Limitations on Precision Cosmology using Clusters of Galaxies

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Abstract

We critically analyze the role of clusters of galaxies as probes for precision cosmology. Using synthetic observations of numerically simulated clusters viewed through their X-ray emission and thermal Sunyaev-Zeldovich effect (SZE), we extract measurements of the cluster gas mass. We quantify the possible sources of uncertainty and systematic bias associated with the common simplifying assumptions used in reducing real cluster observations including isothermality and hydrostatic equilibrium. **We find that intrinsic variations in clusters limit the precision of observational gas mass estimation to ∼10% to 80% confidence excluding instrumental effects.** For the full cluster sample, methods that use SZE profiles out to roughly the virial radius are the most accurate and precise way to estimate cluster mass. X-ray methods are systematically more precise mass estimators than are SZE methods if merger systems are removed, but **X-ray methods slightly overestimate (5-10%) the cluster gas mass on average.** Finally, we find that methods using a universal temperature profile estimate cluster masses to higher precision than those assuming isothermality.

Introduction

The number density of galaxy clusters as a function of mass and redshift can be used to constrain a number of cosmological parameters. In particular, counting the abundance of clusters above some lower mass limit as a function of cluster redshift places constraints on Ω_b, Ω_M, and the dark energy equation of state, w (Pen (1997), Sasaki (1996)). Measuring the apparent change of cluster gas fraction with redshift also produces constraints on w (e.g. Vikhlinin et al. (2005)). In order for such methods to provide strong constraints on cosmological parameters, cluster mass estimators must be accurate to ∼10% (Haiman et al. 2001). Previous studies (e.g. Evrard et al. (1996)) suggest that this level of precision may be difficult to achieve. The often used scaling relation between cluster mass and X-ray spectral temperature has relatively small scatter compared to other methods, but still is uncertain to ∼30% (e.g. Sanderson et al. (2003)). This study aims to determine the limiting accuracy of various X-ray and Sunyaev-Zeldovich effect (SZE) observational methods of cluster gas mass estimation. This determination will indicate whether cluster methods can be accurate enough to do precision cosmology. This study addresses the key question: *What is the best way to measure cluster gas masses with precision in order to do cosmology?*

High resolution X-ray or SZE observations of clusters coupled with assumptions about the gas distribution lead to estimates of the gas mass in the cluster dark matter potential well. The electron number density is often assumed to fit an isothermal β model,

$$n_e(r) = n_{e0}\left(1+\left(\frac{r}{r_c}\right)^2\right)^{-3\beta/2}. \tag{1}$$

Fitting an observed X-ray or SZE profile to these projected isothermal β model X-ray surface brightness and y parameter distributions results in a description of the density distribution, which can be integrated to obtain the gas mass. The difference in dependence on gas density and temperature of X-ray emissivity and the SZE y parameter makes the combination of these two methods of observation very powerful. These two methods of observing clusters not only select a different sample of clusters, but combined SZE/X-ray observations of individual clusters allow one to extract the density and temperature of the gas without relying on X-ray spectral temperatures.

Recent numerical (e.g. Loken et al. (2002)) and observational studies (e.g. Vikhlinin et al. (2005)) suggest that the cluster gas is not isothermal, but fits more closely to a universal temperature profile (UTP), for this study written as

$$T(r) = \langle T\rangle_{500} T_0\left(1+\left(\frac{r}{\alpha r_{500}}\right)^2\right)^{-\delta}, \tag{2}$$

where $\langle T\rangle_{500}$ is the average temperature inside a projected overdensity radius of r_{500}. T_0, α, and δ are parameters whose mean value is measured from the entire cluster population at each redshift. We perform a geometric deprojection of the X-ray and SZE profiles and use this additional assumption about the gas temperature to calculate the density profile and the mass.

With observations of both X-ray and SZE for a particular cluster, an observer can deproject the surface brightness of each simultaneously to determine the gas density. This method is particularly powerful due to the difference in dependence of X-ray and SZE emission on density and temperature. In this study, we also perform such a combined deprojection of X-ray and SZE profiles to obtain the gas density radial profile with no assumption about the temperature profile.

We examine the effect of the assumption of the gas temperature and density profile on the determination of the true cluster gas mass. Using adaptive mesh hydro/N-body cosmological simulations, we have extracted all clusters with $M \geq 10^{14} M_\odot$ out to a redshift of z = 2. The four simulations used progressively more sophisticated baryonic physics. For each cluster, we have fit the X-ray and SZE surface brightness profiles to those produced by a best-fit isothermal gas distribution. We also perform a direct geometric deprojection of the SZE and X-ray surface brightness.

Our simulations use the hybrid Eulerian adaptive mesh refinement/n-body code *Enzo* (O'Shea et al. (2005); http://cosmos.ucsd.edu/enzo) to evolve both the dark matter and baryonic fluid in the clusters; utilizing the piecewise parabolic scheme for the hydrodynamics. With up to seven levels of dynamic refinement in high density regions, we attain spatial resolution up to ∼ 16 kpc in the clusters. We assume a concordance ΛCDM cosmological model with the following parameters: $\Omega_b = 0.026, \Omega_m = 0.3, \Omega_\Lambda = 0.7, h = 0.7$, and $\sigma_8 = 0.928$.

Table 1. Ratio of Estimated Gas Mass to True Gas Mass.

Method	Model	Radius	Median	Mean	80% Upper	80% Lower
Xray	UTP	r_{500}	1.06	1.07	1.11	1.03
Xray	Iso	r_{500}	1.08	1.08	1.13	1.04
Joint	Geometric	r_{500}	1.09	1.09	1.16	1.02
SZE	UTP	r_{200}	0.98	0.99	1.06	0.93
SZE	UTP	r_{500}	1.01	1.01	1.11	0.92
SZE	Iso	r_{500}	1.08	1.07	1.20	0.96
SZE	y-M	r_{500}	0.96	0.98	1.13	0.87
Xray	T_X-M	r_{500}	1.03	1.01	1.27	0.77

Comparison of Methods as a Function of Redshift

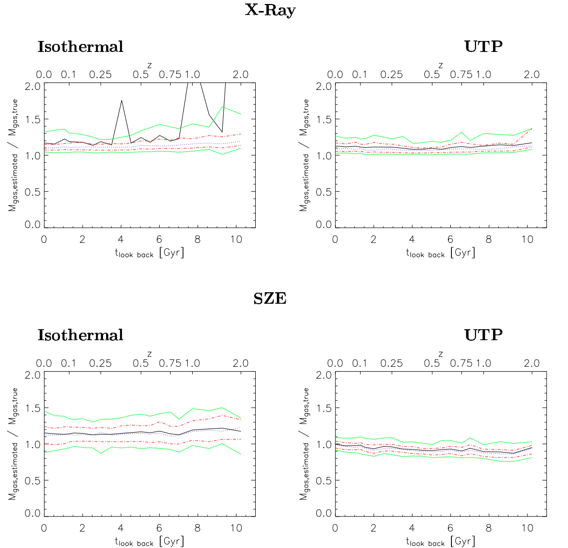

Figure 1. Mass Estimation as a function of redshift in the simulation cluster catalog. Top: Left panel shows mean (solid line) and median (blue dotted line) ratio of estimated gas mass to true gas mass inside r_{200} for isothermal X-ray method. Red dot-dashed lines represent range within which the middle 50% of clusters are estimated, green lines are for 80% limits. Right panel is similar plot for deprojection of X-ray assuming a UTP model for temperature. Bottom: Left panel is mass ratio for fitting SZE y parameter distribution to isothermal model, right panel is similar but for SZ deprojection assuming a UTP for temperature.

Comparison of Estimates at Different Radii

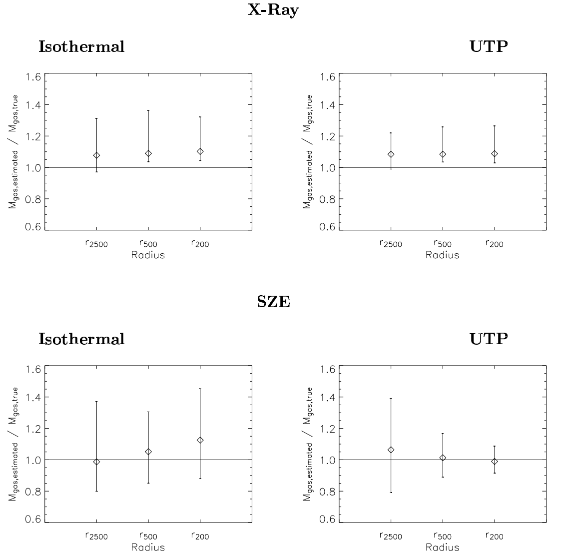

Figure 2. Top: Left panel shows median ratio of estimated gas mass to true gas mass inside various radii as indicated for all clusters above $10^{14} M_\odot$ at z=0 in the simulation for X-ray isothermal mass estimate. Error bars are 80% scatter. Right panel is similar plot for deprojection of X-ray assuming a UTP model for temperature. Bottom: Left panel is mass ratio for fitting SZE y parameter distribution to isothermal model, right panel is similar but for SZ deprojection assuming a UTP for temperature. Line in each case represents $M_{est} = M_{true}$.

X-ray vs. SZE Mass Estimation

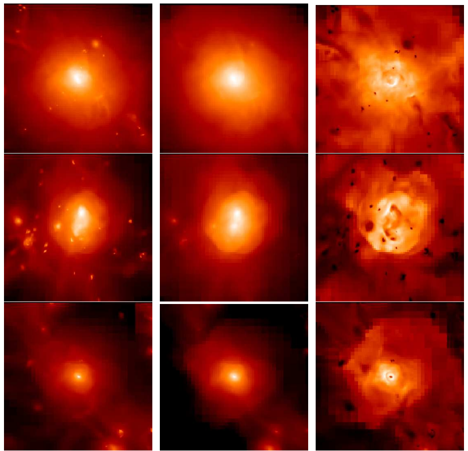

Figure 3. Three clusters. Top row appears relaxed, middle row has disturbed morphology and bottom row has a cool core. Left column shows X-ray surface brightness from simulated cluster, middle column is Compton y parameter and right column is emission weighted temperature. Images are $\sim 5h^{-1} Mpc$ on a side.

Table 2. Gas Mass Estimates for Three Clusters .

Cluster State	X-ray M_{est}/M_{true}	SZE M_{est}/M_{true}	Total Mass ($M_\odot$)
Relaxed	1.00	0.94	1.5×10^{15}
Disturbed	1.54	1.07	5.3×10^{14}
Cooling Core	1.39	1.10	1.4×10^{14}

Summary

The highest precision to which cluster gas masses can be measured using typical assumptions and either X-ray, SZE or a combination of both measurements is ∼ 10% to 80% confidence. This study does not include instrumental or other observational effects, and so is an indication of the limiting ability of observations to correctly gauge the mass of clusters in the ideal case. These limits in precision are a direct result of the deviation of the simulated clusters from simple assumptions about their physical and thermodynamic properties, dynamical state, and sphericity.

Mass estimates fitting radial profiles to a universal temperature profile (UTP) have smaller scatter than similar estimates assuming isothermality.

SZE methods of gas mass estimation assuming a universal temperature profile in the cluster gas produce the smallest scatter when estimating masses in a raw sample of clusters. Cleaning the cluster sample for disturbed or merging clusters is much less important in SZE methods, particularly when profiles can be observed to large radius. As a practical matter, SZE methods are superior for mass estimation for large samples of clusters out to high redshift. The SZE is more representative of the true cluster potential than the X-ray emission.

X-ray methods show a 5-10% bias in median values which is absent is SZE methods. The bias is a result of substructure and mergers in clusters, events which enhance the gas density locally. The stronger density dependence of X-ray emissivity tends to drive up the X-ray mass estimates more than the SZE estimates.

Cool core clusters in our catalogs are particularly poor candidates for precision mass estimation. Even when excising the cool core from the analysis, mass estimation shows larger scatter in both X-ray and SZE methods than for non-cool core clusters. The emission profiles of X-ray and SZE are affected outside the cool core region due to the presence of cold substructure in the cluster.

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Table 1:

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