**Cool-core Clusters: The Role of BCG, Star Formation, and AGN-driven Turbulence**

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**Abstract**

Recent observational studies of cool cluster cores that include the BCG gravity claim that the observed threshold in \(\text{min}(t_{\text{cool}} / t_{\text{ff}})\) (cooling time to free-fall time ratio) lies at a somewhat higher value, close to 10–30, compared with the threshold seen in numerical simulations. There are only a few clusters in which this ratio falls much below 10. In this paper, we compare 3D hydrodynamic simulations of feedback active galactic nuclei (AGNs) jets interacting with the intracluster medium, with and without a BCG potential. We find that, for a fixed feedback efficiency, the presence of a BCG does not significantly affect the temperature, but increases (decreases) the core density (entropy) on average. Most importantly, \(\text{min}(t_{\text{cool}} / t_{\text{ff}})\) is only affected slightly by the inclusion of the BCG gravity. Also notable is that the lowest value of \(\text{min}(t_{\text{cool}} / t_{\text{ff}})\) in the NFW+BCG runs is about twice as large as in the NFW runs. We also look at the role of depletion of cold gas due to star formation, and show that it only affects the rotationally dominant component, while the radially dominant component remains largely unaffected. Stellar gas depletion also increases the repetition rate of AGN jets. The distribution of metals due to AGN jets in our simulations is predominantly along the jet direction, and the equatorial spread of metals is less compared with the observations. We also show that the turbulence in cool-core clusters is weak, which is consistent with recent Hitomi results on the Perseus cluster.

**Key words:** galaxies: clusters: intracluster medium – galaxies: halos – galaxies: jets

### 1. Introduction

Dense X-ray emitting plasma in cool cluster cores is susceptible to thermal fragmentation, leading to the formation of a multiphase medium consisting of cold, dense clouds condensing from the hot intracluster medium (ICM). The infall and accretion of these cold clouds onto the central super massive black hole (SMBH) powers the active galactic nuclei (AGNs) outbursts that maintain the ICM (Pizzolato & Soker 2005) in rough thermal balance. Early idealized simulations predicted that cold gas stochastically condenses out of the hot ICM if the minimum in the ratio of the cooling time to the free-fall time \(\text{min}(t_{\text{cool}} / t_{\text{ff}})\) falls below a threshold close to 10 (McCourt et al. 2012; Sharma et al. 2012). This cold gas is expected to lose angular momentum due to cloud–cloud collisions, and due to drag imparted by the hot gas, fall inward and fuel AGN outbursts (Gaspari et al. 2013; Prasad et al. 2016). The feedback process is self-regulatory with phases dominated by radiative cooling and jet heating (McNamara et al. 2005; Rafferty et al. 2006). Several recent feedback jet simulations that evolved over cosmological timescales are now able to reproduce the gross observed properties of cool cluster cores (Gaspari et al. 2012; Li et al. 2015; Prasad et al. 2015; Yang & Reynolds 2016b).

As AGN feedback is triggered by the precipitation of cold gas from the hot ICM (Sharma et al. 2012; Voit et al. 2015), the feedback process is sensitively dependent on the properties of X-ray-emitting gas in cluster cores. Recent works like Voit & Donahue (2015) and Hogan et al. (2017a, 2017b) highlight the importance of explicitly including the central brightest cluster galaxy (BCG) to determine the acceleration due to gravity \((g)\) and free-fall time \((t_{\text{ff}} \equiv \sqrt{2gr}/3)\) in cluster cores. Most cool-core clusters have BCGs at their centers, whose gravity dominates the gravity due to the dark matter halo within the central 20–30 kpc. Hogan et al. (2017b) argue that including the BCG gravity increases \(\text{min}(t_{\text{cool}} / t_{\text{ff}})\) in most cool-core clusters above 10, hence observations are in tension with the simulation results that find \(\text{min}(t_{\text{cool}} / t_{\text{ff}})\) drop down to a few (albeit for a short time). In this paper, we test whether including the BCG potential changes the value of \(\text{min}(t_{\text{cool}} / t_{\text{ff}})\) in the jet-ICM simulations, and compare our simulation results with observations.

The AGN-ICM coupling can happen through shocks (Fabian et al. 2003; Li et al. 2016); turbulence (Zhuravleva et al. 2014); mixing (Banerjee & Sharma 2014; Hillel & Soker 2016); entrainment (McNamara et al. 2005; Pope et al. 2010); cosmic rays and thermal conduction (Voigt & Fabian 2004; Guo & Oh 2008; Sharma et al. 2009a); or a combination of these processes (Cielo et al. 2018). However, the relative importance of these various processes in heating the cluster core is not clear. Among these mechanisms, turbulent heating seems to be ruled out by recent Hitomi observations of the Perseus cluster (Hitomi Collaboration et al. 2016), which show that the turbulence level in the cluster core is weak. Even if turbulent heating may not be the dominant mechanism for core heating, turbulent mixing and diffusion still play an important role in core thermodynamics and in transporting out the freshly created metals in star-forming cool cluster cores. Consequently, another aim of this paper is to compare AGN-driven turbulence in our simulations with the observational constrains on ICM turbulence.

In addition to maintaining rough thermal equilibrium in cool-core clusters, the lobes and cavities inflated AGN jets, as they rise buoyantly to 100s of kpc, which also play a potential role in distributing metals by entraining metal-enriched gas (Revaz et al. 2008; Pope et al. 2010) from star-forming inner regions of the cool-core clusters. Observations show that in nearby cool-core clusters, the central \(\sim100\) kpc have a sharply rising metallicity, while the outer regions have a constant metallicity (Tamura et al. 2004; Fujita et al. 2008; Simionescu et al. 2011;
The dark matter halo mass \((M_{200})\) for all of our runs is \(7 \times 10^{14} M_\odot\). One of our runs uses only the NFW gravitational potential (Navarro et al. 1997). For the other two runs, the external gravitational potential is the sum of two different potentials: (1) NFW dark matter potential and (2) a singular isothermal sphere (SIS) for the central brightest cluster galaxy, \(\Phi = \Phi_{\text{NFW}} + \phi_{\text{SIS}}\).

\[
\Phi_{\text{SIS}}(r) = \frac{4\pi G \rho_0 a_0^2}{\ln(r/a_0)} \tag{2}
\]

where \(\rho_0 = 1.67 \times 10^{-23} \text{ g cm}^{-3}\), and \(a_0 = 3 \text{ kpc}\). The isothermal sphere circular velocity, \(V_c = \sqrt{4\pi G \rho_0 a_0^2} = 350 \text{ km s}^{-1}\). The circular velocity is in the range of \(V_c\) observed in the cluster sample of Hogan et al. (2017a) (note that this paper uses the equivalent stellar velocity dispersion \(\sigma_s = V_c/\sqrt{2}\)).

2.2. Grid, Initial, and Boundary Conditions

We perform our simulations in spherical coordinates with \(0 \leq \theta \leq \pi\), \(0 \leq \phi \leq 2\pi\), and \(r_{\text{min}} \leq r \leq r_{\text{max}}\), with \(r_{\text{min}} = 0.5 \text{ kpc}\), and \(r_{\text{max}} = 500 \text{ kpc}\). We use a logarithmically spaced grid in radius, and an equally spaced grid in \(\theta\) and \(\phi\).

The outer electron number density is fixed to be \(n_e = 7 \times 10^{-4} \text{ cm}^{-3}\). Given the entropy profile with a core (Equation (7) in Prasad et al. 2015) and the outer density, we solve for hydrostatic equilibrium and obtain the density and pressure profiles in the gravitational potential (for details, see Prasad et al. 2015). As in Prasad et al. (2015), we introduce small (maximum over-density is 0.3) isobaric density perturbations on top of the smooth density. The gas is allowed to cool to 50 K, unlike in Prasad et al. (2015), where cooling was cutoff at \(10^4\) K.

We apply outflow boundary conditions at the inner radial boundary, where gas is allowed to go out of the computational domain, but not allowed to enter it. We fix the density and pressure at the outer radial boundary to the initial value, and the gas is not allowed to flow in/out of the outer radial boundary. Reflective boundary conditions are applied in \(\theta\) (with the sign of \(v_\phi\) flipped at the poles), and periodic boundary conditions are used in \(\phi\).

2.3. Stellar Gas Depletion

One of our runs (see Table 1) implements a crude model for mass depletion of cold gas due to star formation. To simulate the removal of cold gas due to star formation, we deplete the cold gas with temperature \(T < 0.005 \text{ keV} \approx 2 \times 10^4 \text{ K}\) and density \(\rho > 10^{-24} \text{ g cm}^{-3}\), using a sink term in the mass conservation equation

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = S_\rho - D_\rho, \tag{3}
\]

where the depletion term \(D_\rho = \rho / \tau\), and \(\tau = 200 \text{ Myr}\) is the gas depletion timescale (this is on the lower side of the range seen in observations; e.g., see Figure 9 in Pulido et al. 2018). Note that there is a large uncertainty in the determination of the star formation rate (SFR), hence \(\tau\) (e.g., see Mittal et al. 2015). Our choice of \(\tau\) is such that our cold gas mass is in a range consistent with observations. Here, \(S_\rho\) is the usual AGN jet-
mass source term as in Equation (1) of Prasad et al. (2015). Note that, unlike here, in Prasad et al. (2016) we only accounted for stellar depletion in post-processing. We do not consider feedback due to star formation because it is sub-dominant compared with AGN feedback in massive halos.

### 2.4. Metallicity

Using our realistic cool-core simulations, we also wish to study the jet-driven transport of metals produced recently (after the majority of stars within the cluster have already formed and the cluster with a cool core is assembled) in the BCGs of cool-core clusters. To quantify the spread of metals in the ICM, we evolve the passive scalar equation with a source term in the jet-mass source term

\[
\frac{\partial Z}{\partial t} + v \cdot \nabla Z = Z_j \frac{S_j}{\rho},
\]

where \( Z \) is the metallicity defined as the ratio of metal mass and total gas mass (normalized to the solar value, \( Z_{\odot} \)), \( Z_j \) is the normalization of the jet metallicity, and \( S_j \) is the jet-mass source term (see Equation (3)). The jet metallicity, \( Z_j \), is somewhat arbitrary, as our focus is on the spatial spread of metals due to AGN jets on \( \sim 100 \) kpc scales, rather than the actual value of metallicity. We choose \( Z_j = 100 \), as it gives a reasonable metallicity values for the simulated ICM. This value is also justified by considering the mass-loading factor of AGN jets relative to the SFR in the BCG. From our jet feedback prescription, \( M_j = (\epsilon e^2 / v^2) M_{\text{acc}} = 0.05 M_{\text{acc}} \) for our parameters.\(^3\) The mass accretion rate at 0.5 kpc is \( \sim 5 M_\odot \) yr\(^{-1}\) (see Table 1). On the other hand, the average SFR is expected to be a few 10s of \( M_\odot \) yr\(^{-1}\). Because all of the metals produced due to star formation in the BCG are deposited in the jet region in our simulations, \( Z_j \sim (\text{SFR} / M_{\text{acc}}) \times (M_{\text{acc}} / M_j) \approx 5 \times 20 = 100 \) is a reasonable order of magnitude normalization for the metal source term.

In our metallicity profiles (see Figures 9 and 10), we add 0.3 \( Z_{\odot} \) to account for the ambient metallicity close to the viral radius due to early enrichment. The radial spread of metals due to AGN jets is quantified using the average metallicity over radial shells,

\[
Z(r) = \frac{\int_0^r \int_0^{2\pi} Z(r, \theta, \phi) \rho \sin \theta d\theta d\phi}{\int_0^r \int_0^{2\pi} \rho \sin \theta d\theta d\phi},
\]

where \( r \) is the radius. Similarly, the angular distribution of metallicity due to AGN jets is quantified by averaging over the \( r \) and \( \phi \) directions as

\[
Z(\theta) = \frac{\int_0^\pi \int_0^{2\pi} Z(r, \theta, \phi) \rho r \sin \theta dr d\phi}{\int_0^\pi \int_0^{2\pi} \rho r \sin \theta dr d\phi}.
\]

### 3. Results

In this section, we describe the important results of our simulations. Table 1 lists all of our runs. We show that the inclusion of BCG potential does not affect the cluster temperature, but affects the average electron number density, \( t_{\text{cool}}/t_{\text{ff}} \), and entropy profiles in the core. We study the effect of stellar cold gas depletion on cluster evolution. We also show that the turbulence level in cluster cores is weak, consistent with the recent \textit{Hitomi} results. We find that the metal distribution is anisotropic and too narrow in radius as compared with the observations.

#### 3.1. NFW versus NFW+BCG Potential

##### 3.1.1. Average 1D Profiles

Figure 1 shows the initial angle-averaged profiles of electron number density, temperature, \( t_{\text{cool}}/t_{\text{ff}} \), and gravitational acceleration (\( g \)) for the runs with NFW and NFW+BCG potentials.
The plots show that the effect of the BCG is felt only within the central 50 kpc of the cluster. The density and temperature in the core are nearly double when the BCG potential is included. The bottom-right panel of Figure 1 shows that the inclusion of the BCG potential makes the gravitational acceleration rise sharply at small radii. This affects the $t_{\text{cool}}/t_{\text{ff}}$ profile in the inner regions ($r \lesssim 20$ kpc). The BCG potential, as we will discuss later, also shortens the feedback response time and prevents $\min(t_{\text{cool}}/t_{\text{ff}})$ in NFW+BCG runs from falling below $\approx 2$. The initial $\min(t_{\text{cool}}/t_{\text{ff}})$ is 8.8 for the NFW run, while it is 9.8 for the NFW+BCG run.

Figure 2 shows the mean and $1 - \sigma$ spread in the angle-averaged, emissivity-weighted electron number density, temperature, entropy, and $t_{\text{cool}}/t_{\text{ff}}$ profiles and 1σ spread at all radii calculated from the mean value for the X-ray gas (0.5–10 keV) from 1 to 4 Gyr. The electron number density is on the higher side for the NFW+BCG run compared with the NFW run throughout evolution, but the temperature profiles are similar for both cases.

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Figure 2 shows the mean and $1 - \sigma$ spread in the angle-averaged, emissivity-weighted electron number density, temperature, entropy, and $t_{\text{cool}}/t_{\text{ff}}$ profiles for the X-ray-emitting gas (0.5–10 keV) from 1 to 4 Gyr for NFW and NFW+BCG runs. The mean and $1\sigma$ spread about the mean are calculated at each radius for different quantities between 1 and 4 Gyr. The density plot in Figure 2 shows that the average core density and the $1\sigma$ spread about the mean are higher for the NFW+BCG run as compared with the NFW run. This higher electron number density is expected, as the deeper potential well makes it difficult for AGN jets to remove the gas from the cluster core (due to the addition of the BCG potential).

Unlike density, temperature does not show any significant difference for the NFW and NFW+BCG runs. Although there was a difference in the initial cluster core temperature (see Figure 1), radiative cooling and AGN heating cycles remove this difference during the course of long-term evolution. As a result of electron number density being higher for the NFW+BCG run, entropy ($K = T_{\text{keV}}/n_e^{2/3}$) is correspondingly lower. The $1\sigma$ spread of entropy about the mean has a small overlap in the cluster core while they almost lie on top of each other at larger radii. This shows that the effect of BCG is only felt within the central 50 kpc of the cluster. Outer regions are largely unaffected by the presence of BCG at the cluster center.

The evolution of $t_{\text{cool}}/t_{\text{ff}}$ profile in Figure 2 shows a behavior similar to entropy for both NFW and NFW+BCG runs. Similar to entropy, the average $t_{\text{cool}}/t_{\text{ff}}$ profile separates below 50 kpc for the NFW and NFW+BCG runs. Owing to a shallower potential well, AGN jets are able to evacuate the core in the NFW run easily, leading to a longer cooling time. Despite having a longer free-fall time ($t_{\text{ff}}$), the longer cooling time ($t_{\text{cool}}$) leads to a $t_{\text{cool}}/t_{\text{ff}}$ ratio for the NFW run, which is above that of the NFW+BCG run with small overlap in the core. For a shallower potential well, AGN jets are able to cause overheating out to larger distances from the center.
there are fewer, more powerful jet events of longer duration than in the NFW+BCG run (right panel). As the NFW potential is shallower compared with NFW+BCG potential, the jets are able to cause greater disruption. This leads to more frequent and small duration radiative cooling, and AGN heating cycles for the NFW+BCG run as compared with the NFW run. In both cases, we see a rotationally dominant, stable cold gas torus forming in the central few kpc, as has been reported in several works (e.g., Gaspari et al. 2012; Li et al. 2015; Prasad et al. 2015). By the end of 4 Gyr, the amount of cold gas exceeds $10^{10} M_\odot$ in both cases, with most of the cold gas localized in the massive torus.

The NFW run shows larger min($t_{\text{cool}}/t_{\text{ff}}$) values after the jet events compared with the NFW+BCG run. Table 1 shows that the NFW run has min($t_{\text{cool}}/t_{\text{ff}}$) below 10 for 47% of the run time, while for the NFW+BCG run, min($t_{\text{cool}}/t_{\text{ff}}$) is below 10 for a higher fraction (55%) of the time. The fraction of time spent with min($t_{\text{cool}}/t_{\text{ff}}$) < 5 is 14% in both cases. Therefore, we expect only a small number of clusters with min($t_{\text{cool}}/t_{\text{ff}}$) < 5. The range of min($t_{\text{cool}}/t_{\text{ff}}$) for the NFW run is 1–30, while it is 2–22 for the NFW+BCG run. Due to stronger gravity in latter, the feedback response time is shorter; consequently, min($t_{\text{cool}}/t_{\text{ff}}$) in NFW+BCG case never drops below 2, while in the NFW case it can drop below 1. For the same reason, the jet power in the NFW+BCG run does not reach as high as in the NFW run; the heating phase starts quickly before much cooling occurs (followed by large jet power). The min($t_{\text{cool}}/t_{\text{ff}}$) ratio and jet power are not perfectly anti-correlated. There are times when accretion of gas clouds lingering from previous cycle leads to strong jet outburst even when the core is not back to min($t_{\text{cool}}/t_{\text{ff}}$) < 10. At times, multiple such events can occur in quick succession, especially when min($t_{\text{cool}}/t_{\text{ff}}$) is close to 10.

3.2. Effects of Stellar Gas Depletion

One of the problems with recent hydrodynamic simulations of AGN feedback in galaxy clusters is the formation of a massive torus in the central few kpc of the cluster core (Gaspari et al. 2012; Li et al. 2015; Prasad et al. 2015), which is generally on the higher end of the observed cold gas mass spectrum (this, of course, depends on the choice of $\epsilon$). The cold gas in the torus is dominated by rotation and is decoupled from the feedback cycle. However, observations show that only a few clusters like Hydra (Hamer et al. 2014) have rotating cold disks extending to a few kpc. In most clusters, no such prominent structure is observed, and most of the cold gas is in extended filaments (Russell et al. 2016, 2017). To ameliorate the problem of excess cold gas mass in our simulations, we include a simplified model for the depletion of cold gas due to star formation as described in Section 2.3.

For the NFW+BCG run with stellar gas depletion (labeled NFW+BCGd), the mass flux rate across the inner boundary is $7.1 M_\odot \text{yr}^{-1}$, comparable to that in the run without depletion (see Table 1). This means that star formation primarily affects the rotationally dominant cold gas component (torus), while the radially dominant component with a free-fall time shorter than the depletion time ($\tau$; see Equation (3)), which controls the feedback cycle, remains largely unaffected.

Figure 5 shows the evolution of jet power, cold gas mass, and min($t_{\text{cool}}/t_{\text{ff}}$) for the NFW+BCGd run. The dashed magenta line shows the total cold gas mass when cold gas is depleted in post-processing (as in Prasad et al. 2016) for the
stellar gas depletion
is an order of magnitude smaller in comparison with the NFW
between consecutive jet events is shorter. The total cold gas at the end of 4 Gyr
values to the NFW
panel
Figure 5. Jet power (dotted–dashed green line), cold gas mass (solid red line), and \( \min(t_{\text{cool}}/t_{\text{ff}}) \) (blue squares) for the NFW (left panel) and the NFW+BCG (right panel) run. The time duration between consecutive jet events is different in the two cases with the NFW run having more powerful and longer jet events compared with the NFW+BCG run. The cold gas mass at the end of 4 Gyr differs in the two cases by a factor of less than two. The AGN jets are more disruptive in the NFW run in comparison with the NFW+BCG run. While in the NFW run, \( \min(t_{\text{cool}}/t_{\text{ff}}) \) goes below 1, for NFW+BCG it never drops below 2.

Figure 4. Jet power (dotted–dashed green line), cold gas mass (solid red line), and \( \min(t_{\text{cool}}/t_{\text{ff}}) \) (blue squares) for the NFW+BCG run with stellar gas depletion. The magenta dashed line shows the post-processed (using Equation (10) in Prasad et al. 2015) cold gas mass with \( \tau = 200 \) Myr for the NFW+BCG run without stellar depletion. Jet power and \( \min(t_{\text{cool}}/t_{\text{ff}}) \) show similar values to the NFW+BCG run without stellar depletion, but the time duration between consecutive jet events is shorter. The total cold gas at the end of 4 Gyr is an order of magnitude smaller in comparison with the NFW+BCG without stellar gas depletion (see the right panel of Figure 4). Note that the lowest \( \min(t_{\text{cool}}/t_{\text{ff}}) \) is always above 2, like in the NFW+BCG case without stellar gas depletion.

NFW+BCG run, while the solid red line shows the total cold gas mass for the NFW+BCGd run. In both cases, the cold gas depletion time, \( \tau \), is 200 Myr. Both approaches show the dynamic nature of the amount of cold gas, with the peak cold gas mass at \( \approx 10^{10} M_\odot \). This is unlike the run without cold gas depletion, in which the total cold gas mass becomes saturated after 2 Gyr at \( \gtrsim 10^{10} M_\odot \) (see the right panel of Figure 4). With stellar depletion, the total cold gas in the core lies in the range of observed cold gas mass in cool cluster cores (see Figure 8 in Prasad et al. 2016).

The evolution of \( \min(t_{\text{cool}}/t_{\text{ff}}) \) ratio with time for the run with stellar gas depletion in Figure 5 is as expected. Right before a major jet event, this ratio dips below 10, signaling a cooling phase in the cluster core. The cooling phase is followed by a strong accretion phase, which gives rise to a powerful jet outburst. This heats up the core, pushing \( \min(t_{\text{cool}}/t_{\text{ff}}) \) above 10, marking the completion of one cooling-heating cycle. This is repeated multiple times during our simulation. The \( \min(t_{\text{cool}}/t_{\text{ff}}) \) ratio fluctuates between 2 and 20 during the course of the simulation, with it lying below 10 77% of the time, but below 5 only 19% of the time. Like the NFW+BCG run with no depletion, even here the \( \min(t_{\text{cool}}/t_{\text{ff}}) \) ratio never drops below 2.

3.3. Turbulence in Cool-core Clusters

AGN-ICM interaction gives rise to turbulent motion of the gas in the ICM. In our previous work (Prasad et al. 2015), we looked at the cold gas kinematics in the cluster core due to AGN-ICM interaction. Here, we look at the motion of X-ray
emitting hot gas (0.5–10 keV) in the cluster core and compare it with the Hitomi results for the Perseus cluster (Hitomi Collaboration et al. 2016).

Figure 6 shows the average (from 1 to 4 Gyr) velocity–radius distribution for the NFW+BCG run without stellar depletion. The central 100 kpc hot gas velocity distribution shows that most of the hot gas mass (mass of order of $10^{10} M_\odot$) lies in the velocity range of $0–400$ km s$^{-1}$. However, small amounts of gas ($<10^{-1} M_\odot$) have a velocity going up to 1000 km s$^{-1}$. A similar velocity–radius map of the X-ray gas is obtained for the NFW+BCG run with stellar depletion.

Figure 6. Time-averaged (from 1 to 4 Gyr) velocity–radius distribution of the X-ray gas (0.5–10 keV) for the NFW+BCG run without stellar depletion. The plot shows the $|v| - r$ mass distribution—$d^2M/d\ln|v|d\ln r$ ($\Delta r = 10$ km s$^{-1}$, $\Delta \log|v| = 0.03$ are the bin sizes). In the central regions ($r < 60$ kpc), most of the hot gas mass (of the order of $10^{10} M_\odot$) is in the velocity range of $0–400$ km s$^{-1}$. However, small amounts of gas ($<10^{-1} M_\odot$) have a velocity going up to 1000 km s$^{-1}$. A similar velocity–radius map of the X-ray gas is obtained for the NFW+BCG run with stellar depletion.

3.4. Spread of Metals by AGN Jets

AGN jets help transport the metals from star-forming core regions (and also metals produced by type Ia supernovae in the BCG) in cool-core clusters. Here, we use a simplified model of metal transport in which all metals are injected close to the center in the jet injection region. The stars in the BCG are expected to give a more isotropic source of metals, so our metallicity in the off-axis direction on $\lesssim 10$ kpc scales is an underestimate. Our model should be fine to quantify metal transport in cool-core clusters due to AGN jets on ~100 kpc scales.

Figure 8 shows the extent of the metal distribution due to AGN jets in the NFW+BCG simulations, at the end of 4 Gyr for the runs with (left panel) and without (right panel) stellar depletion. These plots show that AGN jets can spread metals beyond 400 kpc in both cases, predominantly in the jet direction. There is a noticeable difference between the metallicity distribution at larger radii in the runs with and without gas depletion. Jets encounter less resistance due to clumpy cold clouds in the simulation with cold gas depletion, and therefore travel mostly along the direction of jet injection without much dispersion in the transverse directions. Without stellar depletion, the metal distribution is much more laterally extended at large radii because of vorticity generation at the hot-cold interface of the cold gas clouds (see the upper panel of Figure 8).

Figure 9 shows the angular distribution of mass-weighted metallicity (Equation (6)) of the ICM for different radial shells ($\Delta r = 20$ kpc) at 4 Gyr for the NFW+BCG runs with and without stellar gas depletion. The distribution shows bimodality with metallicity peaking near the polar regions, as expected from Figure 8. However, the metallicity peak is higher by a factor of two for smaller radii with stellar depletion as compared to the run without stellar depletion, again reflecting higher lateral mixing in the latter case.

Figure 10 shows the angle-averaged distribution of metals as a function of radius at 4 Gyr (Equation (5)) for the NFW+BCG runs without stellar gas depletion. Metallicity shows a steep rise in the cluster core ($r < 0.02 r_{500}$), while beyond $0.02 r_{500}$ there is only $\lesssim 2\times$ change in metallicity over the background $0.3 Z_\odot$. This shows that the impact of AGN jets in distributing the metals is limited to the cluster core. The shaded regions depict the 1σ scatter of metallicity about the mean (cyan is for O, gray is for Fe) as a function of radius for the sample of clusters and groups in Mernier et al. (2017). The observations show a more extended metal distribution (to $0.1 r_{500}$) as compared with our simulations.
4. Discussion

Recent observations of galaxy clusters have put forth many challenges for the simulations of cold mode feedback in cool cores. Two of the key challenges are (i) the near absence of cores with min(t_{cool}/t_{ff}) < 10 (Hogan et al. 2017a, 2017b; see however, Voit & Donahue 2015; Lakhchaura et al. 2016; Pulido et al. 2018), unlike smaller ratios (down to unity) seen in simulations (albeit for a short time); and (ii) the absence of massive rotating cold tori in observations, which are routinely seen within the central few kpc of cool-core simulations, except in Hydra A (Hamer et al. 2014). In light of these discrepancies, we have incorporated two effects in our simulations to see if simulations can be reconciled with observations: (i) a central BCG potential and (ii) a simple model for gas depletion due to star formation. We study the effects of these new physical ingredients on the long-term evolution of cluster cores. Additionally, we quantify other important X-ray observables such as metallicity and level of turbulence in the X-ray emitting gas in cool cluster cores.

4.1. How Much Below 10 does min(t_{cool}/t_{ff}) Fall?

Pinning the gravitational acceleration to that of the central BCG at small radii, Hogan et al. (2017a, 2017b) argue that almost none of the cool cluster cores go below the min(t_{cool}/t_{ff}) = 10 threshold for the presence of cold gas motivated by simulations. While Hogan et al. (2017b) use a sample of 33 Hα line-emitting galaxy clusters, and find one core with min(t_{cool}/t_{ff}) slightly below 10 (they quote a range in min(t_{cool}/t_{ff}) of 10–35), more recent observations of 23 cool cores with confirmed detections of CO-emitting gas (Pulido et al. 2018) find five systems below 10 (although still above seven). In this sample, 10 out of 23 CO-emitting cool cores have min(t_{cool}/t_{ff}) between eight and 12 and one system below eight. Further, the latest observations of the 40 low-mass halos (galaxies) by Babyk et al. (2018) show that min(t_{cool}/t_{ff}) falls to as low as 5. In this sample, eight out of 40 systems have min(t_{cool}/t_{ff}) < 10. Voit & Donahue (2015), using a SIS model (with a fixed velocity dispersion of 250 km s\(^{-1}\)) for the BCG potential, found a min(t_{cool}/t_{ff}) ratio in the range 5–20 for cool-core clusters. Following the method of Voit & Donahue (2015), O’Sullivan et al. (2017) find that out of five galaxy groups with jets, four have min(t_{cool}/t_{ff}) < 15 with lowest value at 7.4. Thus, the disagreement between cool-core observations and simulations highlighted in Hogan et al. (2017b) does not appear to be serious.

The one noticeable discrepancy is the presence of snapshots in which min(t_{cool}/t_{ff}) falls as low as 1 for the NFW run (see the left panel of Figure 4). However, the BCG potential somewhat alleviates this problem by shortening the feedback response time (as t_{ff} in the core is shorter) and preventing the core from cooling below min(t_{cool}/t_{ff}) = 2. In this case, feedback acts fast and the feedback jet heating cycle starts before the core can cool too much. Moreover, for the same reason, the jet power and min(t_{cool}/t_{ff}) after the jet event do not increase to large values.

Figure 11 shows the histograms of min(t_{cool}/t_{ff}) for our NFW and NFW+BCG runs and from the cool-core sample of Pulido et al. (2018) of the clusters with CO detection. Clearly the NFW simulation shows occurrence of clusters with min(t_{cool}/t_{ff}) as low as unity. Moreover, the NFW core distribution is bimodal with another peak in min(t_{cool}/t_{ff}) occurring at \approx 30. Similar results are obtained for 3D NFW cluster simulations in Prasad et al. (2015), which uses a smaller value of feedback efficiency (\epsilon). With the inclusion of BCG, there are no cores with min(t_{cool}/t_{ff}) < 2, and there is no second peak in min(t_{cool}/t_{ff}) distribution. While the latter inference depends on \epsilon, the former is a generic feature of a deeper potential well. Thus the inclusion of a BCG potential brings the simulations in a closer agreement with cool-core observations, but even then the observed distribution is shifted toward higher min(t_{cool}/t_{ff}). The peak of the observed and
The disagreement at low values of $\min(t_{\text{cool}}/t_{\text{ff}})$ may be due to several factors: observational biases due to sample selection (e.g., even different samples by the same group show different distributions of $t_{\text{cool}}/t_{\text{ff}}$; e.g., compare Hogan et al. 2017b; Babyk et al. 2018; Pulido et al. 2018); low spatial resolution (see Figure 8 in Hogan et al. 2017b); and the breakdown of spherical symmetry in the core, where $t_{\text{cool}}/t_{\text{ff}}$ occurs; simulations do not include important physical effects, such as thermal conduction and stellar feedback that can increase $t_{\text{cool}}/t_{\text{ff}}$.

Now, we discuss the issue of the occurrence of cold gas even when $t_{\text{cool}}/t_{\text{ff}} > 10$. Early idealized thermal instability models with heating balancing average cooling in radial shells (McCourt et al. 2012; Sharma et al. 2012; Choudhury & Sharma 2016) for the hydrostatic ICM confined by NFW gravity, showed $t_{\text{cool}}/t_{\text{ff}} \lesssim 10$ to be a necessary condition for cold gas condensation. The amount and extent of cold gas condensation is higher for a smaller $t_{\text{cool}}/t_{\text{ff}}$. In these models without angular momentum, extra gas from the core drops out leaving behind a core with $t_{\text{cool}}/t_{\text{ff}} \gtrsim 10$ (the...
resolution, directly measured the line-of-sight turbulent velocity dispersion \(\approx 164 \pm 10 \text{ km s}^{-1}\) within 30–60 kpc of the Perseus core (Hitomi Collaboration et al. 2016). The turbulent pressure is only \(\sim 4\%\) of the thermal pressure, despite a fairly large jet/cavity power \(\sim 10^{45} \text{ erg s}^{-1}\) (Birzan et al. 2004; see Figure 4 for comparison).

Equating turbulent heating rate density \((\rho v^2/2L; u_t)\) and radiative cooling rate density \((n_e n_p \Lambda; n_e)\) is electron/ion number density and \(\Lambda\) is the cooling function, we obtain that a turbulent velocity of

\[ u_t \approx 450 \text{ km s}^{-1}(L_{30}\Lambda_{-23}n_e_{0.05})^{1/3} \]  

is required for turbulent heating to balance radiative cooling losses, where \(L_{30}\) is the driving length scaled to 30 kpc, \(\Lambda_{-23}\) is the cooling function scaled to \(10^{-23} \text{ erg cm}^{-3} \text{ s}^{-1}\), and \(n_e\) is electron number density scaled to 0.05 cm\(^{-3}\). This is much larger than the 3D velocity dispersion measured in the core of Perseus \(\approx \sqrt[3]{3} \times 164 = 285 \text{ km s}^{-1}\). Moreover, for cold gas condensation not to be suppressed by turbulent mixing, condensation should occur at scales larger than the driving scale (see Section 4.1 in Banerjee & Sharma 2014). While Hitomi observations rule out turbulent heating with a driving scale \(\gtrsim 10 \text{ kpc}\) as the dominant heating mechanism in the core, turbulent mixing of the core and the hot outskirts and/or AGN bubble is still possible (e.g., Banerjee & Sharma 2014; Hillel & Soker 2016; Yang & Reynolds 2016a).

We have quantified turbulent velocities in the hot gas in our simulations that broadly agree with observations. Figure 6 shows the velocity–radius distribution of the 0.5–10 keV gas mass. It shows that most of the X-ray emitting gas has 3D turbulent velocity \(\lesssim 500 \text{ km s}^{-1}\). Figure 7 shows the 1D LOSVD in the core as a function of time (left panel) and the PDF of the LOS velocity (right panel). The turbulent velocity increases with a rise in jet power, but only up to \(\lesssim 300 \text{ km s}^{-1}\). The velocity dispersion in the direction of the jet is higher than in the perpendicular direction and the turbulent velocity even in the quiescent state is \(\gtrsim 60 \text{ km s}^{-1}\). A weak turbulent velocity motivates other models, such as intermittent shocks (e.g., Li et al. 2017) and turbulent mixing (e.g., Banerjee & Sharma 2014; Hillel & Soker 2017) as the agents responsible for heating of the cool core.

4.3. Metal Distribution in Cool Cores

Observations show that the outskirts \((r > r_{2500})\) the radius within which the mean matter density is 2500 times the critical density of the universe; for our choice of parameters, \(r_{2500} = 0.25r_{200} = 459 \text{ kpc}\) of galaxy clusters have roughly isotropic distribution of metals (Tamura et al. 2004; Fujita et al. 2008; Simionescu et al. 2011; Werner et al. 2013), which is close to 0.3 times the solar metallicity across different systems. Moreover, the cool-core clusters have a rising metallicity toward the center (De Grandi & Molendi 2001; Leccardi & Molendi 2008; Ettori et al. 2015). While AGN jets play a key role in metal transport in the central regions of cool-core clusters, our simulations show that they cannot be responsible for the isotropic distribution of metals in cluster outskirts (see Figure 8). Metal enrichment during the galaxy assembly stage at redshifts \(\geq 1\), and mixing driven by mergers, seem responsible for such an isotropic and universal metal distribution in the cluster outskirts. The observed large-scale
metal enrichment of galaxy clusters sheds light on the cluster formation environment at higher redshifts.

Further, a quantitative comparison of our metal distribution with the observed metallicity shows that our metal distribution due to AGN jets is too narrowly distributed toward the center (see Figure 10). This finding is similar to Kannan et al. (2017), who compare metal transport with and without thermal conduction in cosmological simulations of galaxy clusters including AGN feedback. In the absence of thermal conduction, like us, they find a very centrally peaked metallicity distribution. With thermal conduction mixing is more efficient, and metals and heat are spread out more uniformly and to larger radii (see Figure 3 in Kannan et al. 2017 and Figure 1 in Sharma et al. 2009b). Thus, the shallow metallicity profiles of cool-core clusters compared to our simulations (see Figure 10) point to the importance of (anisotropic) thermal conduction in heat and metal transport in cluster cores. An additional caveat is that our idealized simulations do not include cosmological halo mergers that can further stir the ICM, especially at higher redshifts (e.g., see Vogelsberger et al. 2018).

5. Conclusions

We study the effects of the gravity of the brightest central galaxy (BCG) and depletion of cold gas due to star formation in our simulations to compare with the observations of cool-core clusters. We also study the nature of turbulence in cool cluster cores and the metal distribution due to AGN jets. Following are our key conclusions:

1. The presence of BCG potential does not have an impact on the temperature in the cluster core. However, for a fixed feedback efficiency, the presence of the BCG increases the average density of hot gas in the core. A larger core density decreases the core entropy and the $t_{\text{cool}}/t_{\text{ff}}$ ratio, on average (see Figure 2). AGN jets cause greater disruption in the core of the shallower NFW potential as compared with the NFW+BCG potential. Stronger gravity due to the central BCG makes the feedback jets respond faster and prevents $\min(t_{\text{cool}}/t_{\text{ff}})$ from falling below 2, discernibly higher than the minimum value with only the NFW potential ($\approx 1$). For the same reason, the jet power with the inclusion of the BCG potential does not rise beyond $10^{46}$ erg s$^{-1}$. The min($t_{\text{cool}}/t_{\text{ff}}$) distribution of our BCG simulations is still biased toward smaller values compared with the observations (Figure 11), but the discrepancy is at least less than a factor of two level. Moreover, 3D jet simulations produce cold gas with angular momentum which can exist even with $\min(t_{\text{cool}}/t_{\text{ff}})$ as high as 30, in agreement with observations. Given a dispersion in the observational results and the low angular resolution in the core, the discrepancy between observations and realistic 3D feedback jet simulations is not glaring.

2. Star formation, modeled with a gas depletion time of 0.2 Gyr, removes the cold gas present in the clumps and torus in the cluster core. This brings down the cold gas mass within the observed range (see Figure 5). Moreover, the outgoing AGN jets encounter less resistance with the depletion of cold gas, and the transfer of heat from AGN jets to the entire cluster core is less efficient (see Figure 8). This results in more frequent AGN jet events with stellar depletion.

3. The LOSVD of X-ray gas in the cluster core shows that the turbulence due to AGN jets is not strong enough for turbulent heating to balance radiative cooling in cluster cores. We find the 1D velocity dispersion to be in the range of 60–300 km s$^{-1}$, consistent with recent observations of the Perseus cluster by Hitomi (see Figure 6). The turbulent velocity is larger when the AGN jet is active, and the LOSVD is slightly larger along the jet direction rather than perpendicular to this direction during the active jet phase (see Figure 7).

4. Gas depletion due to star formation also modulates the anisotropic metal distribution in galaxy clusters due to AGN jets as outflowing metal-rich gas faces less hindrance from the cold gas clouds. Metals are able to travel unhindered for the most part to outer radii and so the metal distribution is mostly confined in the jet direction. Moreover, the observed metal distribution in our simulations is too sharply peaked toward the center as compared with the observations of cool cores (see Figure 10). Thermal conduction (both isotropic and anisotropic) can help spread heat and metals more uniformly and farther out by overcoming strong entropy stratification. This may bring the metallicity distribution in line with the observations.

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References
Babyk, I. V., McNamara, B. R., Nulsen, P. E. J., et al. 2018, arXiv:1802.02589
Banerjee, N., & Sharma, P. 2014, MNRAS, 443, 687
Birzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J. 2004, ApJ, 607, 800
Choudhury, P. P., & Sharma, P. 2016, MNRAS, 457, 2554
Churazov, E., Forman, W., Vikhlinin, A., et al. 2008, MNRAS, 388, 1062
Cielo, S., Babul, A., Antonuccio-Delogu, V., Silk, J., & Volonteri, M. 2018, arXiv:1801.04276
De Grandi, S., & Molendi, S. 2001, ApJ, 551, 153
Ettori, S., Baldi, A., Balestra, I., et al. 2015, A&A, 578, A46
Fabian, A. C., Sanders, J. S., Allen, S. W., et al. 2003, MNRAS, 344, L43
Fujita, Y., Tawa, N., Hayashida, K., et al. 2010, PASJ, 60, S343
Gaspari, M., Ruszkowski, M., & Oh, S. P. 2013, MNRAS, 432, 3401
Gaspari, M., Ruszkowski, M., & Sharma, P. 2012, ApJ, 746, 94
Guo, F., & Oh, S. P. 2008, MNRAS, 384, 251
Hamers, S. L., Edge, A. C., Swinbank, A. M., et al. 2014, MNRAS, 437, 862
Hillel, S., & Soker, N. 2016, MNRAS, 455, 2139
Hillel, S., & Soker, N. 2017, MNRAS, 466, L39
Hitomi Collaboration, Aharonian, F., Akamatsu, H., et al. 2016, Natur, 535, 117
