Recent statistical X-ray measurements of the intracluster medium (ICM) indicate that gas temperature profiles in the outskirts of galaxy clusters deviate from self-similar evolution. Using a mass-limited sample of galaxy clusters from cosmological hydrodynamical simulations, we show that the departure from self-similarity can be explained by non-thermal gas motions driven by mergers and accretion. Contrary to previous claims, gaseous substructures only play a minor role in the temperature evolution in cluster outskirts. A careful choice of halo overdensity definition in self-similar scaling mitigates these departures. Our work highlights the importance of non-thermal gas motions in ICM evolution and the use of galaxy clusters as cosmological probes.

Key words: cosmology: theory -- galaxies: clusters: general -- galaxies: clusters: intracluster medium -- methods: numerical -- X-rays: galaxies: clusters

1. INTRODUCTION

The outskirts of galaxy clusters mark the transition from the cosmic web to the intracluster medium (ICM). Measurements of gas properties in cluster outskirts directly probe the formation of galaxy clusters and halo accretion physics that affect the ICM. A thorough understanding of physical processes at all radii will further enable cluster cosmology.

The use of clusters as cosmological probes hinges on our ability to tightly constrain the evolution of the galaxy cluster mass function. The mass function is sensitive to cosmological parameters (see Allen et al. 2011 for a review), and cluster masses are inferred from observed thermodynamic properties of the ICM. We can establish relationships between observables and the cluster mass by exploiting self-similar properties of galaxy clusters (see Voit 2005; Kravtsov & Borgani 2012, for a review).

The radial profiles of ICM properties in self-similar galaxy clusters resemble one another when rescaled by mass and redshift-dependent quantities. Radially integrated profile quantities can serve as a proxy of cluster mass. The self-similar model of galaxy clusters is based on simplifying assumptions. In reality, these assumptions are broken in our universe’s cosmology and through non-gravitational baryonic processes, such as radiative cooling and star formation. The way to directly probe and exploit self-similar relations is to self-consistently model galaxy cluster formation and calibrate the observable-mass relations used by observations.

The range of radial integration impacts the scatter in the observable-mass relations. Since baryonic physics primarily affect gas within $R \lesssim R_{500c}$, quantities integrated out to $R \approx R_{500c}$ exhibit less scatter in self-similar relations (Kravtsov et al. 2006). Observations thus have pushed to cluster outskirts to further constrain the power. However, observed properties in cluster outskirts are sensitive to accretion driven processes and require theoretical interpretation.

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Wechsler et al. 2002; Fakhouri & Ma 2009; Tillson et al. 2011), and that group size substructures have lower virial temperatures than the host cluster. X-ray observations cannot identify and mask out accreting subhalos at high redshifts, leading to overestimates in density and underestimates in temperature.

On the other hand, a significant fraction of outskirt gas does not reside in dense substructures. Rather, much of the outskirt gas is in the form of low-density, diffuse gas that cannot identify and mask out accreting subhalos at high virial temperatures than the host cluster. X-ray observations cannot understand cluster gas behavior at large radii, cluster outskirts to recent accretion leaves intermediate radii as the energy content of the ICM consists of thermal and non-thermal components. The latter arises primarily from random gas motions generated by mergers and accretion events. We can define the “total” temperature as the sum of specific kinetic and internal energies of the gas:

Assuming further that the cluster gas is spherically symmetric and is in hydrostatic equilibrium with the cluster’s gravitational potential well, we can define a characteristic temperature $T_\Delta$, which relates to the cluster mass as

$$
T_\Delta \propto \frac{GM_\Delta}{R_\Delta} \propto (\Delta \rho_\text{i})^{1/3} M_\Delta^{2/3}.
$$

(1)

Here, $M_\Delta$ is the mass enclosed within a sphere of radius, $R_\Delta$, both defined with respect to some reference density $\rho_\text{i}$ such that,

$$
M_\Delta = \frac{4\pi}{3} R_\Delta^3 \Delta \rho_\text{i}(z),
$$

(2)

and $\Delta$ is the mean overdensity contrast with respect to a reference density, $\rho_\text{i}(z)$, at a given redshift $z$. The characteristic temperature is then a function of cluster mass and redshift $T_\Delta(T(M_\Delta, z))$.

The temperature profile can then be scaled with respect to this characteristic temperature as

$$
\overline{T}(r/R_\Delta) \equiv \frac{T(r/R_\Delta)}{T_\Delta(M_\Delta, z)}.
$$

(3)

If galaxy clusters were perfectly self-similar under this scaling, the shape and normalization of $\overline{T}(r/R_\Delta)$ would be independent of the cluster mass and redshift.

It is important to note that a mass-limited sample of real galaxy clusters do not satisfy any of the assumptions of the Kaiser model, but have nonetheless empirically exhibited near self-similar behavior. We therefore explore physical effects that lead to observed deviations from self-similar scaling in a similarly representative sample.

Note that the self-similar model depends on which overdensity is used to define cluster mass and radius in Equation (2). A commonly used density contrast in cluster measurements is $\Delta = 500c$, where $c$ denotes the overdensity defined with respect to the critical density of the universe. In this work, we consider several different characteristic overdensities: $\Delta = 200c$, $500c$, $1600c$ and $\Delta = 200 m$, $500 m$, $1600 m$. In the second set of overdensities, $m$ denotes the overdensity defined with respect to the mean mass density of the universe. These overdensities are redshift dependent; e.g., $\Delta = 1600 m$ approximately corresponds to $\Delta = 500c$ at $z = 0$.

2. THEORETICAL FRAMEWORK

2.1. Self-similar Model

The standard self-similar model by Kaiser (1986) describes the properties of galaxy clusters based on their mass and redshifts. The Kaiser model is based on several simplifying assumptions about the formation of galaxy clusters. First, the model assumes that galaxy clusters form from the scale-free gravitational collapse of initial density perturbations in an $\Omega_m = 1$ universe. Second, the amplitude of initial density fluctuations is scale-free; i.e., the matter power spectrum is a power law with $P(k) \propto k^n$. Finally, there are no additional physical processes that introduce any scale dependence. The scale-free setup of this problem defines a self-similar model, where halo properties depend only on the slope and normalization of the initial density field at collapse.

$$
\frac{k_B T_{\text{int}}}{\mu m_p \nu_{\text{gem}}^{2}} = \frac{1}{3} \mu m_p \left( \frac{\nu_{\text{gem}}}{\nu_{\text{mol}}} \right)^{2}.
$$

(5)

where $k_B$ is the Boltzmann constant, $\mu = 0.59$ is the mean molecular weight of the ionized ICM, $m_p$ is the proton mass,
and \( \sqrt{\langle v_{\text{gas}}^2/_{\text{w}}} \) is the three-dimensional mass-weighted root-mean-square velocity of the gas. Physically, this “non-thermal temperature” \( k_B T_{\text{w}} \) represents the specific kinetic energy associated with gas motions in the ICM.

The total temperature of gas in a virialized halo is analogous to the velocity dispersion of dark matter in local Jeans equilibrium with the gravitational potential of that halo (Diemer et al. 2013). The circular velocity profile is a proxy for the gravitational potential and evolves self-similarly when scaled with respect to the critical density of the universe (Diemer & Kravtsov 2014; Lau et al. 2015). The evolution of the critical density of the universe at \( z < 1 \) well-tracks the slow evolution of cluster the potential wells because the gravitational potential wells of galaxy clusters are set early in their history (e.g., van den Bosch et al. 2014) and evolve slowly at late times. If a halo is near-virialized, its total temperature profile should exhibit the same self-similar scaling as the circular velocity profile. The thermal temperature would only exhibit the same self-similar scaling if the cluster were in perfect hydrostatic equilibrium. We use our sample of simulated galaxy clusters to study these effects on our defined ICM quantities. We describe the results in Section 4.2.

3. METHODOLOGY

3.1. Cosmological Simulation

We use galaxy clusters extracted from the Omega500 simulation (Nelson et al. 2014b). The Omega500 simulation is a cosmological hydrodynamical simulation performed with the Adaptive Refinement Tree code (Kravtsov 1999; Kravtsov et al. 2002; Rudd et al. 2008). The simulation box has a comoving length of 500 \( h^{-1} \) Mpc, resolved using a uniform \( 512^3 \) root grid and eight subsequent levels of mesh refinement. The maximum comoving spatial resolution is 3.8 \( h^{-1} \) kpc.

We analyze a mass-limited sample of 65 galaxy clusters with \( M_{500c} \geq 3 \times 10^{14} h^{-1}M_\odot \) at \( z = 0.0 \) and their progenitors at \( z = 0.3, 0.5, \) and 0.7 to match the Chandra-SPT sample analyzed in McDonald et al. (2014). We then measure the average evolution of thermodynamic profiles in our sample.

Initial cluster identification uses a spherical overdensity halo finder described in Nelson et al. (2014b). The final cluster sample is from a re-simulated box with higher resolution dark-matter particles in regions of the identified clusters. The “zoom-in” technique results in an effective mass resolution of 2048\(^3\). For each cluster, this corresponds to a dark-matter particle mass of \( 9 \times 10^8 h^{-1}M_\odot \) inside a spherical region with a cluster-centric radius of three times the virial radius. Further details of the simulation can be found in Nelson et al. (2014b).

Since cluster core physics are not expected to significantly affect cluster outskirts, we present our main results using the Omega500 simulation with non-radiative (NR) gas physics. In order to assess the effects of baryonic physics, we also analyze the outputs of the Omega500 re-simulation with radiative cooling, star formation, and supernova feedback (CSF) based on the same sub-grid model of galaxy formation described in Nagai et al. (2007). We present CSF results in Section 4.6.

3.2. Averaged Radial Profiles

We compute average radial profiles by dividing the gas volume of a galaxy cluster halo into 99 concentric spherical shell bins centered at the minimum of the gravitational potential of the cluster. Throughout this work, we use bins of equal logarithmic spacing in the comoving radial distance from 10 \( h^{-1} \) kpc to 10 \( h^{-1} \) Mpc.

We compute the average temperature profile of each simulated galaxy cluster as

\[
T_w(r_i) = \frac{\sum_j w_{ij} T_{ij} \Delta V_j}{\sum_j w_{ij} \Delta V_j},
\]

where \( \Delta V_j \) is the volume occupied by the hydro cell \( j \) in the radial bin \( i \), \( T_{ij} \) is the temperature of the gas cell, and \( w_{ij} \) is the “weight” for the averaging. We adopt two different weighting schemes.

First, we compute a mass-weighted temperature profile \( T_{\text{mw}} \) with the weight set to the gas mass density of the hydro cell, \( w_{ij} = \rho_{g,j} \). Physically, the mass-weighted temperature corresponds to the specific internal energy of the cluster gas.

Second, we compute the spectral-temperature \( T_{\text{sp}} \), which is the average temperature weighted with the X-ray emission,

\[
w_{ij} = \rho_{g,j}^2 \Lambda_{\text{eff}}(T_{ij}, Z_{ij} = 0.3Z_{\odot}).
\]

\( \Lambda_{\text{eff}} \) is the effective cooling function in the 0.5–2.0 keV energy band using the MEKAL (Liedahl et al. 1995) plasma code, weighted by the effective area of the ACIS-I CCD on the Chandra X-ray telescope. Since the X-ray emission in the 0.5–2.0 keV energy range is not very sensitive to the adopted metallicity, we assume a constant abundance of \( Z = 0.3 \) solar throughout.

Finally, using the self-similar scaling defined by Equation (3), we normalize each galaxy cluster profile,

\[
\bar{T}(r/R_{500c}) = \frac{T(r/R_{500c})}{T_{500c}},
\]

where \( T_{500c} \equiv G M_{500c}/(2R_{500c}) \). We then calculate the average \( \bar{T} \) at each redshift in order to assess the departure of the average normalized temperature profile from self-similar evolution.

3.3. Decomposition of Diffuse and Clumpy Components

To assess the effects of gas clumping on the X-ray emissions, we decompose the ICM into the diffuse and clumpy components using the method described in Zhuravleva et al. (2013). The probability distribution function (PDF) of the density in each shell follows a log-normal distribution with a high density tail. We exclude small-scale gas clumps, infalling subhalos, and penetrating filaments by removing gas that has density higher than \( 2 \sigma \) from the median of the density PDF in each radial bin.

We denote the profiles calculated with or without substructures using the subscripts, “all” or “bulk,” respectively. The mass-weighted temperature profile with (or without) substructures is labeled by \( T_{\text{mw,all}} \) (or \( T_{\text{mw,bulk}} \)). Figure 1 illustrates the mass-weighted temperature maps for one of the simulated clusters. From left to right, the figure shows the temperature map for all gas, substructures, and bulk diffuse gas (see Figure 1 in Lau et al. 2015, for the corresponding projected gas density maps).

4. RESULTS

In this work, we investigate physical mechanisms that contribute to the evolution of scaled thermal temperature
profiles in the outskirts of galaxy clusters. These mechanisms include the evolution of overdense gas substructures, non-thermal gas motions, growth of the cluster halo with respect to the defined reference overdensity, non-equilibrium physics, and baryonic cooling and star formation. With a mass-limited simulated cluster sample, we assess the relative importance of factors that influence temperature profiles in galaxy cluster outskirts.

4.1. Evolution of Substructures

We first quantify the contribution of substructures to the evolution of the gas density profiles. The top panel of Figure 2 shows the ratio of the average density profile of all gas to that of the bulk component (without substructures), \( \Delta \rho \equiv \rho_{\text{all}}/\rho_{\text{bulk}} \), at different redshifts. We normalize the radial range of all profiles using \( R_{500,c} \) of each cluster before computing the average profiles of the cluster sample at each redshift. The lower panel shows the fractional difference of the gas density ratio at high redshifts relative to \( z = 0 \).

At all redshifts, the bulk component comprises more than 90% of the gas at \( r \lesssim R_{500, c} \), while substructures increasingly contribute with radius at \( r \gtrsim R_{500, c} \). Gaseous subhalos and filaments significantly boost the average gas density in the outskirts of galaxy clusters. Additionally, the relative contribution of dense substructures increases with redshift. For example, substructures at \( z = 2 \) boost the average gas density at \( r/R_{500, c} = 1.5 \) by \( \approx 30\% \). At \( z = 0 \), substructures boost the average gas density at that same radius by \( \lesssim 10\% \). High-redshift clusters contain an enhanced level of substructures compared to the low redshift counterparts.

4.2. Evolution of ICM Temperatures

Next, we examine the role of the non-thermal gas motions on the evolution of temperature profiles. The solid lines in the top panel of Figure 3 show the average radial profile of the normalized mass-weighted temperature, \( T_{\text{mw}} \), at \( z = 0.0, 0.3, 0.5, \) and 0.7. The solid lines in the bottom panel of Figure 3 show the ratio between \( T_{\text{mw}} \) at each redshift to that at \( z = 0 \): \( \Delta T_{\text{mw}}(r/R_{500, c}) \equiv T_{\text{mw}}(z)/T_{\text{mw}}(z = 0) - 1 \). A profile where \( \Delta T_{\text{mw}} \approx 0 \) at all radii would indicate that the cluster sample exhibits self-similar evolution when scaled with respect to \( R_{500, c} \).

The magnitude of \( \Delta T_{\text{mw}} \) systematically increases with redshift; the evolution is more dramatic in cluster outskirts. For example, \( \Delta T_{\text{mw}}(r/R_{500, c} = 1.5) \) at \( z = 0.5 \) is \( \approx 10\% \) and \( \Delta T_{\text{mw}}(r/R_{500, c} = 1.5) \) at \( z = 0.7 \) is \( \approx 30\% \). These evolutionary trends are consistent with the results of the recent Chandra measurements, where outskirt gas of high-redshift clusters have lower scaled temperatures than the gas of low redshift clusters (McDonald et al. 2014).

The dotted lines in Figure 3 show the average normalized profiles of the non-thermal temperature, \( T_{\text{nt}} \), at each redshift. At all redshifts, \( T_{\text{nt}} \) increases with radius. For the redshift range illustrated, the non-thermal temperature crosses over \( T_{\text{nt}} \) somewhere between 1.5 \( \lesssim r/R_{500, c} \lesssim 2 \). The crossover occurs at smaller cluster-centric radii in higher redshift clusters, when the potential well occupies a smaller radius. This result is consistent with a physical picture where accretion generated gas motions convert into thermal energy through shocks and
turbulent dissipation. The timescale of turbulent dissipation is shorter in the dense, inner regions of galaxy clusters (Shi & Komatsu 2014). Therefore, a larger fraction of gas motions is thermalized at smaller cluster-centric radii (Yu et al. 2015). The timescale difference leads to monotonically increasing (decreasing) thermal (non-thermal) scaled temperature profiles.

Furthermore, we find a significant redshift evolution in the normalization and shape of $T_m$. At $r/R_{500}$, $T_m$ increases by 40% between $z = 0.0$ and $z = 0.7$. High-redshift clusters have a higher level of the normalized non-thermal temperature than low-redshift clusters, because high-redshift clusters are dynamically younger with more active gas accretion events (Nelson et al. 2014a). The maximum of the $T_m$ profiles occurs at smaller cluster-centric radii at higher redshifts. As the halo grows, more gas begins to thermalize at larger radii, leading to the evolution in profile shape.

The evolution in the scaled profiles also corresponds to an evolution in the ratio between the kinetic and thermal energy in the ICM. We use the integrated Sunyaev–Zel’dovich signal, $Y_{fb}$, and its non-thermal counterpart, $Y_{nt}$, as proxies for the thermal and non-thermal ICM energies. We compute the average ratio between the thermal and kinetic energies within $R_{500}$ for a cluster with $M_{200c} = 10^{14} h^{-1} M_\odot$, with best-fit $\ln Y - \ln M$ relations given in Table 1 of Yu et al. (2015) for the same set of simulated sample of galaxy clusters. The ratio of non-thermal to thermal energies is found to be $Y_{nt}/Y_{fb} = 1/9$ at $z = 0$, and $Y_{nt}/Y_{fb} = 1/3$ at $z = 1$. Note that $Y_{nt}$ only includes the contribution from bulk random motions to the ICM, but contributions from rotational, streaming, and cross terms are negligibly small (Lau et al. 2013). Our simulated cluster sample exhibits a substantial difference in the energy budget between $z = 0$ and higher redshift clusters, with an increased fraction of non-thermal energy at high $z$.

Finally, the dashed lines in the top panel of Figure 3 show the average scaled total temperature profiles in each redshift bin. The scaled total temperature exhibits a remarkable degree of self-similar evolution in cluster outskirts, unlike the non-thermal and thermal temperature profiles. The total temperature self-similarly scales with respect to the critical density of the universe. The self-similar scaling is the same as the circular velocity profile (or potential well depth), as shown in Lau et al. (2015).

We conclude that the evolution in the scaled thermal temperature profile is driven primarily by the thermalization process of the cluster gas, where merger and accretion induced gas motions convert into the thermal energy component of the ICM.

### 4.3. Dependence on Halo Overdensity Definition

In this section, we highlight that the departure from the self-similarity depends on the definition of halo mass and radius. Figure 4 shows the ratio of the normalized mass-weighted, non-thermal, and total temperature profiles at each redshift to the profile at $z = 0$: $\Delta \bar{T} \equiv \bar{T}(z)/\bar{T}(z = 0) - 1$. Each panel corresponds to a normalization with respect to different reference overdensity values: $\Delta Z = 1600, 500, \text{and } 200$ defined with respect to the mean density (left panels) and the critical density of the universe (right panels). The range of the $x$-axis in each panel shows the same physical radii corresponding to the radial range of $0.1 < R/R_{500} < 2.7$ at $z = 0$.

The left panel of Figure 4 shows that a different choice of reference density with respect to the mean density results in varying degrees of self-similar evolution in the ICM profiles. Specifically, we find that the departure from the self-similar model diminishes for the smaller values of $\Delta_{\text{mean}}$. For example, the largest departure from the self-similar model is found for the largest reference mean overdensity of $\Delta = 1600 \text{m}$ in the bottom panel. Here, the fractional evolution since $z = 0.7$ in the normalized thermal temperature at $1.5 \times R_{600}$ is about 30%. In the middle panel, corresponding to $\Delta = 500 m$, the evolution decreases to $\sim 10\%$ at the same radius. In the top panel, corresponding to $\Delta = 200 m$, the evolution is even smaller at the level of $\sim 5\%$. Our results suggest that the reference overdensity of $\Delta = 200 m$ best captures the self-similar evolution of the ICM temperature. $\Delta_{\text{200m}}$ happens to be the radius scaling that best tracks the average evolution of the radial location of the accretion shock (Lau et al. 2015; Shi 2016), where much of the thermalization process in the ICM occurs.

The right panel of Figure 4, on the other hand, illustrates that the choice of different overdensities with respect to the critical density does not significantly affect the evolutionary trends in the inner regions, $r \lesssim R_{500}$. The critical density evolves slowly after $z \lesssim 1$ and tracks the evolution of the gravitational potential in the inner regions. The gas in the inner regions of the potential well has a shorter thermalization timescale. The gas beyond this radial range is less thermalized, especially at high redshifts due to the enhanced mass accretion. The increased normalization of the non-thermal temperature profiles at higher redshifts (indicated by dotted lines) indicates the decreased level of thermalization in the ICM. The total
temperature (indicated by dashed lines), on the other hand, remains self-similar with the difference of an order of 10\% between \( z = 0.7 \) and \( z = 0 \) regardless of reference overdensity with respect to critical.

### 4.4. Effects of Substructures

In this section, we quantify the relative contribution of substructures to the temperature evolution. We compare the average temperature profile, normalized to \( T_{500c} \), with and without high density gas that is associated with clumps, infalling subhalos, and filaments.

The solid linestyle in Figure 5 corresponds to the ratio of \( T_{mw,all} \), the normalized mass-weighted temperature of all gas, to \( T_{mw,bulk} \), the normalized mass-weighted temperature of the substructure-excluded bulk component. Each line color corresponds to the average ratio profile at \( z = 0.0, 0.3, 0.5 \), and 0.7 for our simulated cluster sample. The ratio \( \Delta T_{mw} = T_{mw,all}/T_{mw,bulk} \) is less than unity at all radii and all redshifts because the dense gas associated with substructures is typically cooler than the diffuse gas. At \( r/R_{500c} = 2 \), \( \Delta T_{mw} \) is 92\% at \( z = 0 \), \( \Delta T_{mw} \) decreases with redshift; by \( z = 0.7 \), the ratio drops to 70\% at \( r/R_{500c} = 2 \).

The dashed linestyle in the top panel of Figure 5 corresponds to the ratio \( \Delta T_{sp} = T_{sp,all}/T_{sp,bulk} \), where we use the spectral-weighted temperature with weighting given by Equation (7). The line colors also correspond to the average ratio profiles at \( z = 0.0, 0.3, 0.5 \), and 0.7. Within \( r/R_{500c} < 1.5 \), \( \Delta T_{sp} \) are nearly identical to those of \( \Delta T_{mw} \) at all redshifts. At larger radii, \( \Delta T_{sp} \) is closer to unity and evolves less than \( \Delta T_{mw} \).

The behavior of the \( \Delta T_{sp} \) profiles indicates that spectrally weighted gas more heavily weights gas in the bulk component. Spectral weighting has both a temperature and density dependence, whereas the mass weighting simply gives more weight to cells that contain more gas mass. The former places slightly more weight on the warmer bulk component of the gas.
at large radii, decreasing the difference between $\bar{T}_{\text{sp,all}}$ and $\bar{T}_{\text{sp,bulk}}$.

In summary, substructures lead to a change in the average normalized temperature profile at most 10% at $r/R_{500c} = 1.5$ from $z = 0.7$ to $z = 0$, regardless of the weighting scheme.

**4.5. Effects of Non-equilibrium Electrons**

The X-ray temperature is sensitive to the thermal energy of electrons in the ICM plasma. However, since the equilibration time of electrons and ions can be comparable to the Hubble time in the low-density outskirts of galaxy clusters (Spitzer 1962; Rudd & Nagai 2009), the X-ray measured ICM temperature could be biased low.

The temperature bias from non-equilibrium electrons also depends on the mass accretion rate and the mass of the cluster (Avestruz et al. 2015). On average, high-redshift clusters have higher mass accretion rates, which magnifies the bias. However, high-redshift clusters have lower average masses and therefore lower temperatures. We expect high-redshift clusters to then have shorter average Coulomb equilibration timescales, which counteracts the effect of higher mass accretion rates. Figure 6 illustrates the net effect of the non-equilibrium electron bias. We show the non-equilibrium electron bias, the profile of the ratio between the normalized electron temperature to the normalized mean gas temperature, $\Delta T_e = \bar{T}_e/\bar{T}_{\text{mw}}$ (upper panel). We also show the ratio of the bias at each redshift to the bias at $z = 0$, $\Delta T_e(z)/\Delta T_e(z = 0)$. At $r/R_{500c} \approx 1.5$, non-equilibrium electrons bias the temperature by a comparable amount at $z = 0$ as they do at $z = 0.7$ (see the $z = 0.7$ profile in the bottom panel of Figure 6). We therefore conclude that non-equilibrium electrons contribute no more than 5% to the temperature evolution between $z = 0$ and $z = 0.7$ at $r/R_{500c} \approx 1.5$.

**4.6. Effects of Baryonic Physics**

While we expect baryonic heating and cooling processes to minimally affect the outskirts of galaxy clusters, these dissipative processes can potentially introduce physical scales that break the self-similarity of ICM properties. To assess these effects, we analyze a re-simulation of the Omega500 box that includes radiative cooling, star formation, and supernova feedback (CSF). Since our CSF simulation does not include feedback from active galactic nuclei, this simulation suffers from the well-known “overcooling” problem. Due to overcooling, too many stars form in the cluster core, compared with observations. Overall, the CSF simulation overestimates the impact of baryonic effects. Results from our CSF simulations, therefore, provide an upper limit to the role of cooling and star formation.

Figure 7 shows the evolution of the ICM temperature profiles in the CSF simulation, with the same corresponding linestyles and axes as Figure 3 to enable direct comparison. The normalized mass-weighted temperature, $\bar{T}_{\text{mw}}$, within 0.1 $\lesssim r/R_{500c} \lesssim 1.0$ evolves to about 20% over the redshift range of $0 \leq z \leq 0.7$. The fractional evolution is roughly consistent with the evolutionary trend seen in the NR run. The non-thermal temperature profiles, $\bar{T}_{n}$, in the CSF run (dotted lines in the upper panel of Figure 7) show a higher normalization in the inner regions compared to their NR counterparts. Rotational gas motions induced by strong gas cooling in the CSF run boost the non-thermal temperature profile normalization (see, e.g., Lau et al. 2011). Finally, even with baryonic physics, the total temperature profile in the CSF run remains self-similar in the regions $0.2 \leq r/R_{500c} \leq 2.5$.

Figure 8 shows the temperature ratio $\Delta T = \bar{T}_{\text{all}}/\bar{T}_{\text{bulk}}$ in the CSF simulation. Similar to the results for the NR case in Figure 5, the temperature ratio shows little evolution within $r/R_{500c} \lesssim 1.5$ for both mass-weighted (solid lines) and X-ray spectral-weighted temperatures (dashed lines). In fact, the
3. The effects of spectral-weighting and non-equilibrium electrons each contribute less than a 10% effect in the evolution of the ICM temperature. Baryonic physics do not alter these conclusions.

These results suggest that the temperature evolution in the outskirts of galaxy clusters measured by McDonald et al. (2014) is primarily due to the evolution of the non-thermal pressure profiles in the ICM. Our findings contradict the original interpretation of “superclumping” as the driver for outskirt temperature evolution.

Our work further suggests that it is possible to account for the accretion induced non-thermal gas motions that affect departures from self-similar scaling. First, we find that an appropriate choice of cluster mass and radius can scale out the accretion dependence of the temperature profiles. In particular, the reference density of 200 times the mean background density best scales with the accretion shock in the outskirts and captures a self-similar evolution of the temperature profile in the outskirts. Other reference densities with respect to the mean density, e.g., $\rho_{1000m}$ and $\rho_{500m}$ do not scale as well. Second, we find that the “total” temperature, which is the sum of thermal and non-thermal gas energies, exhibits a remarkable degree of self-similar evolution when scaled with respect to the critical density.

However, currently, the total temperature is not a directly observable quantity. While X-ray and SZ observations can directly image the thermal component of the ICM, measurements of the non-thermal pressure contribution from gas motions require high angular or spectral resolution. Emerging observations in both the X-ray and microwave can measure fluctuations of ICM properties, which are sensitive to gas motions and the turbulent energy in the ICM (e.g., Schuecker et al. 2004; Gaspari et al. 2014; Khatri & Gaspari 2016). Future X-ray observatories with high spectral resolution, such as Athena+, promise to provide more direct measurements of gas motions in the ICM through Doppler broadening of Fe lines.

Note that our simulations do not include scale-dependent plasma physics, such as thermal conduction and magnetic fields. We expect these physical processes to have subdominant effects on the temperature evolution for the following reasons. Thermal conduction has long timescales in cluster outskirts; conduction should therefore be inefficient in outskirt regions (e.g., McCourt et al. 2013). Observations of the bulk gas in the Coma cluster support this picture (Gaspari & Churazov 2013). Magnetic fields can drive turbulence through magnetothermal instability (MTI; Parrish et al. 2012). However, McCourt et al. (2013) showed that MTI-driven turbulence is subdominant to the gas motions driven by mergers and accretion. Therefore, neither thermal conduction nor magnetic fields are likely to play significant roles in the evolution of temperature profiles in cluster outskirts. Other effects, such as pressure from cosmic rays, can in principle alter ICM properties in cluster outskirts. We leave the study of the effects of plasma physics for future work.

Additional work in cluster outskirts is necessary to fully understand ICM properties and their evolution. This will require a particular focus on: (1) improving theoretical modeling of both thermal and non-thermal components including turbulence, cosmic rays, magnetic fields, and their interactions; (2) deriving observational constraints on the non-thermal temperature/pressure in the ICM based on pressure fluctuations as well as direct measurements with upcoming.
X-ray missions; and (3) developing techniques to control the still poorly understood astrophysical uncertainties and their impact on cluster-based cosmological inferences.

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