^{10.5} M_\odot < M_{\text{vir}} < 10^{11.5} M_\odot$. Consequently, the ejective baryonic feedback, which has been vastly adopted and investigated in galaxy formation models and simulations (Naab & Ostriker 2017 and references therein), will still play an important role. Nevertheless, a precise understanding of the impact of preheating would be helpful in ascertaining the required efficiency and the mechanism of ejective feedback, which vary significantly in various semianalytical models and simulations at present.

5.2. Numerical Convergence

As discussed by Mo et al. (2005), the resolutions of shocks and of low-mass halos are crucial to exploring the preheating effect in simulations. Although our simulations are performed on a fixed grid with a spatial resolution of 24.4 $h^{-1}$ kpc, the advantage of the WENO scheme in capturing shocks can resolve well the shocks coming up with the formation of large-scale structure in our simulations as demonstrated in Zhu et al. (2013). However, the resolution of dark matter halos in our simulations is largely constrained by the size of the grid cell. Underestimated density of gas within and surrounding the halos may amplify the average entropy, i.e., $S_{\text{vir}}$ and $S_0$, and hence overestimate the preheating effect. This shortcoming is partly remedied by two means in our investigation. First, only halos with more than 250 dark matter particles are inspected. Second, our investigation puts more emphasis on the entropy and cooling of gas surrounding the halos, i.e., $R_{\text{vir}} < r < 2R_{\text{vir}}$.

To test the numerical convergence, we perform an adiabatic simulation with a lower spatial resolution, 48.8 $h^{-1}$ kpc, i.e., using a $512^3$ grid and an equal number of particles. This simulation is denoted by “LowR-ada.” Figure 10 shows the comparison between L025-ada and LowR-ada on the fraction of IGM heated up to $S > 17$ keV cm$^2$ and the fraction of halos having $f_{\text{cool}} > \eta_4$. Obviously, the contribution to IGM with $S > 17$ keV cm$^2$ from clusters and sheets exhibits a notable discrepancy between the two simulations. Nevertheless, minor differences are found regarding the total mass fraction of IGM heated up to $S > 17$ keV cm$^2$ and those in filaments at $z < 2.0$. Hence, the global effect of gas preheating due to gravitational collapse in two simulations should basically be consistent with each other. The fractions of halos with $f_{\text{cool,cl}} > \eta_4$ in L025-ada are smaller than that in LowR-ada by about 5%. Therefore, the insufficiency of gravitational heating to provide the entropy needed by the model in Lu et al. (2015) might be more serious if the resolution is further increased.

5.3. Baryon Fraction, Environment Quenching, and Large-scale Conformity

The delayed cooling by preheating is expected to suppress the accretion rate of gas and further reduce the star formation and baryon fraction in low-mass dark matter halos (Lu & Mo 2007; Lu et al. 2015). However, the power for estimating the baryon fraction in this work is restrained by the limited resolution of our simulations. In addition, star formation and feedback are also important to the state of baryons in dark matter halos, which are not included yet. Despite these constraints, the rapid growth of strength of preheating over time at $z < 2$ revealed in our simulations is consistent with very recent observational study of the environmental effect on star formation. Based on the Four Star Galaxy Evolution survey, Kawinwanichakij et al. (2017) reported that the environmental quenching was very inefficient at $z > 1.5$, but grew rapidly toward low redshifts, and could account for most of the low-mass quiescent galaxies ($M_{\text{stellar}} \sim 10^{9–10} M_\odot$). The impact of preheating on the baryon fraction of low-mass halos will be tackled in the future by adaptive-mesh refinement (AMR) simulations implemented with star formation and feedback.

Moreover, our simulations show that the filaments are the primary contribution to the preheated IGM with $S > 8$ keV cm$^2$. In addition, the fraction of halos with $f_{\text{cool,cl}} > \eta_4$ is relatively higher in filaments than in other morphological types of cosmic structures. The rapid growth of this fraction since $z = 2$ is actually in accordance with the
The preheating of the IGM, i.e., heated up to certain entropy levels before collapsing into dark matter halos, has been proposed in preventative models to suppress the formation of low-mass galaxies, providing an alternative or a supplement to the ejective models (Mo & Mao 2002; Mo et al. 2005; Lu & Mo 2007; Lu et al. 2015, 2017). Meanwhile, the preheating of the IGM may offer a physical explanation to the reported large-scale galactic conformity (Kauffmann et al. 2013; Kauffmann 2015). In this paper, we make a study of the preheating of the IGM in three-dimensional cosmological hydrodynamical simulations for the first time. We summarize our findings as follows:

(i) Preheating due to pure gravitational collapse can heat up about 60% and 45% of the IGM to $S > 8$ and 17 keV cm$^2$, respectively, by $z = 0$. However, the fractions drop rapidly as redshift increases, falling to a few percent at $z = 2$, which might be lower than the entropy prescription given by Mo et al. (2005). The inclusion of heating by a uniform UVB (Haardt & Madau 2012) is unable to increase the fraction of IGM with $S > 17$ keV cm$^2$.

(ii) If gravitational collapse is the sole preheating source, the mass-weighted average entropy of the circumbulge gas $S_{\text{circ}}$ and halo gas $S_h$ in our simulations is higher than the virial entropy for more than 75% of the halos with $M_{\text{vir}} < 10^{11.5} M_\odot$ at $z < 2$. However, the fraction of halos whose $S_{\text{circ}}$ is higher than the entropy level $S_{\text{pr}}$, required in the preventative model of galactic formation (Lu et al. 2015), is only $\sim 15\%$–$20\%$ for halos with $M_{\text{vir}} < 10^{10.5} M_\odot$ at $z = 0$. This fraction drops moderately toward high redshifts. The heating provided by UVB can increase the fraction of $S_{\text{circ}} > S_{\text{pr}}$ to nearly 70% for $M_{\text{vir}} < 10^{10.5} M_\odot$ at $z = 0$ and to above 50% for $M_{\text{vir}} < 10^{9.5} M_\odot$ at $z > 0$.

(iii) Assuming a metallicity $Z \leq 0.03 Z_\odot$, we measure the fraction of halos whose circumbulge gas would experience significant delay of cooling, i.e., having a cooling time longer than the Hubble time $t_{\text{cool, circ}} > t_H$. For halos less massive than $10^{10.0} M_\odot$, the fraction of halos that have $t_{\text{cool, circ}} > t_H$ remains only a few percent at $z > 1$ and increases to 5\%–10\% at $z \lesssim 0.5$, due to gravitational heating. The fractions of halos that meet a relaxed criterion $t_{\text{cool, circ}} > 0.5 t_H$ are $\sim 1.3$ times larger. A richer metallicity results in a slightly decreased fraction and vice versa.

(iv) The formation of filaments, instead of sheets/pancakes, serves as the primary gravitational preheating process, contributing more than half of the IGM with $S > 8$, 17 keV cm$^2$. In addition, the fraction of halos with $t_{\text{cool, circ}} > t_H$ in filaments is generally the highest, and that in sheets ranks second in the same halo mass bin. This trend is demonstrated in simulations both including the UVB and without it.

6. Summary

The dramatic rising of filaments during the same epoch (e.g., Zhu & Feng 2017). Low-mass halos in the filaments may witness relatively stronger reduction of gas accretion due to preheating. This trend is supported by some recent observational studies. Using a mass-complete sample in the COSMOS field, Darvish et al. (2017) suggested that most satellite galaxies would undergo a rapid quenching as they fall from the field into clusters via filaments.

On the other hand, the preheating of the IGM could provide a physical explanation for the large-scale conformity in gas-poor central galaxies that are less massive than $10^{10} M_\odot$, although the significance is still under debate (Kauffmann et al. 2013; Kauffmann 2015; Berti et al. 2017; Tinker et al. 2017). Our simulations demonstrate that a considerable fraction of the IGM is indeed heated up by the collapsing of large-scale structures and the UV ionizing background. So far, these mechanisms are unable to sustain the level of entropy required in semianalytical models to entirely solve the number density and scaling relations of low-mass galaxies. However, with the circumbulge gas of $\sim 50\%$ halos going through significant preheating, i.e., $S_{\text{circ}} > S_{\text{pr}}$, or $\sim 15\%$–$30\%$ for $t_{\text{cool, circ}} > t_H$, the preheating sources discussed in this work may be able to cause the reported large-scale conformity in the local universe. Further investigation on the impact of preheating on baryon fractions will provide more direct hints.
The results presented in this paper indicate that preheating due to the collapse of cosmic structures and UVB can provide part of the IGM entropy required by semianalytical preventative models in order to match the observed properties of low-mass galaxies, such as the number density, scaling relation, and so on. To fulfill the request by preventative models, more sources are urged to heat the gas surrounding low-mass dark halos, especially those with mass $10^{10.5} - 10^{11.5} \, M_{\odot}$. Nevertheless, the two preheating mechanisms explored in this work might be able to give rise to the observed large-scale conformity at the local universe. The validity will be tested by further investigation regarding the impact of preheating on the baryon fraction and star formation in low-mass halos, combined with more observations in the future.

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Appendix

Mass Fractions of the IGM in Various Phases

Figure 11 gives the mass fractions of the IGM in four types of density–temperature phases in our simulations. The definition of IGM phases varies in the literature. Throughout this paper, the definitions in Dave et al. (2010) with the thresholds of $T_{\text{th}} = 10^{5} \, \text{K}$ and $\delta_{\text{th}} = 100$ are adopted, i.e., diffuse ($T < T_{\text{th}}$, $\delta_{b} < \delta_{\text{th}}$), WHIM ($T > T_{\text{th}}$, $\delta_{b} < \delta_{\text{th}}$), hot halo ($T > T_{\text{th}}$, $\delta_{b} > \delta_{\text{th}}$), and condensed ($T < T_{\text{th}}$, $\delta_{b} > \delta_{\text{th}}$). Due to the lack of star formation process, the mass fraction of the stellar component is not available in our simulations. The global trend and values of the fractions in L025-ucc are generally in agreement with Dave et al. (2010). Along with the growth of cosmic structures, gas in the diffuse phase keeps converting into WHIM, hot halo, and condensed phases. The mass fraction of diffuse gas drops from $\sim 90\%$ at $z = 3$ to $\sim 4\%$ at $z = 0$. Meanwhile, the fractions of gas in the WHIM and hot halo grow from a few percent to $\sim 20\%$. The condensed baryons contribute about $10\%$ since $z = 3$. We note that the mass fractions in the phases of diffuse, WHIM, and hot halo gas extracted from L025-ucc show differences of $\sim 5\%$ in absolute terms compared with Dave et al. (2010) at $z \leq 0.5$. While similar differences can be found between various works (e.g., Cen et al. 2006; Dave et al. 2010; Snedden et al. 2016), this discrepancy can be attributed to different modeling of physical processes, including star formation and supernova and stellar feedback, as well as some numerical factors, including the hydrodynamic solver and resolution.

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