On the Efficiency of Thermal Conduction in Galaxy Clusters

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Abstract

Galaxy clusters host a large reservoir of diffuse plasma with radially varying temperature profiles. The efficiency of thermal conduction in the intracluster medium (ICM) is complicated by the existence of turbulence and magnetic fields, and has received a lot of attention in the literature. Previous studies suggest that the magnetothermal instability developed in outer regions of galaxy clusters would drive magnetic field lines to be preferentially radial, resulting in efficient conduction along the radial direction. Using a series of spherically symmetric simulations, here we investigate the impact of thermal conduction on the observed temperature distributions in the outer regions of three massive clusters, and find that thermal conduction substantially modifies the ICM temperature profile. Within 3 Gyr, the gas temperature at a representative radius of 0.3r500 typically decreases by ~10%–20% and the average temperature slope between 0.3r500 and r500 drops by ~30%–40%, suggesting that the observed ICM would not stay in a long-term equilibrium state in the presence of thermal conduction. However, X-ray observations show that the outer regions of massive clusters have remarkably similar radially declining temperature profiles, suggesting that they should be quite stable. Our study thus suggests that the effective conductivity along the radial direction must be suppressed below the Spitzer value by a factor of 10 or more, unless additional heating sources offset conductive cooling and maintain the observed temperature distributions. Our study provides smoking-gun evidence for the suppression of parallel conduction along magnetic field lines in low-collisionality plasmas by kinetic mirror or whistler instabilities.

Key words: conduction – galaxies: clusters: intracluster medium – hydrodynamics – methods: numerical – plasmas – X-rays: galaxies: clusters

1. Introduction

As the largest gravitationally bound systems in the universe, galaxy clusters contain a large amount of hot, diffuse plasma, which is usually referred as the intracluster medium (ICM). X-ray observations by Chandra and XMM-Newton have been widely used to measure the density and temperature distributions of the ICM, finding that typical electron number densities of the ICM are in the range of $10^{-3}$–$10^{-1}$ cm$^{-3}$ and typical temperatures are $1$–$15$ keV (Peterson & Fabian 2006). Presumably heated by gravitational infall, the ICM is ionized and weakly collisional with a typical Coulomb mean free path $\lambda \sim 3(T/10$ keV)$^2(n_e/0.01$ cm$^{-3})^{-1}$ kpc, where $T$ and $n_e$ are the temperature and electron number density of the ICM, respectively. The ICM is also weakly magnetized with a typical magnetic field strength $B \sim 1$–$10$ $\mu$G, corresponding to a large plasma beta ($\beta = 8\pi P/\rho B^2$) of typically several hundreds (see Carilli & Taylor 2002 and Feretti et al. 2012 for recent reviews). The magnetic and low-collisionality nature of the ICM makes it an ideal laboratory to study plasma astrophysics.

The temperature profiles of many galaxy clusters have been measured by X-ray observations to a concentric radius of nearly $r_{500}$ or beyond, and show remarkable similarity in the outer parts of galaxy clusters beyond $\sim 0.1r_{500}$ with radially declining temperature profiles (Vikhlinin et al. 2005; Sanderson et al. 2006; Baldi et al. 2007; Pratt et al. 2007; Leccardi & Molendi 2008; Zhu et al. 2016). Here $r_\Delta$ is the radius enclosing a mean matter density of $\Delta$ times the critical density of the universe at the cluster redshift. The observed temperature gradients in the high-temperature ICM point to the potential importance of thermal conduction on the evolution of galaxy clusters, where the conduction timescale based on the classic Spitzer conductivity (Spitzer 1962) in an unmagnetized plasma could be substantially shorter than the cluster age. Thermal conduction in the ICM has thus attracted a lot of attention in the literature, particularly for cool-core clusters where inward conduction into low-temperature cool-core regions may potentially be an important energy source to solve the so-called cooling flow problem (Narayan & Medvedev 2001; Zakamska & Narayan 2003; Guo & Oh 2008; Guo et al. 2008). Due to the complications caused by magnetic fields and turbulence, the efficiency of thermal conduction in the ICM is a long-standing problem in astrophysics. Since the electron gyroradius is many orders of magnitude smaller than its Coulomb mean free path, thermal conduction in the ICM is expected to be highly anisotropic and dominated by parallel conduction along magnetic field lines (e.g., Narayan & Medvedev 2001; Robberg-Clark et al. 2016). The ICM is likely turbulent (see, e.g., Inogamov & Sunyaev 2003; Schuecker et al. 2004; Zhuravleva et al. 2014), and the tangled magnetic fields may strongly suppress effective thermal conduction by a factor of $10^2$ to $10^3$ (Rechester & Rosenbluth 1978; Chandran & Cowley 1998). However, if the turbulence extends over a wide range of length scales, Narayan & Medvedev (2001) argued that thermal conductivity can be boosted to be $\sim 1/5$ of the classic Spitzer value. Such efficient thermal conduction could contribute significantly to offsetting radiative cooling from cool-core regions of massive clusters (Zakamska & Narayan 2003; Guo & Oh 2008; Guo et al. 2008;
Jacob & Pfurtoener 2017). However, cool cluster cores typically exhibit radially increasing temperature profiles with positive gradients and are susceptible to the heat-flux-driven buoyancy instability (HBI; Quataert 2008), which may saturate by rearranging the magnetic field lines to be perpendicular to the radial direction, resulting in strong suppression of radial thermal conduction (Parrish & Quataert 2008; McCourt et al. 2011).4

On the other hand, the outer regions of clusters typically show radially declining temperature profiles with negative gradients and are susceptible to the magnetothermal instability (MTI; Balbus 2000), which would quickly reorient magnetic field lines to be preferentially radial (Parrish & Stone 2007; Parrish et al. 2008; Sharma et al. 2008). Therefore, thermal conduction becomes very efficient along the radial direction and is capable of substantially modifying the ICM temperature profiles in massive clusters within several billion years (Parrish et al. 2008). The outer regions of massive galaxy clusters are thus an ideal place to investigate the efficiency and impact of thermal conduction in diffuse, low-collisionality plasmas.

More recently, theoretical studies and particle-in-cell simulations indicate that parallel thermal conduction along magnetic field lines in a low-collisionality high-\(\beta\) plasma may be significantly suppressed by kinetic mirror or whistler instabilities on the length scale of the ion or electron gyroradius, respectively (Komarov et al. 2016; Riquelme et al. 2016). These kinetic-scale instabilities are triggered by pressure anisotropies resulting from plasma motions and amplify local magnetic fields, which pitch-angle scatter electrons and suppress the transport of heat. Roberg-Clark et al. (2016, 2018) and Komarov et al. (2017) further show that the electron heat flux could self-generate turbulence and drive whistler waves, which in turn strongly suppress thermal conduction. These studies suggest that thermal conduction in the ICM may be very inefficient. Nonetheless, observational evidences for the importance of these plasma microphysics processes are still scarce.

To investigate the efficiency of thermal conduction in galaxy clusters, in this paper we use a series of hydrodynamic simulations to study the impact of thermal conduction on the temperature profiles in the outer regions of three massive clusters: A1795, A2029, and A478. The temperature and density profiles of these clusters have been determined by Chandra X-ray observations out to a large radius \(~\sim r_{500}\) or beyond (Vikhlinin et al. 2005). The outer regions of these clusters show similar radially declining temperature profiles, and if electron heat conduction along magnetic field lines is not suppressed by kinetic instabilities, the MTI would quickly develop there and reorient field lines to be preferentially radial. Thermal conduction in the radial direction is thus expected to be very efficient with an effective conductivity estimated to be close to half of the Spitzer value (Parrish et al. 2008). We specifically choose these three massive clusters with high gas temperatures, corresponding to relatively short Spitzer conduction timescales. Starting with the observed ICM temperature and density profiles in hydrostatic equilibrium, we investigate the evolution of the ICM temperature profile under the influence of various levels of thermal conduction and aim to constrain the efficiency of thermal conduction with respect to the classic Spitzer value and find smoking-gun signatures of kinetic-scale instabilities in the ICM.

The rest of the paper is organized as follows. In Section 2, we describe the details of our methods, including hydrodynamic equations, modeling of thermal conduction, the ICM model, initial conditions, and the simulation setup. Then, we present the simulation results on the ICM temperature evolution in Section 3.1 and investigate the physics behind the ICM temperature evolution in Section 3.2. We discuss important implications of our simulations in Section 3.3. Finally, we summarize our main results in Section 4.

2. Methods

To the first-order approximation, the ICM distribution in galaxy clusters is spherically symmetric, which is also assumed in our model. X-ray observations indicate that, when scaled with the average cluster temperature and the virial radius, the radially declining temperature profiles in outer regions \((r \gtrsim 0.1r_{200})\) of galaxy clusters show remarkable similarity (e.g., Vikhlinin et al. 2005; Pratt et al. 2007), suggesting that they are likely long-lasting and stable. This is roughly consistent with predictions from cosmological simulations where the physics of thermal conduction has not yet been included (e.g., Loken et al. 2002; Borgani et al. 2004; Hahn et al. 2017), and further suggests that the temperature profiles in outer regions of massive clusters may be used to constrain the efficiency of thermal conduction in the ICM. If thermal conduction along the radial direction is efficient, it may substantially modify the temperature profiles so that they become inconsistent with observations. Along with these thoughts, in this paper we use a series of hydrodynamic simulations to investigate the evolution of the radial temperature profiles of three massive clusters A1795, A478, and A2029 under the influence of various physically motivated levels of thermal conduction. In this section below, we present the details of our methodology.

2.1. Basic Equations

We approximate the weakly collisional ICM as a thermal fluid and study its evolution under the influence of gravity and thermal conduction. The basic hydrodynamic equations governing the ICM evolution may be written as

\[
\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0, \tag{1}
\]

\[
\frac{d\mathbf{v}}{dt} = -\nabla P - \rho \nabla \Phi, \tag{2}
\]

\[
\frac{\partial e}{\partial t} + \nabla \cdot (e\mathbf{v}) = -P \nabla \cdot \mathbf{v} - \nabla \cdot \mathbf{F} - C, \tag{3}
\]

where \(\rho, \mathbf{v}, P, e\) are the density, velocity, pressure, and energy density of the ICM, respectively, \(\Phi\) is the gravitational potential in the ICM (see Section 2.3), and \(d/dt = \partial/\partial t + \mathbf{v} \cdot \nabla\). \(C\) is the radiative cooling rate per unit volume, and as the cooling time in the outer regions of galaxy clusters is typically longer than the age of the universe, it is set to \(C = 0\) in our simulations (see Figure 7 and the relevant text in Section 3.3). These basic hydrodynamic equations are closed by the relation \(P = (\gamma - 1)e\), where \(\gamma = 5/3\) is the adiabatic index.

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4 Strictly speaking, this is only correct in the extremely high-\(\beta\) case (i.e., when the initial magnetic fields are very weak). For intermediate field strengths more realistic for real clusters, Kunz et al. (2012) and Avara et al. (2013) show that vertical magnetic filaments form and are HBI-stable, enabling significant conductive heat flux.
The gas temperature $T$ and electron number density $n_e$ can be derived from the ideal gas law,

$$P = \frac{\rho k_B T}{\mu m_n} = \frac{\rho \mu e k_B T}{\mu},$$

where $k_B$ is Boltzmann’s constant, $m_n$ is the atomic mass unit, and $\mu = 0.62$ and $\mu_e = 1.18$ are the mean molecular weight per particle and per electron, respectively, corresponding to a fully ionized plasma with the Helium mass fraction $Y = 0.28$ (Zakamska & Narayan 2003; Guo & Oh 2008).

### 2.2. Modeling of Thermal Conduction

$F$ in Equation (3) is the heat flux due to thermal conduction, and it may be written as

$$F = -\kappa \nabla T,$$

where $\kappa$ is the effective conductivity in the ICM. As in previous studies (e.g., Narayan & Medvedev 2001; Komarov et al. 2016), the suppression of conductivity by turbulent magnetic fields and kinetic-scale instabilities is often represented by the effective conductivity reduced from the Spitzer formula,

$$\kappa_{\text{eff}} = f \kappa_{\text{sp}},$$

where $f$ (0 ≤ $f$ ≤ 1) is the conductivity suppression factor, and $\kappa_{\text{sp}}$ is the classic Spitzer Coulombic conductivity (Spitzer 1962),

$$\kappa_{\text{sp}} = \frac{1.84 \times 10^{-5}}{\ln \lambda} T^{5/2} \text{erg s}^{-1} \text{K}^{-7/2} \text{cm}^{-1},$$

where $\ln \lambda \sim 40$ is the usual Coulomb logarithm for the ICM (Cowie & McKee 1977).

Assuming spherical symmetry, our simulations focus on thermal conduction along the radial direction. The inner regions of galaxy clusters show positive temperature gradients and are susceptible to the HBL, which tends to rearrange magnetic field lines to be perpendicular to the radial direction, suppressing radial conduction. In contrast, outer regions of galaxy clusters exhibit negative temperature gradients and are susceptible to the MTI, which tends to rearrange magnetic field lines to be preferentially radial, enhancing radial conduction. Therefore, we treat radial thermal conductivity in the inner and outer regions of galaxy clusters separately:

$$f = \begin{cases} 
  f_{\text{in}} & \text{when } dT/dr > 0 \text{ (inner regions)}, \\
  f_{\text{out}} & \text{when } dT/dr \leq 0 \text{ (outer regions)}. 
\end{cases}$$

To investigate the impact of thermal conduction on the ICM temperature profile, we performed a large suite of hydrodynamic simulations with various levels of thermal conductivity for three massive galaxy clusters: A1795, A478, and A2029. Table 1 lists our simulations with the adopted values of $f_{\text{in}}$ and $f_{\text{out}}$. As discussed in Section 1, we focus on the outer regions of galaxy clusters with $dT/dr \leq 0$ (i.e., $r \geq r_{\text{peak}}$, where $r_{\text{peak}}$ is the radial location where the ICM temperature profile has the peak value; see Table 3). The value of $f_{\text{out}}$ is particularly important, and we consider three cases for $f_{\text{out}}$:

1. $f_{\text{out}} = 0.5$ represents efficient radial conductivity in largely radial magnetic fields induced by the MTI, which is expected to develop if thermal conduction along field lines operates unimpeded (Parrish et al. 2008).
2. $f_{\text{out}} = 0.3$ is the intermediate case, which may represent the level of thermal conductivity in a turbulent ICM (Narayan & Medvedev 2001) induced by external processes (e.g., cosmic inflows).
3. $f_{\text{out}} = 0.1$ represents the maximum level of thermal conductivity if thermal conduction along magnetic field lines is suppressed by kinetic mirror or whistler instabilities. Komarov et al. (2016) demonstrate that mirror instability alone could suppress conductivity along field lines by a factor of five. Along the radial direction, further suppression of conduction may result from the existence of non-radial field lines. Considering the most favorable situation where field lines are preferentially radial due to the MTI, this additional suppression factor is about 0.5, leading to $f_{\text{out}} = 0.1$. In reality, when mirror or whistler instabilities operate, the MTI may not have time to develop and field lines are thus not preferentially radial, with the result that the value of $f_{\text{out}}$ is significantly less than 0.1. In addition, Roberg-Clark et al. (2016) argued that unstable whistler waves driven by the electron heat flux may suppress thermal conduction by an extreme factor of $10^5$ (but see Roberg-Clark et al. 2018 and Komarov et al. 2017 for further discussions).

In addition, we also consider a case for each cluster where $f_{\text{out}} = f_{\text{in}} = 0$ (e.g., run A0 for A1795), and the ICM in this case remains in its initial hydrostatic equilibrium state, as expected.

Inner cluster regions with $r \leq r_{\text{peak}}$ contain cool cluster cores, where the temperature evolution is complicated by the
effects of radiative cooling and active galactic nucleus (AGN) feedback (see, e.g., McNamara & Nulsen 2012; Guo 2016; Guo et al. 2018) and is beyond the scope of the present work. Nonetheless, inward conduction in inner regions may affect the temperature evolution in outer regions, and therefore we consider two cases for the value of \( f_m \): \( f_m = f_{\text{out}} \) or 0. In the latter case, we manually turn off inward thermal conduction in outer regions with \( dT/dr > 0 \) and consider the impact of outward conduction alone on the outer temperature profile. Physically, the value of \( f_m \) is affected by the development of HBI and turbulence. For very weak magnetic fields, the HBI wraps field lines to be perpendicular to the radial direction, leading to \( f_m \sim 0 \) (Parrish & Quataert 2008). For intermediate magnetic fields, HBI-stable filaments form along the radial direction, enabling radial conduction at a level of 10%–25% of the Spitzer value (Avara et al. 2013).

### 2.3. Initial Conditions and Gravitational Potential

The initial conditions of our clusters are directly adopted from Chandra X-ray observations presented in Vikhlinin et al. (2005) and Vikhlinin et al. (2006). For the initial temperature profile, we adopt the analytic model in Vikhlinin et al. (2006), which fits very well the deprojected three-dimensional temperature distribution measured by Chandra:

\[
T(r) = T_0 \frac{(x + T_{\text{min}}/T_0)}{[1 + (r/r_i)^\gamma/b]^\alpha}.
\]

The numerical values of the parameters listed in this table are adopted from Vikhlinin et al. (2006).

### Table 2
Parameters for Initial Gas Temperature Profiles in Our Galaxy Clusters

| Cluster | \( T_0 \) \(^{a}\) (keV) | \( r_i \) \(^{a}\) (Mpc) | \( a \) | \( b \) | \( c \) | \( T_{\text{min}}/T_0 \) | \( r_{\text{cool}} \) \(^{a}\) (kpc) | \( a_{\text{cool}} \) |
|---------|-----------------|-----------------|--------|--------|--------|-----------------|--------------------|--------|
| A1795   | 9.68            | 0.55            | 0.00   | 1.63   | 0.9    | 0.10            | 77                 | 1.03   |
| A478    | 11.06           | 0.27            | 0.02   | 5.00   | 0.4    | 0.38            | 129                | 1.60   |
| A2029   | 16.19           | 3.04            | −0.03  | 1.57   | 5.9    | 0.10            | 93                 | 0.48   |

Note.

\(^{a}\) The numerical values of the parameters listed in this table are adopted from Vikhlinin et al. (2006).

### Table 3
Various Properties of Our Galaxy Clusters

| Cluster | \( r_{300} \) \(^{a}\) (kpc) | \( M_{500} \) \(^{a}\) \( (10^{14}M_\odot) \) | \( r_{\text{peak}} \) \(^{b}\) (kpc) | \( T_{\text{peak}} \) \(^{c}\) (keV) | \( 0.3r_{500} \) | \( T_{0.3r_{500}} \) \(^{d}\) (keV) |
|---------|-----------------|----------------|-----------------|-----------------|----------|--------------------|
| A1795   | 1235            | 6.03           | 258             | 6.73            | 370.5    | 6.54               |
| A478    | 1337            | 7.68           | 266             | 8.95            | 401.1    | 8.62               |
| A2029   | 1362            | 8.01           | 329             | 9.24            | 408.6    | 9.22               |

Note.

\(^{a}\) The values of \( r_{500} \) and \( M_{500} \) are adopted from Vikhlinin et al. (2006).

\(^{b}\) \( r_{\text{peak}} \) is the radial location where the initial temperature profile has the peak value.

\(^{c}\) \( T_{\text{peak}} \) is the maximum temperature in the initial ICM temperature profile.

\(^{d}\) \( T_{0.3r_{500}} \) is the initial gas temperature at \( r = 0.3r_{500} \).

where

\[
x = \left( \frac{r}{r_{\text{cool}}} \right)^{2_{\text{cool}}}.
\]

The values of the parameters in the above temperature model for each cluster are directly adopted from Vikhlinin et al. (2006), and listed in Table 2. The resulting initial temperature profiles of our clusters are shown in the left panel of Figure 1. In the right four columns of Table 3, we list the values of \( r_{\text{peak}} \), \( T_{\text{peak}} \), \( 0.3r_{500} \), and \( T_{0.3r_{500}} \) for each cluster. Here \( T_{\text{peak}} = T(r_{\text{peak}}) \) and \( T_{0.3r_{500}} = T(0.3r_{500}) \) are, respectively, the peak temperature and the temperature at \( r = 0.3r_{500} \) in the initial ICM temperature profile.
For initial gas density profiles, we adopt the analytic expression for the observed emission measure profile in Vikhlinin et al. (2006), which provides an adequately good fit to Chandra data for all our clusters:

\[
n_e n_p = n_0^2 \frac{(r/r_0)^{-\alpha}}{(1 + r^2/r_0^2)^{3\beta/2}} \frac{1}{(1 + r^3/r_1^3)^{3/2}} + \frac{n_{\odot}^2}{(1 + r^2/r_2^2)^{3\beta_2}},
\]

where \( n_p \) is the proton number density. The initial gas density profile could be derived via \( \rho = 1.27 m_p (n_e n_p)^{1/2} \), where \( m_p \) is the proton mass. The numerical values of density parameters in Equation (11) for our clusters are directly adopted from Vikhlinin et al. (2006), and listed in Table 4. The resulting initial electron number density profiles of our clusters are shown in the right panel of Figure 1.

We assume that the ICM is initially in hydrostatic equilibrium, i.e., \( \rho \nabla \Phi = -\nabla P \), which is used to solve for the gravitational potential \( \Phi \). Vikhlinin et al. (2006) show that the resulting \( \Phi \) profile is consistent with that contributed by a total density distribution of the Navarro–Frenk–White (NFW) profile (Navarro et al. 1996, 1997). The second and third columns of Table 3 list the numerical values of \( r_{500} \) and \( M_{500} \), respectively, of the corresponding NFW profile for each of our clusters. Except for central regions dominated by brightest cluster galaxies, \( \Phi \) in galaxy clusters is dominantly contributed by the dark matter distribution, and for simplicity, we assume that \( \Phi \) is fixed during our simulations.

2.4. Simulation Setup

Assuming spherical symmetry, we solve Equations (1)–(3) for the ICM by using the one-dimensional mode of the ZEUS-3D hydrodynamic code (Stone & Norman 1992; Clarke 1996, 2010). This particular version of the code has been successfully used in several previous studies (e.g., Guo & Oh 2008, 2009; Guo & Mathews 2014; Guo 2014).

Our computational domain extends from an inner boundary at \( r_{\text{min}} = 10 \) kpc to an outer boundary at \( r_{\text{max}} = 2 \) Mpc. We have also tried with smaller inner boundaries and larger outer boundaries and found that our conclusions do not change. We adopt a logarithmically spaced grid with \( (\Delta r)_i = 1/(\Delta r) = (r_{\text{max}}/r_{\text{min}})^{1/N_r} \), where \( N_r = 800 \) is the total number of active zones. We performed a convergence test for the radial resolution in the cluster A1795 with \( f_{\text{in}} = f_{\text{out}} = 0.1 \), and the results are shown in Figure 2. The outer temperature profile beyond its peak value converges very well in all our test runs with \( N_r \geq 400 \), while the inner temperature profile converges in runs with \( N_r = 800 \) and 1000. In all the simulations presented in the rest of the paper, the default resolution is chosen to be \( N_r = 800 \), corresponding to a smallest grid size \( \Delta r = 66 \) pc at the cluster center. At the inner radial boundary, we choose the regular outflow boundary condition (Stone & Norman 1992). At the outer boundary \( r_{\text{max}} = 2 \) Mpc (close to the virial radius of our clusters), we assume that the gas density and temperature are fixed with time, as they may be maintained by cosmic accretion of baryons into the cluster potential (also see Guo & Oh 2008 and Guo & Oh 2009). We start our simulations at \( t = 0 \) and typically stop at \( t = 7 \) Gyr.

3. Results

We performed a large suite of hydrodynamic simulations for three representative clusters: A1795, A478, and A2029, and here we present our main results in this section. In Section 3.1, we investigate the evolution of the ICM temperature profile in our simulations with different levels of conductivity. We discuss the relevant implications on the level of thermal conductivity and the potential importance of kinetic-scale instabilities in real clusters in Section 3.3.

3.1. Evolution of the ICM Temperature Profile

We first look at runs A0, B0, and C0 (for the cluster A1795, A478, and A2029, respectively), where thermal conduction is turned off (i.e., \( f_{\text{in}} = f_{\text{out}} = 0 \)). In each of these runs, the ICM temperature and density profiles do not evolve with time during...
the whole simulation, confirming that the clusters in our simulations are indeed initially in hydrostatic equilibrium.

We then investigate how different levels of conductivity affect the temperature evolution in our clusters. Figure 3 shows the evolution of temperature profiles in our simulations for A1795 (top row), A478 (middle row), and A2029 (bottom row) with the conductivity suppression factor \( f_{\text{out}} = 0.1 \) (left column), 0.3 (middle column), and 0.5 (right column). Figure 4 shows results in simulations with \( f_{\text{in}} = f_{\text{out}} \), while Figure 4 corresponds to runs with \( f_{\text{in}} = 0 \) (i.e., with inward conduction prohibited). It is clear that inward thermal conduction from the temperature peak to the cluster center has a dramatic impact on inner cool-core regions, especially in runs with \( f_{\text{in}} = 0.3 \) or 0.5, where the core temperature is gradually heated up to be roughly isothermal. This is consistent with previous global stability analyses of cluster models where cool cores could not be stably maintained by thermal conduction alone (Guo et al. 2008). On the other hand, the temperature evolution in outer regions \( (r > r_{\text{peak}}) \) is not substantially affected by the level of inward conduction in inner regions, as clearly seen by comparing runs with \( f_{\text{in}} = f_{\text{out}} \) shown in Figure 3 to the corresponding ones with \( f_{\text{in}} = 0 \) shown in Figure 4 (also see Figure 5). Therefore in the rest of the paper, we limit our analysis to the runs with \( f_{\text{in}} = f_{\text{out}} \).

As can be seen in the top panels of Figure 3, the evolution of the outer temperature profile in A1795 depends rather sensitively on the level of thermal conductivity: the larger the conduction suppression factor is, the more dramatic the temperature profile changes. The evolution of the outer temperature profile in run A1Y with \( f_{\text{out}} = 0.1 \) may be considered as insignificant, but in runs A3Y and A5Y with \( f_{\text{out}} = 0.3 \) and 0.5, respectively, the temperature evolution is really significant. For higher-temperature systems A478 and A2029 shown in the middle and bottom rows, the evolution of the outer temperature profiles in our runs with \( f_{\text{out}} = 0.1, 0.3, \) or 0.5 is all quite substantial. Furthermore, Figures 3 and 4 indicate that the temperature evolution in the outer regions in these simulations can be roughly separated into two stages: an early fast-evolving stage during \( 0 < t < 3 \) Gyr, and a later slowly evolving stage at \( t > 3 \) Gyr. During the former stage in runs with \( f_{\text{out}} = 0.3 \) or 0.5, the outer temperature profile evolves quickly, and particularly gas temperatures between \( r_{\text{peak}} \) and \( \sim 800 \) kpc drop substantially within about 3 Gyr.

In order to quantify the significance of temperature evolution in our simulations, we show in Figure 5 the evolution of the ICM temperature \( T_{r=0.3} \) at \( r = 0.3 r_{500} \) in our simulations for the clusters A1795 (top), A478 (middle), and A2029 (bottom). As shown in Table 3, \( r = 0.3 r_{500} > r_{\text{peak}} \) is located in outer
cluster regions with $dT/dr < 0$, and this location in our clusters has also been well studied by Chandra X-ray observations. Figure 5 shows clearly that the value of $T_{r=0.3\,r_{500}}$ drops with time due to thermal conduction, and the decrease in $T_{r=0.3\,r_{500}}$ is more significant in more massive clusters with larger values of $f_{\text{out}}$. When $f_{\text{out}} = 0.1$, the value of $T_{r=0.3\,r_{500}}$ drops from $t = 0$ to $t = 3 \text{ Gyr}$ by $\approx 5\%$ in A1795, and by $\approx 10\%$ in the more massive clusters A478 and A2029. When $f_{\text{out}} = 0.3$ or 0.5, $T_{r=0.3\,r_{500}}$ typically decreases by $\approx 10\%$–20% during this fast-evolving stage. Note that the temperature decrease is even more prominent at $r = r_{\text{peak}}$.

In addition to the decrease in gas temperatures, the temperature profile in the outer cluster regions becomes flatter, as clearly seen in Figures 3 and 4. To quantify this effect, we calculate the average temperature slope $\alpha_T$ between $0.3r_{500}$ and $r_{500}$:

$$\alpha_T = -\left( \frac{d \log T}{d \log r} \right) = \frac{\log T_{r=0.3\,r_{500}} - \log T_{r=r_{500}}}{\log r_{500} - \log (0.3r_{500})},$$

and we show its evolution in our simulations for the clusters A1795 (top), A478 (middle), and A2029 (bottom) in Figure 6. It is clear that the drop in the outer temperature slope $\alpha_T$ is more significant than that in gas temperatures. When $f_{\text{out}} = 0.3$ or 0.5, the value of $\alpha_T$ typically decreases by $\approx 30\%$–40% during the early fast-evolving stage $0 < t < 3 \text{ Gyr}$. Note that for the clusters A478 and A2029, $\alpha_T$ drops by $\approx 20\%$ from $t = 0$ to 3 Gyr even when $f_{\text{out}} = 0.1$.

### 3.2. Physics Behind the ICM Temperature Evolution

What drives the ICM temperature evolution in our simulations? According to the hydrodynamic Equations (1)–(3) and the ideal gas law, the temperature evolution is governed by

$$\frac{\partial T}{\partial t} = -\frac{T}{\gamma - 1} \nabla \cdot \mathbf{v} - \frac{T}{\gamma - 1} \nabla \cdot 
abla T,$$

where the terms on the right-hand side represent temperature variations due to adiabatic compression (or rarefaction), thermal conduction, and gas advection, respectively. Therefore, we may define the adiabatic timescale:

$$t_{\text{adi}} = \frac{T}{\gamma - 1} \left| \frac{\nabla \cdot \mathbf{v}}{\nabla \cdot \nabla T} \right| = \frac{1}{(\gamma - 1) I} \left| \nabla \cdot \mathbf{v} \right|,$$

the conduction timescale:

$$t_{\text{cond}} = \frac{T}{\gamma - 1} \left| \frac{\nabla \cdot \mathbf{F}}{\nabla \cdot \mathbf{F}} \right| = \frac{e}{\left| \nabla \cdot \mathbf{F} \right|},$$
and the advection timescale:

\[ t_{\text{adv}} = \frac{T}{|\mathbf{v} \cdot \nabla T|}, \tag{16} \]

for the temperature evolution as a function of radius in galaxy clusters.

Figure 7 shows the above timescales for the cluster A2029 at \( t = 0.1 \) Gyr (top row) and 3.5 Gyr (bottom row) in runs C1Y (left column; \( f = 0.1 \)), C3Y (middle column; \( f = 0.3 \)), and C5Y (right column; \( f = 0.5 \)). For comparison, also shown is the gas cooling time (green lines), defined as \( t_{\text{cool}} = e/(n_e n_i \Lambda(T)) \), where \( n_e n_i \Lambda(T) \) is the gas cooling rate per unit volume adopted from Equation (35) of Guo & Oh (2008), which is an analytic expression originally given by Tozzi & Norman (2001) to fit cooling rates in Sutherland & Dopita (1993) at metallicity \( Z = 0.3Z_\odot \). From Figure 7, it is clear that the gas cooling time in outer regions \( r > r_{\text{peak}} \) \( (r_{\text{peak}} = 329 \) kpc for A2029) is longer than 10 Gyr, which justifies our neglect of radiative cooling in our simulations. Note that radiative cooling is important in central regions \( (r < 100 \) kpc), where AGN feedback may play a key role in offsetting cooling (e.g., Guo & Oh 2008; Guo et al. 2018).

The top row of Figure 7 clearly shows that, at \( t = 0.1 \) Gyr, the conduction timescale \( t_{\text{cond}} \) in most outer regions is significantly shorter than all other timescales in all of our simulations with \( f = 0.1, 0.3, \) and \( 0.5 \), indicating that the early temperature evolution in outer regions is dominated by thermal conduction. The conduction timescale \( t_{\text{cond}} \) also decreases as the value of \( f \) increases, and when \( f = 0.3, \) or \( 0.5, t_{\text{cond}} \lesssim 4 \) Gyr in most outer regions. This confirms that the early fast temperature evolution during \( 0 < t < 3 \) Gyr discussed in Section 3.1 is driven by thermal conduction. Note that thermal conduction operates as a cooling mechanism for the ICM between the two \( t_{\text{cond}} \) peaks located at \( r \approx 150 \) and \( 1100 \) kpc, respectively. For the very inner and outer regions, conduction acts as a heating source for the ICM. These two \( t_{\text{cond}} \) peaks, which refer to the locations with \( \nabla \cdot F = 0 \), move with time, and the region with conductive cooling expands during our simulations.

The bottom panels of Figure 7 show that at \( t = 3.5 \) Gyr, the adiabatic timescale becomes comparable to the conduction
When temperature by the radial direction would lead to a decrease of the ICM the loss of thermal equilibrium, and thermal conduction along clusters would not stay in a long-term equilibrium state due to radius of in the simulations with gas cooling time for comparison. In these simulations, temperature slope timescale between 100 kpc and \( r_{500} \), indicating that compressional heating is competing with conductive cooling in these regions. Both timescales at this time are longer than 4 Gyr in most regions between 100 and 1000 kpc, which is consistent with the later slowly evolving stage at \( t \geq 3 \) Gyr found in Section 3.1.

The results for the other two clusters A1795 and A478 are very similar, except that the conduction timescale in A1795 is slightly longer due to its relatively lower temperature and thus conductivity. X-ray observations show that, when scaled with the average cluster temperature and the virial radius, the temperature profiles in outer regions \( (r \gtrsim 0.1r_{200}) \) of massive clusters are remarkably similar (e.g., Vikhlinin et al. 2005; Pratt et al. 2007), suggesting that our results in Sections 3.1 and 3.3 are very robust.

3.3. Implications and Discussions

Let us summarize our main findings in Sections 3.1 and 3.2. When \( f = 0.3 \) or larger, the ICM in outer regions of massive clusters would not stay in a long-term equilibrium state due to the loss of thermal equilibrium, and thermal conduction along the radial direction would lead to a decrease of the ICM temperature by \( \sim 10\% \sim 20\% \) within 3 Gyr at a representative radius of \( r = 0.3r_{500} \). During the same period, the average temperature slope \( \alpha_T \) between \( 0.3r_{500} \) and \( r_{500} \) typically decreases by \( \sim 30\% \sim 40\% \). Even when \( f = 0.1 \), \( T_{90,3r_{500}} \) drops by \( \sim 10\% \) and \( \alpha_T \) drops by \( \sim 20\% \) within 3 Gyr for massive clusters such as A478 and A2029.

However, when scaled with the average cluster temperature and the estimated virial radius, the observed temperature profiles in the outer regions of galaxy clusters show remarkable similarity (Vikhlinin et al. 2005; Pratt et al. 2007). Although these observed profiles still have substantial (typically \( \sim 10\% \sim 20\% \)) scatters around the average temperature profile, it is notable that the same average profile applies to clusters covering a substantial range in mass, including very massive clusters such as A478 and A2029 with relatively short conduction timescales, suggesting that this universal temperature distribution may be long-lasting and stable. If this is indeed the case, our simulations indicate that the effective thermal conductivity along the radial direction in the outer regions of massive clusters must be suppressed below the classic Spitzer value by a factor of 10 or more (i.e., \( f \lesssim 0.1 \)).

Thermal conduction along magnetic field lines may be strongly suppressed by kinetic mirror or whistler instabilities on the length scale of the ion or electron gyroradius (Komarov et al. 2016; Riquelme et al. 2016; Roberg-Clark et al. 2016), Komarov et al. (2016) show that mirror instability alone could suppress conductivity along field lines by a factor of five. Assuming that radial conduction is further suppressed by another factor of five due to tangled magnetic fields in turbulence (Narayan & Medvedev 2001), radial conductivity is roughly \( \sim 1/25 \) of the Spitzer value, consistent with our current results.

On the other hand, if thermal conduction along magnetic field lines is not suppressed, the MTI may develop in the outer regions of clusters with negative temperature gradients. When it saturates, magnetic field lines become largely radial, leading to efficient thermal conduction along the radial direction with \( f \sim 0.5 \) (Parrish et al. 2008), which is clearly in contradiction with the observed stable temperature profiles in outer regions of massive clusters. However, the development of MTI may be affected by g-mode overstabilities (Balbus & Reynolds 2010) or external turbulence driven by cosmic accretion (e.g., merging substructures), which
may further lead to tangled magnetic field lines. Due to strong suppression of effective conductivity by field-line tangling (Rechester & Rosenbluth 1978), this argument may potentially hinder us to put a strong constraint on the efficiency of conduction along magnetic field lines. While a comprehensive analysis is beyond the scope of the present paper, we note that if turbulence cascades and extends over a wide range of length scales, the effective conductivity may reach \( \sim 1/5 \) of the Spitzer value (Narayan & Medvedev 2001), which is still too large to be consistent with observations.

If true, the suppression of parallel conduction along magnetic field lines would have profound implications in several important topics in astrophysics. It could easily explain the existence of sharp temperature jumps across cold fronts observed in many galaxy clusters (Zuhone & Roediger 2016). It could affect the slope of the power spectrum of gas density perturbations in galaxy clusters (Gaspari & Churazov 2013; Eckert et al. 2017) and explain the long-lasting temperature gradients observed in ram-pressure-stripped gas tails in galaxy clusters (De Grandi et al. 2016). It implies that thermal conduction contributes negligibly to heating cool cores of galaxy clusters, corroborating the current paradigm that AGN feedback plays the key role in solving the cooling flow problem (McNamara & Nulsen 2012). It also has important implications for hot circumgalactic medium around galaxies (e.g., the Milky Way; Guo & Mathews 2012; Fang et al. 2013) and the local thermal instability therein (Tumlinson et al. 2017) and for hot accretion flows around black holes (Bu et al. 2011; Yuan & Narayan 2014).

If radial conductivity in real clusters is larger than \( \sim 1/10 \) of the Spitzer value (i.e., \( f \gtrsim 0.1 \)), our study implies that additional heating sources must operate in the outer regions of massive clusters to offset the effect of thermal conduction and maintain the observed temperature distributions. One potential heating source is accretion shocks formed when cosmic baryonic matter falls into galaxy clusters (e.g., McCourt et al. 2013). However, cosmological simulations indicate that for relaxed galaxy clusters, dark matter haloes are typically in the later slow accretion phase when cosmic accretion mainly affects the very outer regions and the mean radial velocity of dark matter within \( r \lesssim r_{200} \) is about zero (Zhao et al. 2003; Cuesta et al. 2008). This suggests that cosmic accretion may not have a strong impact on the ICM regions of our interest (say, \( r \lesssim r_{500} \)). Furthermore, the observed temperature profiles in the outer regions of massive clusters are roughly consistent with cosmological hydrodynamic simulations where thermal conduction is not considered (e.g., Loken et al. 2002; Borgani et al. 2004; Hahn et al. 2017). Future cosmological simulations incorporating thermal conduction would be helpful to investigate this issue in greater detail.

4. Summary

As one major type of low-collisionality plasma in the universe, the hot, diffuse ICM is the dominant baryonic component in galaxy clusters. Due to the high temperatures of the ICM, thermal conduction is expected to be very efficient along magnetic field lines in the traditional kinetic theory (Spitzer 1962). While complicated by the existence of turbulence and magnetic fields, the efficiency and effects of thermal conduction in the ICM have thus received a lot of attention in the literature. The outer regions of galaxy clusters typically have radially declining temperature profiles, and previous studies suggest that the MTI may develop in these regions and quickly reorient magnetic field lines to be largely radial, resulting in efficient thermal conduction along the radial direction (Balbus 2000; Parrish & Stone 2007; Parrish et al. 2008; Sharma et al. 2008). Such efficient radial conduction is expected to have a substantial impact on the observed temperature profiles in the outer cluster regions, which may potentially be an ideal testbed to investigate the efficiency of thermal conduction in low-collisionality plasmas.

In this paper, we performed a series of hydrodynamic simulations to investigate the impact of thermal conduction on the radially declining temperature profiles in the outer regions of three representative massive clusters, A1795, A478, and A2029, which have all been well observed by Chandra X-ray observations up to a relatively large radius of nearly \( r_{500} \) or beyond. Starting with the observed temperature and density distributions in hydrostatic equilibrium, we investigate how different levels of thermal conduction affect the evolution of the ICM temperature profile. Our simulations clearly indicate that thermal conduction substantially modifies the ICM temperature profile, whose evolution can be roughly separated into two stages: an early fast-evolving stage during \( 0 < t < 3 \) Gyr dominated by thermal conduction, and a later slowly evolving stage at \( t > 3 \) Gyr under the effects of both conduction and adiabatic compression. When the conductivity suppression factor \( f = 0.3 \) or larger, the gas temperature at a representative radius of \( 0.3r_{500} \) typically decreases by \( \sim 10\% - 20\% \) and the average temperature slope \( \alpha_T \) between \( 0.3r_{500} \) and \( r_{500} \) drops by \( \sim 30\% - 40\% \) during the first stage. Even when \( f = 0.1 \), \( T_{0.3r_{500}} \) drops by \( \sim 10\% \) and \( \alpha_T \) drops by \( \sim 20\% \) within \( 3 \) Gyr for massive clusters such as A478 and A2029.

Our simulations therefore indicate that the outer regions of massive clusters would not remain in a long-term equilibrium state if the effective thermal conductivity along the radial direction is larger than \( \sim 1/10 \) of the classic Spitzer value. However, X-ray observations show that the outer regions of massive clusters have remarkably similar radially declining temperature profiles (e.g., Vikhlinin et al. 2005; Pratt et al. 2007), suggesting that the observed temperature distributions in outer cluster regions are usually long-lasting and stable. Our study thus suggests that the effective conductivity along the radial direction in the outer cluster regions must be suppressed below the Spitzer value by a factor of 10 or more, unless additional heating sources offset conductive cooling, maintaining the observed temperature distributions.

Our results are consistent with recent theoretical studies on the suppression of parallel conduction along magnetic field lines in low-collisionality plasmas by mirror or whistler instabilities on kinetic scales (Komarov et al. 2016; Riquelme et al. 2016; Roberg-Clark et al. 2016). On the other hand, if thermal conduction along magnetic field lines operates unimpeded, effective conduction along the radial direction is expected to be quite efficient in the outer cluster regions, no matter whether the MTI or external turbulence dominates \( (f \sim 0.5 \text{ and } \sim 0.2) \). This is in contradiction with the rather stable outer temperature profiles of massive clusters commonly observed by X-ray observations. Our study may provide smoking-gun evidence for the suppression of parallel conduction along magnetic field lines by kinetic mirror or whistler instabilities in low-collisionality plasmas.
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References

Avara, M. J., Reynolds, C. S., & Bogdanović, T. 2013, ApJ, 773, 171
Balbus, S. A. 2000, ApJ, 534, 420
Balbus, S. A., & Reynolds, C. S. 2010, ApJL, 720, L97
Baldi, A., Ettori, S., Mazzotta, P., Tozzi, P., & Borgani, S. 2007, ApJ, 666, 835
Borgani, S., Murante, G., Springel, V., et al. 2004, MNRAS, 348, 1078
Bu, D.-F., Yuan, F., & Stone, J. M. 2011, MNRAS, 413, 2808
Carilli, C. L., & Taylor, G. B. 2002, ARA&A, 40, 319
Chandran, B. D. G., & Cowley, S. C. 1998, PhRvL, 80, 3077
Clarke, D. A. 1996, ApJ, 457, 291
Clarke, D. A. 2010, ApJS, 187, 119
Cowie, L. L., & McKee, C. F. 1977, ApJ, 211, 135
Cuesta, A. J., Prada, F., Klypin, A., & Moles, M. 2008, MNRAS, 389, 385
De Grandi, S., Eckert, D., Molendi, S., et al. 2016, A&A, 592, A154
Eckert, D., Gaspari, M., Owers, M. S., et al. 2017, A&A, 605, A25
Fang, T., Bullock, J., & Boylan-Kolchin, M. 2013, ApJ, 762, 20
Feretti, L., Giovannini, G., Govoni, F., & Murgia, M. 2012, A&ARv, 20, 54
Gaspari, M., & Churazov, E. 2013, A&A, 559, A78
Guo, F. 2014, ApJL, 797, L34
Guo, F. 2016, ApJ, 826, 17
Guo, F., Duan, X., & Yuan, Y.-F. 2018, MNRAS, 473, 1332
Guo, F., & Mathews, W. G. 2012, ApJ, 756, 181
Guo, F., & Mathews, W. G. 2014, ApJ, 780, 126
Guo, F., & Oh, S. P. 2008, MNRAS, 384, 251
Guo, F., & Oh, S. P. 2009, MNRAS, 400, 1992
Guo, F., Oh, S. P., & Ruszkowski, M. 2008, ApJ, 688, 859
Hahn, O., Martizzi, D., Wu, H.-Y., et al. 2017, MNRAS, 470, 166
Inogamov, N. A., & Sunyaev, R. A. 2003, AStL, 29, 791
Jacob, S., & Pfrommer, C. 2017, MNRAS, 467, 1449
Komarov, S., Schekochihin, A., Churazov, E., & Spitkovsky, A. 2017, arXiv:1711.11462
Komarov, S. V., Churazov, E. M., Kunz, M. W., & Schekochihin, A. A. 2016, MNRAS, 460, 467
Kunz, M. W., Bogdanović, T., Reynolds, C. S., & Stone, J. M. 2012, ApJ, 754, 122
Lecceardi, A., & Molendi, S. 2008, A&A, 486, 359
Loken, C., Norman, M. L., Nelson, E., et al. 2002, ApJ, 579, 571
McCourt, M., Parrish, I. J., Sharma, P., & Quataert, E. 2011, MNRAS, 413, 1295
McCourt, M., Quataert, E., & Parrish, I. J. 2013, MNRAS, 432, 404
McNamara, B. R., & Nulsen, P. E. J. 2012, NuPh, 14, 055023
Narayan, R., & Medvedev, M. V. 2001, ApJL, 562, L129
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Parrish, I. J., & Quataert, E. 2008, ApJL, 677, L9
Parrish, I. J., & Stone, J. M. 2007, ApJ, 664, 135
Parrish, I. J., Stone, J. M., & Lemaster, N. 2008, ApJ, 688, 905
Peterson, J. R., & Fabian, A. C. 2006, PhR, 427, 1
Pratt, G. W., Böhringer, H., Croston, J. H., et al. 2007, A&A, 461, 71
Quataert, E. 2008, ApJL, 673, 758
Rechuster, A. B., & Rosenbluth, M. N. 1978, PhRvL, 40, 38
Riquelme, M. A., Quataert, E., & Verscharen, D. 2016, ApJ, 824, 123
Roberg-Clark, G. T., Drake, J. F., Reynolds, C. S., & Swisdak, M. 2016, ApJL, 830, L9
Roberg-Clark, G. T., Drake, J. F., Reynolds, C. S., & Swisdak, M. 2018, PhRvL, 120, 035101
Sanderson, A. J. R., Ponman, T. J., & O’Sullivan, E. 2006, MNRAS, 372, 1496
Scheuerer, P., Finoguenov, A., Miniati, F., Börhringer, H., & Brüel, U. G. 2004, A&A, 426, 387
Sharma, P., Quataert, E., & Stone, J. M. 2008, MNRAS, 389, 1815
Spitzer, L. 1962, Physics of Fully Ionized Gases (2nd ed.; New York: Interscience)
Stone, J. M., & Norman, M. L. 1992, ApJS, 80, 753
Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253
Tozzi, P., & Norman, C. 2001, ApJ, 546, 63
Tumlinson, J., Peeples, M. S., & Werk, J. K. 2017, ARA&A, 55, 389
Vikhlinin, A., Kravtsov, A., Forman, W., et al. 2005, ApJ, 628, 655
Yuan, F., & Narayan, R. 2014, ARA&A, 52, 529
Zakamska, N. L., & Narayan, R. 2003, ApJ, 582, 162
Zhu, Z., Xu, H., Wang, J., et al. 2016, ApJ, 816, 54
Zhu, Z., Xu, H., Wang, J., & Zhou, T. 2018, ApJ, 816, 54
Zhu, Z., Xu, H., Wang, J., et al. 2016, A&ARv, 24, 56