Large Scale Models of Clusters of Galaxies

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ABSTRACT

The major difficulty in using clusters of galaxies to determine cosmological parameters is the conversionbetween their observed and theoretical physical properties. Thus, an understanding of the physics of clusters of galaxies and modeling them out to distances as far as the intra-cluster gas extends is of crucial importance. This task can not be done using observations today since we can not observe the intra-cluster gas out to the virial shock around clusters. Therefore we have been using a sample of clusters of galaxies drawn from high resolution cosmological N-body-hydro simulations to derive large scale models for the intra-cluster gas. We are planning to compare our models to observations of the intra-cluster gas out to large radii using AMiBA observations. We present our preliminary intra-cluster gas models and briefly discuss their impact on determining cosmological parameters using the SZX-ray method and an XXL type sample of clusters of galaxies.

1. Instroduction

The formation and evolution of clusters of galaxies, the largest virialized objects in the Universe, are very sensitive to the underlying cosmological model. Therefore clusters of galaxies have been used extensively to determine cosmological parameters. We may cast these methods into two main categories: individual methods (i.e. Sunyaev-Zel'dovich–X-ray [SZX-ray] method) and statistical methods (i.e. cluster number counts, X-ray luminosity and mass functions). Both main methods have advantages and disadvantages. One of the advantages of the individual methods is that we can choose relaxed clusters which can be modeled more accurately. However, at present, we can observe the intra-cluster gas in clusters out to only about half of their virial radii, and therefore we need a well motivated theoretical model for the intra-cluster gas out to the virial shock. We used a sample of clusters of galaxies drawn from cosmological N-body-hydro simulations to derive large scale models for the intra-cluster gas in relaxed clusters. Numerical simulations show that accretion into massive clusters of galaxies occur via filaments, which plunge deep into the clusters. However,

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filaments are not part of the virialized cluster, nor they contribute to our X-ray observations due to their low temperature. Removing the filaments also makes it possible to determine the extent of the intra-cluster gas. Therefore we determined a physical model for clusters of galaxies after we located and removed the filaments. Other proposed models for the intra-cluster gas based on numerical simulations have not removed the filaments.

2. Cluster Sample and Analysis

We used four relaxed clusters from a sample of 10 massive clusters of galaxies drawn from AMR simulations, each located at zero redshift. The simulations were performed with the cosmological code ENZO (O'Shea et al. 2004; Bryan 1999) assuming a spatially flat ΛCDM cosmology with (Ω_m, Ω_Λ, Ω_b, h, σ_8) = (0.25, 0.75, 0.046, 0.7, 0.75). This cosmological model is consistent with the WMAP results (Spergel et al. 2007). The clusters of galaxies in our sample were re-simulated with high resolution (Younger & Bryan 2007). The total virial mass of the clusters in our sample is in the range of 9×10^{14}-2×10^{15} $M_\odot$. The resolution (AMR cell size) of the cluster simulations at distances from the cluster centers, $r = 0$, 1 and 4 R_{vir} were about 25 kpc, 80 kpc and 250 kpc.

We are interested in radially averaged properties of clusters of galaxies, therefore we used polar coordinates with the center placed in the center of mass of the clusters. We sampled physical variables from the simulation output at points, $\vec{x}$, described by their distance from the cluster center, and their direction expressed as pixel number, $\vec{x} = (r, P)$, where P refers to pixel numbers based on the HEALPix pixelization scheme (Gorski et al. 2005). This coordinate system provides a convenient way of describing physical variables around collapsed objects. The resolution was choosen to be somewhat higher than the cell size of the simulations. The physical size of the pixels is larger at larger radii, but, in our case, that is even desired, since the resolution of the simulations also decreases with distance from the cluster center (except for substructures, which we are not interested in our analysis). We used the averages in cells if more AMR points fell in that cell, otherwise we used the nearest AMR point. Owing to our choice of the coordinates most cells contained at least one AMR point.

We removed the filaments using a density threshold close to the characteristic density of the filaments. We determined this density from visual inspection of each cluster. We found this method very effective in isolating and removing filaments. We show the radially averaged dark matter and gas density distribution as a function of the distance from the cluster center towards all directions (solid lines) and towards no filament regions (dashed lines) for all of our 10 clusters in Figure 1. It can be seen from this Figure that at about 1.5 R_{vir} the averaged gas density towards no filament regions falls below the all direction average indicating the extent of the intra-cluster gas. Note, that the gas cut off is farther out than the usually assumed one virial radius.

3. Large Scale Model for the Intra-cluster Gas

We used relaxed clusters from our sample of massive clusters. Relaxed clusters were selected based on their density distribution: we required a smooth density distribution with small error bars on their radially averaged density profile (after removal of filaments) and no sign of recent major merger events in the cluster core region. Radially averaged gas density, temperature and pressure distributions for our relaxed clusters are shown in Figure 2. The dashed lines with error bars represent averages over the 4 relaxed clusters in our sample. The solid lines show our fit. Note that the pressure model is not a fit to the pressure data but calculated based on the fits to density and temperature distributions and serves as a consistency test. Interesting to note that, while the density distribution is quite similar in all 4 relaxed clusters, the temperature show more variations. This is due to the high sensitivity of the temperature to shocks from accretion and internal flows.

We used a β model to describe the density distribution of the intra-cluster gas in the inner 70% of R_{vir}. In this region we fit the same functional form to the temperature distribution as given by Loken et al (2002). At about 0.7 R_{vir} we find that the slope of the gas density and temperature distributions change and they can be described by power law distributions. Our fitted intra-cluster gas model: within $0 \le r \le 0.7R_{vir}$: density: β model with $\beta = 1$ and $r_{core} = 0.14R_{vir}$ (about 300 kpc), temperature: $\bar{T}_{gas}(r) \propto (1 + r/0.8)^{-1.6}$ (cf. Loken et al 2002); within $0.7R_{vir} \le r \le 3R_{vir}$: density: power law with $\alpha = -4.3$, temperature: power law with $\alpha = -1$; both density and temperature are assumed to be zero for $r > 3R_{vir}$. The resulting pressure model is shown with the pressure distribution and serve as a consistency test shown in Figure 2(c). We have found that the NFW profile is a good fit to the dark matter in relaxed clusters. According to our results the cluster gas density distribution follows the r^{-3} fall off of the NFW profile for large radii out to about 5 r_{core}, but farther out it cuts off more sharply, as $r^{-4.3}$.

The value we obtained for the β parameter, $\beta = 1$, is larger than $\beta \approx 0.7 - 0.8$ determined from X-ray observations, but similar to other results based on cosmological numerical simulations. Note, however, that Hallman et al. (2007) showed that the X-ray observations are biased towards lower values of the β parameter.

4. Future Work

We are planning to use relaxed clusters with different masses and redshifts to derive large scale models for the intra-cluster gas and compare our models with future AMiBA observations of clusters of galaxies. We are also planning to use these models to determine cosmological parameters using our AMiBA observations of clusters of galaxies supplemented with other X-ray and gravitational lensing observations. We will briefly discuss the impact of our intra-cluster gas models on cosmological parameter estimation based on the SZX-ray method and an XXL type sample of clusters on the XXL meeting.

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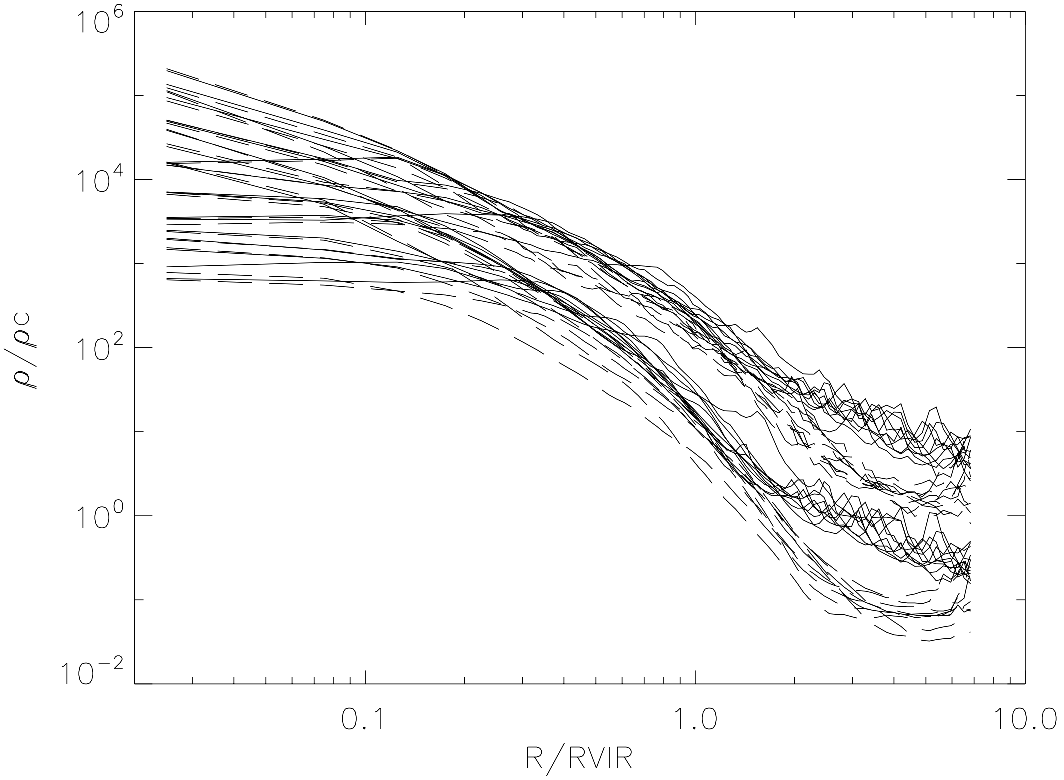
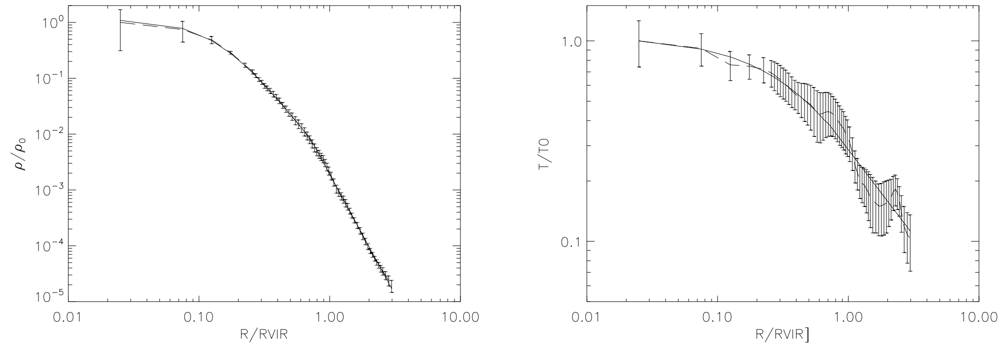
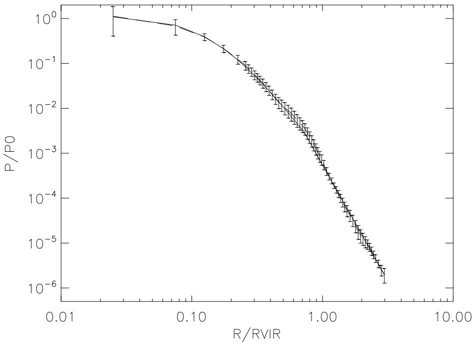


Fig. 1.— Average dark matter (upper solid and dashed lines) and gas densities (lower solid and dashed lines) as a function of radius in units of R_{vir} for all 10 clusters in our sample. Solid and dashed lines show density averages in all pixel directions and towards no filament pixels.



(a) $\bar{\rho}(r)$ (b) $\bar{T}_{gas}(r)$



(c) $\bar{p}(r)$

Fig. 2.— Relaxed cluster radially averaged density (a), temperature (b) and pressure (c) distribution (dashed lines with error bars). Solid lines show our models (see text for details).