ROTATION AND TURBULENCE OF THE HOT INTRAcluster MEDIUM IN GALAXY CLUSTERS

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ABSTRACT

Cosmological simulations of galaxy clusters typically find that the weight of a cluster at a given radius is not balanced entirely by the thermal gas pressure of the hot intracluster medium (ICM), with theoretical studies emphasizing the role of random turbulent motions to provide the necessary additional pressure support. Using a set of high-resolution, hydrodynamical simulations of galaxy clusters that include radiative cooling and star formation and are formed in a cold dark matter (CDM) universe, we find instead that in the most relaxed clusters rotational support exceeds that from random turbulent motions for radii \(0.1 \sim 0.5 r_{500}\), while at larger radii, out to \(0.8 r_{500}\), they remain comparable. We also find that the X-ray images of the ICM flatten prominently over a wide radial range, \(0.1 \sim 0.4 r_{500}\). When compared with the average ellipticity profile of the observed X-ray images computed for nine relaxed nearby clusters, we find that the observed clusters are much rounder than the relaxed CDM clusters within \(\sim 0.4 r_{500}\). Moreover, while the observed clusters display an average ellipticity profile that does not vary significantly with radius, the ellipticity of the relaxed CDM clusters declines markedly with increasing radius, suggesting that the ICM of the observed clusters rotates less rapidly than that of the relaxed CDM clusters out to \(\sim 0.6 r_{500}\). When these results are compared with those obtained from a simulation without radiative cooling, we find a cluster ellipticity profile in much better agreement with the observations, implying that overcooling has a substantial impact on the gasdynamics and morphology out to larger radii than previously recognized. It also suggests that the 10–20% systematic errors from nonthermal gas pressure support reported for simulated cluster masses, obtained from fitting simulated X-ray data over large radial ranges within \(r_{500}\), may need to be revised downward. These results demonstrate the utility of X-ray ellipticity profiles as a probe of ICM rotation and overcooling which should be used to constrain future cosmological cluster simulations.

Key words: cosmology: theory – galaxies: clusters: general – methods: numerical – turbulence – X-rays: galaxies: clusters

Online-only material: color figures

1. INTRODUCTION

Clusters of galaxies, the largest virialized structures in the universe, play a critical role in understanding the formation and evolution of large-scale structure, and determining fundamental cosmological parameters. It is now well known that the dark matter, the dominant component, makes up about 80% of the total gravitational mass of a typical galaxy cluster. The baryonic matter in galaxies accounts for about 3–5% of the total mass. The remaining mass is made up by hot gas distributed between galaxies, with temperatures over \(10^{7}\) K. This hot gas, called the “intracluster medium” (ICM), emits X-rays through thermal bremsstrahlung radiation and makes galaxy clusters the second brightest source of high-energy radiation in the universe, after quasars. In the era of precision cosmology, it becomes imperative to accurately measure cluster properties, such as its gravitational mass, to a precision of a few percent.

The X-ray measurement of the density and temperature profiles of the hot ICM provides one of the most accurate methods to determine the cluster total gravitational mass. For clusters that have not been disturbed recently by a major merger, the hot ICM should obey hydrostatic equilibrium to a good approximation, representing a balance between the gravitational force and thermal gas pressure. For the special case of spherical symmetry, the equation of hydrostatic equilibrium may be written as

\[
d\frac{P_g}{dr} = -\rho_g \frac{GM(r)}{r^2},
\]

where \(\rho_g\) is the gas density, \(P_g\) is the thermal gas pressure, and \(M(r)\) is the mass enclosed within radius \(r\). Applications of the X-ray method to constrain cosmological parameters include, e.g., measurements of the gas mass fraction (Allen et al. 2008, and references therein), virial mass function (e.g., Stanek et al. 2006, and references therein), and the relationship between the virial concentration and mass (Buote et al. 2007).

It is necessary to use cosmological hydrodynamical N-body simulations to test the key assumptions underlying Equation (1), i.e., spherical symmetry and negligible nonthermal pressure support of the hot ICM (e.g., Evrard et al. 1996; Thomas et al. 1998). Early studies showed that it is possible to recover the cluster mass within a factor of \(\sim 2\) with X-ray telescopes such as EINSTEIN and EXOSAT (e.g., Tsai et al. 1994), where isothermal gas had to be assumed in the mock X-ray analysis. Most recent studies, which involve mock observations with the most advanced telescopes such as Chandra, allow the radial gas temperature profile to be measured, and use simulations that include a wider range of physical processes. They find that the global cluster mass, typically computed within a radius of fixed overdensity (e.g., \(r_{500}\)), can be recovered more accurately with systematic errors typically ranging from 5% to 20% (see Nagai et al. 2007).

Over the past decade, simulators have emphasized how much additional pressure support from random turbulent gas motion contributes to systematic errors in the X-ray method (e.g., Norman & Bryan 1999; Kay et al. 2004; Faltenbacher et al. 2005; Dolag et al. 2005; Rasia et al. 2006; Hallman et al. 2006; Vazza et al. 2006; Nagai et al. 2007; Brunetti & Lazarian 2007).
It has also been noticed in such high-resolution, hydrodynamic simulations that while the velocity dispersion tensor of the ICM is approximately isotropic in the outskirts of clusters, it becomes increasingly tangential at smaller radii, especially for the most relaxed systems (Rasia et al. 2004; E. Lau et al. 2009, in preparation). Recently, Lau et al. have shown that the ICM velocity dispersion becomes increasingly tangentially anisotropic as one moves inward from $r_{500}$, such that for their relaxed clusters the anisotropy parameter falls to $\beta \approx -0.3$ near $0.2 \times r_{500}$. These authors consider the nonthermal pressure support of this random turbulent motion (both radial and tangential) on estimates of $M_{500}$ assuming hydrostatic equilibrium. However, rotational support of the gas, and its observable signatures, is not addressed.

In this paper, we show that for the relaxed clusters studied by E. Lau et al. (2009, in preparation; Nagai et al. 2007) the support of the ICM from rotational and streaming motions is comparable to the support from the random turbulent pressure out to $0.8 \times r_{500}$. While the overall magnitude of the rotational motion ($\sim$ a few hundred km s$^{-1}$) is not large enough to be detected directly through Doppler shifts of emission lines in X-ray spectra, even with the most advanced X-ray telescopes we have today (e.g., Sunyaev et al. 2003; Inogamov & Sunyaev 2003; Schuecker et al. 2004; Brüggen et al. 2005; Pawl et al. 2005; Chepurnov & Lazarian 2006; but see Dupke & Bregman 2006 for a recent measurement), simulated clusters with large-scale rotation are significantly flat, and this translates to observable large ellipticities of the X-ray isophotes. By comparing the ellipticities of the X-ray isophotes of the relaxed simulated clusters to those of the nine observed clusters, we show that the observed clusters are, on average, much rounder and have a distinctly different radial variation in ellipticity. This demonstrates the utility of X-ray ellipticity profiles as a constraint for future cosmological cluster simulations.

This paper is organized as follows. In Section 2, we study the importance of ICM rotation in the 16 simulated clusters of E. Lau et al. (2009, in preparation; Nagai et al. 2007), focusing our discussion using the examples of one relaxed and one disturbed cluster. In Section 3, we present ellipticity profiles of nine clusters obtained from X-ray observations with Chandra and ROSAT and compare them to the simulated clusters. The last section is devoted to summary and discussion.

2. NONTHERMAL GAS MOTION IN THE SIMULATED CLUSTERS

2.1. Simulation Data

We use a set of 16 high-resolution, cosmological hydrodynamic simulations of cluster-sized systems in a flat Λ CDM model: $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $\Omega_b = 0.043$, and $\sigma_8 = 0.9$ (the power spectrum normalization at $8 h^{-1}$ Mpc scale). These cluster-sized simulations include collisionless dynamics of dark matter, star, and intracluster gas. They also include several critical physical processes such as radiative cooling, star formation, and metal enrichment (CSF simulation). For comparison, we also analyze one adiabatic cluster simulation, i.e., no radiative cooling and star formation (NC simulation). We refer readers to Nagai et al. (2007) for details, and provide a brief summary here. We adopt a Hubble constant of $H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$ where $h = 0.7$ throughout the paper.

The simulations use the Adaptive Refinement Tree (ART) N-body + gasdynamics code (Klypin et al. 2001; Kravtsov et al. 2002, 2006; Nagai et al. 2007), and run in two computational boxes: $120 h^{-1}$ Mpc for CL101–107 and $80 h^{-1}$ Mpc for the rest. The ART is a shock-capturing code that is particularly suited for capturing shocks and turbulent motion, and the use of adaptive mesh refinement also allows us to resolve the detailed cluster structure and the internal gas flows in clusters. These simulations achieve a dynamic range of $\sim 5 \times 10^{13}$–$10^{15} h^{-1} M_{\odot}$ and a peak resolution of $\sim 6 h^{-1}$ kpc, which is well matched to the spatial resolution of Chandra X-ray observations of nearby galaxy clusters. Table 1 of Nagai et al. 2007 shows the typical properties of simulated clusters; all the parameters are computed from simulations within a region with an overdensity of 500, with respect to the critical density of the universe. These clusters have masses ranging between $\sim 3 \times 10^{14} h^{-1} M_{\odot}$ and $10^{15} h^{-1} M_{\odot}$, and temperatures between 1 keV and 8.7 keV.

The simulated clusters are projected along three orthogonal directions $(x, y, z)$ and X-ray flux maps are created for each projection. (These coordinate axes reflect the orientation of the entire simulation box and are not adjusted to match the principal axes of each cluster.) We make the mock Chandra images by convolving the emission spectrum with the response of the Chandra front-illuminated CCDs and with an exposure of 100 ks, a typical exposure for Chandra observations. We show the images and velocity structures of a relaxed cluster (CL7) in Figure 1 and a disturbed cluster (CL11) in Figure 2. CL7 is judged to be the most relaxed cluster in the simulation sample, with a gravitational mass of $M_{500} = 2.01 \times 10^{14} M_{\odot}$ and a size of $r_{500} = 0.891$ kpc. Here, $r_{500}$ is defined as a radius of 500 times the mean density of the universe, and $M_{500}$ is the total gravitational mass within $r_{500}$. In contrast, CL11 is a very disturbed system with $M_{500} = 1.29 \times 10^{14} M_{\odot}$ and $r_{500} = 0.767$ kpc.

The top panel of Figure 1 shows the projected X-ray emission maps of CL7 in the three orthogonal directions $x$, $y$, $z$ from left to right, respectively. The X-ray contours (solid lines) are separated by a factor of $\sim 2$ in surface brightness, with the highest contour at a level of $\sim 500$ photons per pixel. The box size of the image is $1 h^{-1}$ Mpc. The cluster has a very regular appearance in all projections. However, the X-ray isophotes display significant elongation in the $y$- and $z$-projections compared with the much rounder isophotes of the $x$-projection.

The bottom panel of Figure 1 shows the two-dimensional velocity field in the central slices of the simulated cluster CL7. The left plot is along the $y$–$z$ plane, the middle plot is along the $x$–$z$ plane, and the right is along the $x$–$y$ plane. The velocity vector is color-coded between 0 and 500 km s$^{-1}$, with the magnitude shown in the bottom color bar. The most striking feature is that while in both the $x$–$z$ and $x$–$y$ planes the gas moves largely randomly, in the $y$–$z$ plane the gas shows a very regular, counterclockwise, rotational motion with velocities between 200 and 400 km s$^{-1}$.

In contrast, CL11 is a merging cluster with violent gas motion (Figure 2). Merging in the central region creates large-scale gas motions on the order of 1000 km s$^{-1}$. Such merging activity is clearly visible in the velocity fields shown in the $y$–$z$ and $x$–$z$ planes: gas is moving from the northwest and southeast directions toward the center. The X-ray images in the three projections are also distorted. Unlike CL7 ordered rotational motion is unimportant in all projections.

In the following subsections, we compare the contribution of rotation (and other streaming motion) to that of random turbulent motion in supporting the weight of the ICM of the simulated clusters.
2.2. Analysis Method

The total cluster mass \( M \) enclosed within a surface \( S \) is given by Gauss’s law,

\[
M = \frac{1}{4\pi G} \int \nabla \Phi \cdot d^2S,
\]

(2)

where \( \Phi \) is the gravitational potential and \( G \) is the gravitational constant. Assuming that the ICM is a steady state, inviscid, collisional fluid, we may use Euler’s equation to eliminate \( \Phi \) in favor of the gas pressure and terms involving the velocity components of the ICM,

\[
M = \frac{1}{4\pi G} \int \left[ -\frac{1}{\rho_g} \nabla P_g - (\mathbf{v} \cdot \nabla) \mathbf{v} \right] \cdot d^2S,
\]

where \( \rho_g \) is the gas density and \( P_g \) represents the pressure arising from gas motions having a random (i.e., Maxwellian) velocity distribution.

We rewrite the previous equation as a sum of four terms,

\[
M = M_{\text{therm}} + M_{\text{turb}} + M_{\text{rot}} + M_{\text{stream}},
\]

(3)

The first two terms on the right-hand side,

\[
M_{\text{therm}} = -\frac{1}{4\pi G} \int \left( \frac{1}{\rho_g} \nabla P_{\text{therm}} \right) \cdot d^2S
\]

(4)

represent pressure support from random gas motions. Here \( P_{\text{therm}} = kT/\mu m_p \) is the thermal gas pressure, where \( k \) is the Boltzmann constant, \( T \) is the temperature, \( m_p \) is the proton mass, and \( \mu \) is the atomic weight. The quantity \( P_{\text{turb}} \) is the pressure from random turbulent motions. The last two terms on the right-hand side,

\[
M_{\text{rot}} = \frac{1}{4\pi G} \int \left( \frac{\upsilon_r^2}{r} + \frac{\upsilon_\theta^2}{r^2} + \frac{\upsilon_\phi^2}{r^2 \sin^2 \theta} \right) \cdot d^2S,
\]

(5)

\[
M_{\text{stream}} = -\frac{1}{4\pi G} \int \left( \frac{\partial \upsilon_r}{\partial r} + \frac{\upsilon_\theta}{r} \frac{\partial \upsilon_r}{\partial \theta} + \frac{\upsilon_\phi}{r \sin \theta} \frac{\partial \upsilon_r}{\partial \phi} \right) \cdot d^2S,
\]

(6)

follow by evaluating \( (\mathbf{v} \cdot \nabla) \mathbf{v} \) in spherical coordinates (Binney & Tremaine 1987). Here \( M_{\text{rot}} \) is the contribution from rotational motion while \( M_{\text{stream}} \) includes the contributions from other streaming motion.

The combination \( M_{\text{rot}} + M_{\text{stream}} \) represents the total contribution to the gravitational support from nonrandom gas motions. In this paper, we are especially concerned with assessing the relative importance of nonrandom gas motions to that of the random turbulent motion. However, we also find it useful to separate the
nonrandom contribution into the terms $M_{\text{rot}}$ and $M_{\text{stream}}$. For a cluster supported mostly by rotation $M_{\text{rot}}$ will dominate $M_{\text{stream}}$. For a nonrotating cluster with substantial nonrandom motions, $M_{\text{rot}}$ and $M_{\text{stream}}$ will be of similar magnitude (but will not necessarily cancel). Hence, in our discussion below we always consider the total $M_{\text{rot}} + M_{\text{stream}}$ when assessing the relevance of nonrandom gas motions, but we use $M_{\text{rot}} (\gg M_{\text{stream}})$ as a rotation proxy particularly for the relaxed clusters.

In what follows, we choose the surface $S$ to be that of a sphere, but we emphasize that we do not assume the cluster is spherical and use the full three-dimensional ICM properties produced by the simulation to evaluate the integrals. Furthermore, we do not explicitly calculate $M_{\text{turb}}$ since it critically depends on the sizes, velocities, temperatures, and densities of the coherent clumps that move randomly within the ICM. Instead, we infer its magnitude from $M_{\text{turb}} = M - M_{\text{therm}} - M_{\text{rot}} - M_{\text{stream}}$, where $M$ is the total “true” mass of the gas and dark matter computed directly from the particles in the simulation.

To compute the mass profile associated with both the “true” mass and the mass components based on Equations (4)–(7), we make use of the grid data that are generated from the raw data of the adaptive mesh refinement simulation. Specifically, the raw data are interpolated onto a uniform $256^3$ cube grid in a $2\,h^{-1}\times 2\,h^{-1}\times 2\,h^{-1}$ Mpc$^3$ box, centered on the simulated cluster. The spatial resolution therefore is $7.8\,h^{-1}$ kpc.

We divide the simulation box into a number of radial bins and compute each mass component. At each radial bin, the entire surface is divided into small cells along $\theta$ and $\phi$ directions, over which the integration is performed. Specifically, in each cell we throw test particles randomly and then compute the mean density, thermal pressure, and velocity by averaging all the test particles. Again, since we use Gauss’s law and compute the integration in three dimensions, our analysis is entirely general with regard to the cluster geometry.

2.3. Mass Profiles

In the top panel of Figure 3, we show the “true” mass profile of the relaxed cluster CL7 obtained by directly counting the dark matter and mass particles from the simulation. Also displayed are various combinations of $M_{\text{therm}}$, $M_{\text{rot}}$, and $M_{\text{stream}}$ that result from substituting Euler’s equation into Gauss’s law as discussed in the previous section. We consider seriously the gas properties of the simulated clusters down to a radius of $\approx 0.08\,r_{500}$. Below this radius the well-known effect of overcooling produces unphysical gas density and temperature profiles.

Over most of the cluster region displayed, $M_{\text{therm}}$ systematically underestimates the “true” mass by 5–10%. Rotational and other streaming motions provide most of the nonthermal support of the cluster weight over a large range of radii. The combination of $M_{\text{therm}} + M_{\text{rot}} + M_{\text{stream}}$ (the green solid line in Figure 3) is within a few percent of the “true” mass out to $\approx 0.5\,r_{500}$. For these radii, $M_{\text{rot}} \gg M_{\text{stream}}$ (see the bottom panel of Figure 3), indicating that rotation is the most important streaming motion, consistent with the visual impression of the velocity field shown in Figure 1.
Figure 3. Top panel: mass profiles of the relaxed simulated cluster CL7. The “true” mass $M$ obtained by directly counting the masses of the gas and dark matter particles from the simulations is given by the dark solid line. The other lines represent the different mass components obtained by substituting Euler’s equation into Gauss’s law (see Section 2.2): the component from thermal gas pressure, $M_{\text{therm}}$ (red solid line), rotation and streaming motion, $M_{\text{rot}} + M_{\text{stream}}$ (red dashed line), and their sum, $M_{\text{therm}} + M_{\text{rot}} + M_{\text{stream}}$ (green solid line). Bottom panel: separate contributions of $M_{\text{rot}}$ (red solid line) and $M_{\text{stream}}$ (red dotted line) to the mass profile in units of $10^{13} M_\odot$. The dashed black line is the total contribution, $M_{\text{rot}} + M_{\text{stream}}$. (A color version of this figure is available in the online journal.)

We provide a direct comparison of rotation and streaming motions to random turbulent motions in Figure 4. (Note that we take the absolute value of $M_{\text{turb}}$ since it fluctuates about zero when its magnitude is small.) Over approximately $0.1$–$0.5 \, r_{500}$, $M_{\text{rot}} + M_{\text{stream}}$ generally dominates $M_{\text{turb}}$ and remains comparable to $M_{\text{turb}}$ all the way out to $\approx 0.8 \, r_{500}$. Since, as noted above, $M_{\text{rot}} \gg M_{\text{stream}}$ within $\approx 0.5 \, r_{500}$, it follows that $M_{\text{rot}}$ dominates the nonthermal support of the cluster weight in that region.

In contrast, for the disturbed cluster CL11 $M_{\text{turb}} \gtrsim M_{\text{rot}} + M_{\text{stream}}$ over all radii shown (Figure 5). Rotational motion does not dominate, consistent with the lack of circular motion noted from visual inspection of the velocity field shown in Figure 2. Despite the differences between CL7 and CL11, it is interesting to note that for CL11 $M_{\text{therm}}$ typically lies within $\pm 10\%$ of the “true” mass. This is of similar magnitude to CL7, except that CL7 only underestimates the “true” mass.

The basic results for CL7 and CL11 apply generally to the other relaxed and disturbed clusters in the simulation.

Figure 4. Top panel: relative contribution of rotation and other streaming motion to the (absolute value of the) turbulent motion in CL7 (solid black line) and CL11 (dashed red line). Bottom panel: the same quantity is plotted by averaging the results for all of the seven relaxed clusters (solid black line) and all of the nine disturbed clusters (dashed red line) in the simulation. (A color version of this figure is available in the online journal.)

In particular, in the bottom panel of Figure 4 we show the relative contribution of rotation and other streaming motion to the turbulent motion by averaging the results for all of the relaxed clusters (solid black line) and all of the disturbed clusters (dashed red line) in the simulation. (We have used the same clusters designated as “relaxed” or “disturbed” as Nagai et al. (2007).) While there is substantial scatter (not shown) about these average profiles, particularly for the disturbed systems, $M_{\text{rot}} + M_{\text{stream}}$ generally dominates $M_{\text{turb}}$ over approximately $0.1$–$0.5 \, r_{500}$ and remains comparable to $M_{\text{turb}}$ all the way out to $\approx 0.8 \, r_{500}$. In the disturbed clusters, $M_{\text{turb}}$ exceeds the rotational and streaming terms over most of the region within $r_{500}$.

2.4. Adiabatic Simulation

We also analyze a simulation that starts from the same initial conditions as those adopted in CL7. However, in this simulation, the ICM of the cluster—called “CL7a”—evolves adiabatically, i.e., without radiative cooling. The major difference between these two sets of simulations is that the CSF clusters suffer the so-called overcooling problem (e.g., Balogh et al. 2001): cooling can produce a substantial amount of cold gas that is likely to be a few times higher than what are observed in real clusters (Gnedin et al. 2004).
In the top panel of Figure 6 we plot mass profiles for various terms in CL7a, applying the same method that we used for CL7. For this simulation unfortunately part of the temperature data is corrupted, and we have only those within $1 \, h^{-1}$ Mpc box and compute the mass profiles out to $\sim 0.6 \, r_{500}$. Clearly, for the simulation without radiative cooling, $M_{\text{therm}}$ closely follows the total mass, and the contribution from ($M_{\text{rot}} + M_{\text{stream}}$) is less than 5% over most radii. This is in sharp contrast to the case of CL7, in which the contribution from the ($M_{\text{rot}} + M_{\text{stream}}$) can be up to 10–20%, especially in the inner regions (see the top panel of Figure 3). This suggests that rotation and streaming motion contribute less to the gasdynamics in the NC simulations, i.e., that without radiative cooling.

To illustrate the difference between the CSF and NC simulations, we also plot the rotational velocities in the CL7 and CL7a. The bottom panel of Figure 6 shows the rotational velocity as a function of radius. We take the equatorial plane and average the gas velocity projection in the plane in each radial bin. We note that both NC and CSF simulations show similar gas velocities at $\gtrsim 0.3 \, r_{500}$, between 200 and 300 km s$^{-1}$. However, at the inner regions, the gas velocity in the CSF simulation rises sharply to above 1000 km s$^{-1}$, while the NC simulation shows a steady decline.

The substantial gas rotation has a strong impact on the gas dynamics in the central regions. This can be quantified by the ratio ($R_E$) between the kinetic energy in rotation ($KE_{\text{rot}}$) and the thermal energy ($E_{\text{therm}}$). For the CSF cluster CL7, we have

$$ R_E = \frac{KE_{\text{rot}}}{KE_{\text{therm}}} = \frac{(1/2)\rho v_{\text{rot}}^2}{(3/2)\rho k_B T_g} \quad (8) $$

$$ = 0.23(v_{\text{rot}}/600 \, \text{km s}^{-1})^2(T_g/3.5 \, \text{keV})^{-1}, \quad (9) $$

where $v_{\text{rot}}$ is the rotation velocity. Taking the typical rotational velocity of $\sim 600$ km s$^{-1}$ at $\sim 0.1 \, r_{500}$ in CL7 (see Figure 6), we estimate that the rotational kinetic energy can be as high as about 23% of the thermal energy. This is actually a conservative lower limit since the gas temperature peaks at $\sim 3.5$ keV (Nagai et al. 2007). It can be as low as $\sim 1$ keV in the innermost regions. This ratio decreases to about 10% between 0.2 and 0.3 $r_{500}$. However, for CL7a, due to the relative low velocity, this ratio stays below 10% at most radii. In fact, in the adiabatic simulation the $R_E$ value at $0.1 \, r_{500}$ is only about 1/10 the value obtained for the simulation with cooling and star formation.

3. ICM ROTATION AND ELLIPTICITY

3.1. Motivation

The substantial ICM rotation predicted by the simulations for relaxed CDM clusters needs to be tested by observations. The straightforward approach to detect rotation and other bulk...
motion of the ICM in clusters is to measure Doppler shifts and broadening of emission lines in their X-ray spectra. For a typical bulk-motion velocity of $\sim 500 \text{ km s}^{-1}$, Sunyaev et al. (2003) estimated that the Doppler shift of an iron line at 6.7 keV would be $\sim 10$ eV. The X-ray Spectrometer (XRS) on Astro-E2 would have been the first instrument to perform such measurements for many clusters, but its failure soon after launch means that we must await the next generation of X-ray satellites, such as Constellation-X, XEUS, and Spectrum-X, for direct measurements of ICM motions in many clusters.

In the classic cooling flow model, gas rotation is expected near the center of the flow due to mass and angular momentum conservation (e.g., Mathews & Brighenti 2003). In the case of elliptical galaxies, the X-ray images are expected to be considerably flattened toward the equatorial plane (e.g., Brighenti & Mathews 1996; Mathews & Brighenti 2003). X-ray morphological information, such as ellipticity, can be used to probe this process. X-ray studies that assume negligible ICM rotation indicate that both the radial profile (e.g., Pratt & Arnaud 2003; Lewis et al. 2003; Vikhlinin et al. 2006; Gastaldello et al. 2007) and ellipticity (Buote & Canizares 1996) of the flattening mass of nearby clusters agree with the radial profile and ellipticity of the dark matter of simulated CDM clusters. Therefore, if the ICM of the simulated CDM clusters in our study is flattened substantially by rotation, their X-ray images on average should have larger ellipticities than observed clusters.

Since X-ray ellipticity can be measured precisely for many clusters, below we compare results for the simulated CDM clusters with a sample of observed clusters. We will also compare the results with a simulated CDM cluster that involves no radiative cooling and star formation. This comparison will help us understand the role of overcooling. We note that previous studies found that the simulation we use here reproduces reasonably well the spherically averaged global ICM properties of observed clusters (Nagai et al. 2007; Kravtsov et al. 2006).

3.2. Ellipticity of Relaxed CDM Clusters

We begin by computing the ellipticity profiles of the X-ray images of the relaxed simulated cluster CL7 for the three orthogonal projections shown in Figure 1. The iterative moment-based procedure we use to evaluate the ellipticities of the simulated X-ray images is the same as that discussed below for the observations of real clusters (Section 3.4.4). We show the X-ray ellipticity profiles for CL7 in Figure 7.

The X-ray ellipticities of the $x$-projection are small and have a nearly constant value ($\approx 0.10$) from $0.1-0.7 r_{500}$, eventually falling to ($\approx 0.05$) at $r_{500}$. The very round X-ray isophotes are expected in this projection since one is essentially looking down the axis of rotation. In contrast, the ellipticities are much larger and show a much stronger variation with radius in the other two projections. For the $y$-projection, the ellipticity is $0.6-0.7$ between radii $0.1$ and $0.2 r_{500}$, declines to $\approx 0.5$ at $0.3 r_{500}$, and continues to fall with radius until reaching a value of $\approx 0.25$ at $r_{500}$. The $z$-projection has ellipticities similar to the $y$-projection but with $\approx 10\%$ smaller values for most radii.

The X-ray ellipticities for radii $0.1-0.3 r_{500}$ in the $y$- and $z$-projections are considerably larger than those of the dark matter ($\approx 0.4$), which also decline with increasing radius. The larger X-ray ellipticities with respect to the dark matter imply substantial rotational flattening of ICM, because (1) the gravitational potential of an ellipsoid is never flatter than the mass distribution that generates it, (2) for (nonrotating) single-phase hot gas in hydrostatic equilibrium, the X-ray emissivity has the same shape as the gravitational potential, independent of the temperature profile of the gas ("X-ray shape theorem," Buote & Canizares 1994, 1998), and (3) $M_{\text{rot}}$ dominates $M_{\text{stream}}$ and $M_{\text{turb}}$.

As a consistency check, we note that at $0.1 r_{500}$ both $M_{\text{rot}}/M_{\text{therm}}$ and $R_E$ (Section 2.4) are about 0.25 for CL7, indicating substantial rotational support. Moreover, $1 + R_E \approx 1.25$ provides an approximate indication of the axial ratio induced by rotation, and this can explain most of the excess X-ray ellipticity over that produced by the flattened dark matter potential.

To make a proper comparison of the X-ray ellipticity profile of the simulated CDM clusters to the average ellipticity profile of observed clusters we average the ellipticity profiles of CL7 obtained by viewing 100 projections of random orientation ($\theta, \phi$). The average ellipticity profile is calculated by averaging all the ellipticity values of a particular radius obtained for the 100 simulations. To achieve fast computation, we approximate the X-ray emissivity in each cell as $\alpha n_e^2 T^{1/2}$, appropriate for thermal bremsstrahlung radiation. We verified this approximation by comparing the profiles for the three orthogonal projections computed using the full expression for the plasma emissivity.

The angle-averaged X-ray ellipticity profile for CL7 is shown in Figure 7. The average profile is similar to that from the $y$- and $z$-projections but with somewhat smaller values, i.e., the ellipticity declines from $\approx 0.6$ at $0.1 r_{500}$ to $\approx 0.3$ at $0.3 r_{500}$ and then settles to a value between 0.15 and 0.20 at larger radii.

Using the same procedure, we computed average ellipticity profiles for the other "relaxed" clusters in the simulation. Since we considered observations of clusters (rather than lower mass groups), we include only the relaxed simulated clusters with masses above $10^{14} h^{-1} M_\odot$, i.e., CL3, CL5, CL7, and CL104. We angle-averaged the profiles of these systems and plot the combined average profile of these four systems in Figure 8. The combined profile is very similar to that of CL7 (Figure 7).

3.3. Comparison to Adiabatic Simulation

For comparison, in Figure 7 (dark dashed line) we show the average ellipticity profile of CL7a obtained from the simulation without cooling or star formation (NC). Since we do not have

![Figure 7](image-url)
the temperature data outside of the $1\, h^{-1} $ Mpc box and the X-ray emissivity has a very weak dependency on temperature, we approximate the X-ray emissivity in each cell as $\propto \rho^2$. We test our results within the $1\, h^{-1} $ Mpc box and do not find any major difference between these two approximations. Within the central regions ($\sim 0.25 \, r_{500}$) the ellipticity of the NC cluster is considerably smaller compared with the CSF simulation. In fact, the ellipticity profile remains nearly constant with a value $\sim 0.25$ for radii larger than $0.1 \, r_{500}$. The much smaller ellipticity in CL7a is consistent with the much smaller rotational support compared to CL7. From Figure 6 one can see that the very different gas velocities near $0.1 \, r_{500}$ translate to $R_e$ values in CL7a, a factor of 10 smaller than in CL7. At $0.3 \, r_{500}$, the gas velocities of CL7 and CL7a are similar, as are their average X-ray ellipticities. The slightly smaller ellipticity values of CL7 at larger radii reflect both the slightly smaller gas velocities over that range (see Figure 6) and the fact that CL7 is slightly more centrally concentrated than CL7a. Clearly, the gasdynamics and morphology differ substantially, particularly within $\sim 0.3 \, r_{500}$, depending on whether cooling is included in the simulations.

3.4. Ellipticity of Observed Clusters

3.4.1. Sample Definition

In order to effect a comparison between the observable properties of the simulated clusters and real data, we selected a sample of nearby relaxed clusters observed with the ROSAT PSPC and with Chandra. We opted to use these complementary satellites since the large, unobstructed field of view ($\sim 20'$ radius) makes ROSAT ideal for the unbiased computation of ellipticities outside of the $2'$ radius in excess of $\sim 500$ kpc for most interesting systems. Its modest spatial resolution ($0.5$ FWHM at 1 keV; corresponding to $\sim 50$ kpc at $z = 0.1$) of the PSPC will not significantly bias the ellipticity calculation within radii $\geq 100–200$ kpc. In contrast, Chandra’s excellent spatial resolution ($\sim 0.5$, corresponding to scales of $\leq 2$ kpc even at redshifts as high as $\sim 0.2$) but modest field of view ($\leq 4'$ radius on any single CCD) allows ellipticities to be measured from scales ranging from $\sim 1$ to $\sim 100$ kpc. We did not use the ROSAT HRI due to its smaller field of view and lower sensitivity than the PSPC.

To define a sample of relaxed clusters, we selected the 10 clusters from the PSPC sample of Buote & Tsai (1996) which had the lowest $P_3/P_0$ ratio within an aperture of $500 \, h^{-1}$ kpc. We adopted the $P_3/P_0$ ratio since it is sensitive to unequal-sized mergers (Buote & Tsai 1995), and therefore allows us to eliminate obviously disturbed objects. Although there is evidence of correlations between $P_3/P_0$ and $P_2/P_0$ (which is sensitive to the cluster ellipticity) for disturbed systems (Buote & Tsai 1996), we would expect a relaxed cluster to have $P_3/P_0 \simeq 0$, and so this selection should not bias us toward low-ellipticity (relaxed) clusters. We excluded one cluster, A 2255, since it has a very extended surface-brightness profile that implies that it is not in a relaxed state. We also excluded A 1651 since the existing Chandra observation is very shallow and the cluster is centered close to a chip gap (restricting the range of radii over which the ellipticity can be computed). Although it is difficult to choose relaxed clusters that exactly match the mass distribution of the simulated clusters, to increase the coverage of lower-mass systems we included A 2589, which just missed our $P_3/P_0$ cut but is nonetheless very relaxed and has a virial mass $\sim 5 \times 10^{14} M_\odot$ (Zappacosta et al. 2006). The selected objects, along with properties from Buote & Tsai (1996), are shown in Table 1. To ensure a fair comparison, we also examine the $P_3/P_0$ ratio for the simulated clusters, and find that they are in the range of $10^{-8}–10^{-10}$, consistent with those of observations.

3.4.2. Chandra Data Reduction

Archival observations of the clusters were drawn from the public Chandra archive, and the data were reduced and analyzed with the CIAO 3.4 and Heasoft 5.3.1 software suites, in conjunction with Chandra calibration database (Caldb) version 3.3.0.1. To ensure up-to-date calibration, all data were reprocessed from the “level 1” event files, following the standard Chandra data-reduction threads.1 We applied the standard correction to take account of the time-dependent gain drift and, where possible, charge transfer inefficiency, as implemented in the CIAO tools. To identify periods of enhanced background (“flaring”), which seriously degrades the signal-to-noise ratio, we accumulated background light curves for each data set from low surface-brightness regions of the active chips, excluding obvious point sources. Periods of flaring were identified by eye and excised. The final exposure times are listed in Table 1. For each data set, we generated a full-resolution image in the energy 0.3–7.0 keV and the corresponding exposure map, computed at an energy of 1.7 keV. Based on experience, such a monochromatic exposure map is sufficient for our present purposes.

Since our adopted procedure to calculate the ellipticity of a cluster involves taking moments of this image, the presence of bright point sources (most likely AGN) can lead to errors in the computation. It is therefore essential to identify and remove these objects from the image. Point sources were detected by application of the CIAO task wavdetect, which was set to

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1 http://cxc.harvard.edu/ciao/threads/index.html
search for structure at scales of 1, 2, 3, 4, and 16 pixels, and supplied with the exposure maps to minimize spurious detections at the image boundaries. The detection threshold was set to 10−6, corresponding to ≲1 spurious source detections per cluster. All detected sources were confirmed by visual inspection, and, for each, appropriate elliptical regions containing approximately 99% of its photons were generated. The detection algorithm also generated a “normalized background” image, which is effectively a smoothed, flat-fielded image, having removed the point sources found by wavdetect.

To generate a cleaned image, suitable for the calculation of ellipticities, the data within each of the elliptical point-source regions were replaced with Poisson-deviated noise. For each pixel, the mean of the Poisson deviate was drawn from the corresponding point on the normalized background image, taking into account variations in the exposure map. Provided the detection algorithm accurately characterizes all the point sources, this is a very robust method for source removal. However, wavdetect occasionally misidentifies extended cluster emission as a point source, or misestimates the radius enclosing most of the source photons, and so the background map may be locally imperfect. In such cases where the source replacement was obviously imperfect, suspicious sources were replaced by assuming that the mean (flat-fielded) count rate per pixel is uniform over the point-source region (this is most correct if the source is at a large radius from the cluster center). This count rate was estimated for each source by centering a circular extraction region on the source centroid and expanding its radius iteratively until at least 50 photons were found within it, taking care to exclude all photons within any of the source regions. Since the exposure may vary over the pixels within a given source region (especially near the edge of the image), the exposure map was used to correct this rate on a pixel-by-pixel basis before Poisson noise was added. The final “cleaned” images were visually inspected to confirm reliable source removal. Provided the brightest of the point sources in an image are removed in this way, any residual (unidentified) sources should not significantly bias our results (Buote & Tsai 1995). Finally, for the computation of the ellipticity profiles, we flattened the image by dividing it by its exposure map. To confirm the accuracy of the exposure correction, we visually inspected each image (having first mildly smoothed it with a ~10′ Gaussian filter to aid the eye) for obvious signs of poor flat-fielding. In general, away from the gaps between CCDs, the exposure correction appeared reliable.

### 3.4.3. ROSAT Data Reduction

We obtained RDF data for each cluster from the HEASARC archive, which were reduced and processed with HEASOFT 5.3.1 and CIAO 3.3.0.1. The data were initially screened to remove (probably spurious) bursts of events with the burat task. To ensure conservative screening criteria, we generated a PSPC “makefilter file” using the pcfil1t task, and screened out events corresponding to a master veto rate in excess of 170 s−1. A light curve was generated from outer parts of the field of view, chosen to avoid obvious bright point-like or extended sources, and was examined by eye to identify periods of enhanced background. Any data taken during such “flares” were excluded from further analysis. Full field of view images were generated in the 0.4–2.0 keV band, with a pixel size of 15′, and the corresponding exposure maps were generated with the pcfilm task. In addition, a circular cut-out region, centered on the peak of the cluster emission and extending as far as the shadow of the inner PSPC support ring, was created using the dxcopy task for both the image and exposure map. Such a cut prevents the support structure shadows (which are not perfectly removed during flat-fielding) from compromising the calculation of the ellipticities. For those objects with multiple pointings (Table 1), the images and exposure maps were summed to produce a single “merged” image and exposure map using custom software. Before addition, each image was aligned with the image having

#### Table 1

| Cluster | Redshift | $r_{500}$ (kpc) | $P_2/P_0$ | $P_3/P_0$ | Chandra ObsID | Exposure (ks) | $R_{max}$ (kpc) | ROSAT ObsID | Exposure (ks) |
|---------|----------|------------------|-----------|-----------|--------------|---------------|----------------|-------------|---------------|
| A2589   | 0.041    | 820$^a$          | $2.6^{+0.8}_{-1.2} \times 10^{-6}$ | $1.1^{+5.9}_{-0.9} \times 10^{-8}$ | 7190         | 53            | 250            | 800526      | 5.9           |
| A2597   | 0.085    | 900$^b$          | $1.0^{+0.3}_{-0.1} \times 10^{-6}$ | $1.6^{+31.3}_{-1.3} \times 10^{-9}$ | 7329         | 58            | 320            | 800112      | 6.2           |
| A2199   | 0.030    | 990$^c$          | $5.9 \pm 1.00 \times 10^{-7}$    | $5.1^{+12.5}_{-3.5} \times 10^{-9}$ | 497          | 18            | 310            | 150083,800644 | 43.          |
| MKW3s   | 0.043    | 1200$^d$         | $1.6^{+0.5}_{-0.4} \times 10^{-6}$ | $5.3^{+33.4}_{-4.4} \times 10^{-9}$ | 900          | 57            | 230            | 800128      | 7.5           |
| A1795   | 0.062    | 1240$^e$         | $1.3 \pm 0.1 \times 10^{-6}$    | $3.0^{+22.2}_{-3.0} \times 10^{-10}$ | 5287         | 14            | 310            | 800055,800105 | 54.          |
| A2052   | 0.035    | 1290$^f$         | $1.3 \pm 0.4 \times 10^{-6}$    | $3.3^{+26.7}_{-2.7} \times 10^{-9}$ | 5807         | 130           | 290            | 800275(a01,000) | 6.7         |
| A1413   | 0.14     | 1300$^g$         | $5.2^{+2.2}_{-1.7} \times 10^{-6}$ | $2.2^{+13.3}_{-1.3} \times 10^{-9}$ | 5003         | 75            | 270            | 800183      | 6.4           |
| A2029   | 0.077    | 1360$^h$         | $1.4 \pm 0.3 \times 10^{-6}$    | $3.1^{+9.7}_{-2.9} \times 10^{-9}$ | 4977         | 77            | 300            | 800161,800249 | 12.          |
| HydraA  | 0.052    | 1390$^i$         | $4.9 \pm 1.3 \times 10^{-7}$    | $4.4^{+10.0}_{-3.6} \times 10^{-9}$ | 4969         | 86            | 260            | 800318      | 16.           |

Notes. The sample of “relaxed” galaxy clusters, sorted in order of increasing $P_2/P_0$ ratio, as obtained from Buote & Tsai (1995). Also shown are the cluster redshift, the mean cluster temperature ($kT$), the $P_2/P_0$ and $P_3/P_0$ ratios from Buote & Tsai (1996), the observation numbers (“ObsID”) of each ROSAT PSPC and Chandra data set used in the present paper, and the total cleaned exposure time, following background screening (“Exposure”). For the Chandra data, we also indicate the maximum radius to which the data were used in computing the ellipticity profile ($R_{max}$). $r_{500}$ taken from references:

$a$ Finoguenov et al. (2001).
$b$ Pointecouteau et al. (2005).
$c$ Sanderson et al. (2006).
$d$ Vikhlinin et al. (2006).
$e$ Zappacosta et al. (2006).

2 ftp://legacy.gsfc.nasa.gov

\[ \text{ObsID} \]
the longest exposure by shifting it an integer number of pixels in the x and y directions.

Point sources were detected in the merged cut-out image with the wavdetect algorithm, which was set to search for structure at scales of 1, 2, 4, and 8 pixels, and supplied with the exposure maps to minimize spurious detections at the image boundaries. The detection threshold was set to $10^{-6}$, corresponding to $\lesssim 0.1$ spurious source detections per image. After visual confirmation of the detected sources, the images were “cleaned” of point sources and flat-fielded, in exactly the same manner as the Chandra data. To prevent overcorrection during flat-fielding (particularly in areas where the exposure correction may be questionable), we reset any pixel for which the exposure map fell below 30% of its peak value to zero, and reset the maximum radius inside which the ellipticity can be computed so as not to contain any such pixels.

### 3.4.4. Ellipticity Profiles

To compute the ellipticity profiles, we adopted a moment-based method that was first developed by Carter & Metcalfe (1980) and later was implemented in the study of the ROSAT and Chandra image of NGC 720 (see, e.g., Buote & Canizares 1994; Buote et al. 2002) and a sample of five ROSAT clusters (Buote & Canizares 1996). In this method, the two-dimensional principal moments of inertia line within an elliptical region. The ellipticity, $\epsilon$, is defined as the square root of the ratio of the principal moments. We refer the readers to Buote & Canizares (1994) and Buote et al. (2002) for details.

For each cluster we visually inspected the Chandra image for evidence of disturbances in the core, such as bubbles, shocks, or cavities, which are most likely a consequence of active galactic nucleus (AGN) activity (Birzan et al. 2004; Forman et al. 2005; Fabian et al. 2006). Such effects will distort the ellipticity profile computed within the disturbed region but, crucially, the physics of these interactions is not captured by the simulations. Therefore, for each cluster, we estimated the extent of the disturbed region and ignored the ellipticity profile computed within this radius. The moment method we adopted to compute the profile does incorporate information from the pixels in the suspect region. However, the ellipticity is strongly biased toward pixels at large radius and so the method should still yield reliable results. The Chandra profiles were computed to as large a radius as possible before a circular aperture of that radius would come in contact with a chip gap or, alternatively, the error bars on the profile became large. The maximum extent of each Chandra profile is given in Table 1. Outside this radius, the ellipticity data points were taken from the ROSAT data, for which the profile was computed until the edge of the "cut-out" image. In general, we found that the ROSAT and Chandra profiles matched up well.

In Table 2, we list the observed ellipticity profiles derived for each of the clusters in our sample. In general, the profiles are relatively flat, with a peak ellipticity of $\sim 0.2$–0.3. We do not find any evidence of sharply rising profiles.

### 3.5. Comparison of Observed and Simulated CDM Clusters

We show the average X-ray ellipticity profiles of the observed clusters and the simulated CDM clusters ($M > 10^{14} h^{-1} M_\odot$) in Figure 8, with $\sigma$ statistical errors on the mean observed values. We also list the average observed ellipticities and their errors in the last column of Table 2. The differences between the profiles are very striking. While the observed clusters have a nearly constant ellipticity profile ($\sim 0.15$), the simulated CSF clusters have much larger ellipticity values ($\sim 0.3$–0.6) at small radii ($0.1$–$0.4 \ r_{500}$) before declining to $\sim 0.15$ near $r_{500}$. For radii above $\approx 0.6 \ r_{500}$, both the shape and normalization of the profiles are similar for both the simulated and observed clusters. However, the ellipticity profile of the NC cluster CL7a shows much better agreement with the observed clusters over all radii examined. The relatively small deviations of this single cluster (formed in the simulation without cooling or star formation) from the average ellipticity profile of the observed clusters is consistent with the stochastic variation between the observed clusters (see Table 2).

The pronounced discrepancy over $0.1$–$0.4 \ r_{500}$, taken together with the discussion in Section 3.2, clearly demonstrates that the ICM in the simulated clusters rotates much more rapidly than in the observed clusters. Furthermore, this excess ICM rotation in the simulated CDM clusters extends out to $\approx 0.6 \ r_{500}$ since that is where the ellipticity profiles of the observed and simulated clusters diverge. The averaged profiles for the CSF clusters are also slightly lower than the observations at $> 0.6 \ r_{500}$, indicating that the CSF clusters may rotate a little slower than the observed clusters at larger radii and, perhaps more likely, the CSF clusters are slightly more centrally concentrated.

### 4. DISCUSSION AND CONCLUSION

Over the past decade, theoretical studies of cosmological hydrodynamical simulations have emphasized the important role of random turbulent motions in providing pressure support of the ICM in galaxy clusters. Using the set of high-resolution CDM simulations of Nagai et al. (2007), we have shown instead that rotational support of the cluster weight exceeds that of random turbulence from $0.1$–$0.5 \ r_{500}$ and remains comparable out to $\approx 0.8 \ r_{500}$ for the clusters classified as the most relaxed in the simulations.

When we compared the average ellipticity profile of the relaxed CDM clusters with that obtained for a set of nine real nearby clusters observed by Chandra and ROSAT, we found that the simulated CDM clusters are significantly flatter within $\approx 0.4 \ r_{500}$ and the profile shapes differ interior to $\approx 0.6 \ r_{500}$. By comparing simulations with and without radiative cooling and star formation, we conclude that this flatness is mainly caused by gas overcooling and large-scale rotation.

The substantial ICM rotation present in the relaxed simulated CDM clusters very likely indicates that a classical "rotating cooling flow" (Nulsen 1983; Kley & Mathews 1995; Brighenti & Mathews 1996) operates in those systems, implying large mass deposition rates which are not observed. At very small radii ($< 0.1 \ r_{500}$), it is well known that cosmological hydrodynamical simulations fail to reproduce observed ICM properties because of overcooling, but since the ICM rotation we have discussed extends to much larger radii, the overcooling problem apparently does as well.

We stress that the Nagai et al. (2007) simulations are not unusual with regard to displaying signatures of ICM rotation. Recently, Jeltema et al. (2008) compared X-ray images of simulated and observed clusters using power ratios (Buote & Tsai 1995). They found that $P_2 / P_0$, which is similar to ellipticity, computed within a 0.5 Mpc aperture for their relaxed simulated CDM clusters is slightly larger than for the observed clusters. They also found that distribution of $P_2 / P_0$, which is sensitive to asymmetry but not ellipticity, is consistent for the simulated and observed clusters, implying that it is very unlikely that the
We show in Table 2 the observed ellipticity profiles of each of the clusters considered in Section 3.4.4.

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