COMPARISON OF HECTOSPEC VIRIAL MASSES WITH SUNYAEV–ZEL’DOVICH EFFECT MEASUREMENTS

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ABSTRACT

We present the first comparison of virial masses of galaxy clusters with their Sunyaev–Zel’dovich Effect (SZE) signals. We study 15 clusters from the Hectospec Cluster Survey (HeCS) with MMT/Hectospec spectroscopy and published SZE signals. We measure virial masses of these clusters from an average of 90 member redshifts inside the radius \( r_{100} \). The virial masses of the clusters are strongly correlated with their SZE signals (at the 99% confidence level using a Spearman rank-sum test). This correlation suggests that \( Y_{\text{SZ}} \) can be used as a measure of virial mass. Simulations predict a power-law scaling of \( Y_{\text{SZ}} \propto M_{200}^\alpha \) with \( \alpha \approx 1.6 \). Observationally, we find \( \alpha = 1.11 \pm 0.16 \), significantly shallower (given the formal uncertainty) than the theoretical prediction. However, the selection function of our sample is unknown and a bias against less massive clusters cannot be excluded (such a selection bias could artificially flatten the slope). Moreover, our sample indicates that the relation between velocity dispersion (or virial mass estimate) and SZE signal has significant intrinsic scatter, comparable to the range of our current sample. More detailed studies of scaling relations are therefore needed to derive a robust determination of the relation between cluster mass and SZE.

Key words: cosmology: observations – galaxies: clusters: individual – galaxies: kinematics and dynamics

1. INTRODUCTION

Clusters of galaxies are the most massive virialized systems in the universe. The normalization and evolution of the cluster mass function is therefore a sensitive probe of the growth of structure and thus cosmology (e.g., Rines et al. 2007, 2008; Vikhlinin et al. 2009; Henry et al. 2009; Mantz et al. 2008; Rozo et al. 2010, and references therein). Many methods exist to estimate cluster masses, including dynamical masses from either galaxies (Zwicky 1937) or intracluster gas (e.g., Fabricant et al. 1980), gravitational lensing (e.g., Smith et al. 2005; Richard et al. 2010), and the Sunyaev–Zel’dovich effect (SZE; Sunyaev & Zeldovich 1972). In practice, these estimates are often made using simple observables, such as velocity dispersion for galaxy dynamics or X-ray temperature for the intracluster gas. If one of these observable properties of clusters has a well-defined relation to the cluster mass, a large survey can yield tight constraints on cosmological parameters (e.g., Majumdar & Mohr 2004). There is thus much interest in identifying cluster observables that exhibit tight scaling relations with mass (Kravtsov et al. 2006; Rozo et al. 2010; Lopes et al. 2009). Numerical simulations indicate that X-ray gas observables (Nagai et al. 2007) and SZE signals (Motl et al. 2005) are both candidates for tight scaling relations. Both methods are beginning to gain observational support (e.g., Henry et al. 2009; Mantz et al. 2010; Locutus Huang et al. 2010). Dynamical masses from galaxy velocities are unbiased in numerical simulations (Diaferio 1999; Evrard et al. 2008), and recent results from hydrodynamical simulations indicate that virial masses may have scatter as small as \( \sim 5\% \) (Lau et al. 2010).

Previous studies have compared SZE signals to hydrostatic X-ray masses (Bonamente et al. 2008; Plagge et al. 2010) and gravitational lensing masses (Marrone et al. 2009, hereafter M09). Here, we make the first comparison between virial masses of galaxy clusters and their SZE signals. We use SZE measurements from the literature and newly measured virial masses of 15 clusters from extensive MMT/Hectospec spectroscopy. This comparison tests the robustness of the SZE as a proxy for cluster mass and the physical relationship between the SZE signal and cluster mass. Large SZ cluster surveys are underway and are beginning to yield cosmological constraints (Carlstrom et al. 2010; Hincks et al. 2010; Staniszewski et al. 2009). We assume a cosmology of \( \Omega_m = 0.3, \Omega_{\Lambda} = 0.7, \) and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) for all calculations.

2. OBSERVATIONS

2.1. Optical Photometry and Spectroscopy

We are completing the Hectospec Cluster Survey (HeCS), a study of an X-ray flux-limited sample of 53 galaxy clusters at moderate redshift with extensive spectroscopy from MMT/Hectospec. HeCS includes all clusters with \( \textit{ROSAT} \) X-ray fluxes of \( f_X > 5 \times 10^{-12} \text{ erg s}^{-1} \) at [0.5–2.0] keV from the Bright Cluster Survey (BCS; Ebeling et al. 1998) or the REFLEX survey (Bohringer et al. 2004) with optical imaging in the Sixth Data Release (DR6) of Sloan Digital Sky Survey (SDSS; Adelman-McCarthy et al. 2008). We use DR6 photometry to select Hectospec targets. The HeCS targets are all brighter than \( r = 20.8 \) (SDSS catalogs are 95% complete for point sources to \( r \approx 22.2 \)). Out of the HeCS sample, 15 clusters have published SZ measurements.

2.1.1. Spectroscopy: MMT/Hectospec and SDSS

HeCS is a spectroscopic survey of clusters in the redshift range \( 0.10 \leq z \leq 0.30 \). We measure spectra with the Hectospec instrument (Fabricant et al. 2005) on the MMT 6.5 m telescope. Hectospec provides simultaneous spectroscopy of up to 300 objects across a diameter of 1.\(^\circ\). This telescope and instrument combination is ideal for studying the virial regions and outskirts of clusters at these redshifts. We use the red sequence to preselect...
likely cluster members as primary targets, and we fill fibers with bluer targets (K. Rines et al. 2010, in preparation, describe the details of target selection). We eliminate all targets with existing SDSS spectroscopy from our target lists but include these in our final redshift catalogs.

Of the 15 clusters studied here, one was observed with a single Hectospec pointing and the remaining 14 were observed with two pointings. Using multiple pointings and incorporating SDSS redshifts of brighter objects mitigate fiber collision issues. Because the galaxy targets are relatively bright \( r \leq 20.8 \), the spectra were obtained with relatively short exposure times of \( 3 \times 600 \text{ s} - 4 \times 900 \text{ s} \) under a variety of observing conditions.

Figure 1 shows the redshifts of galaxies versus their projected clustrocentric radii for 9 of the 15 clusters studied here. The infall patterns are clearly present in all clusters. We use the caustic technique (Diaferio 1999) to determine cluster membership. Briefly, the caustic technique uses a redshift–radius diagram to isolate cluster members in phase space by using an adaptive kernel estimator to smooth out the galaxies in phase space and then determining the edges of this distribution (see Diaferio 2009, for a recent review). This technique has been successfully applied to optical studies of X-ray clusters and yields cluster mass estimates in agreement with estimates from X-ray observations and gravitational lensing (e.g., Rines et al. 2003; Biviano & Girardi 2003; Diaferio et al. 2005; Rines & Diaferio 2006; Rines et al. 2007, and references therein).

We apply the prescription of Danese et al. (1980) to determine the mean redshift \( c z_\odot \) and projected velocity dispersion \( \sigma_p \) of each cluster from all galaxies within the caustics. We calculate \( \sigma_p \) using only the cluster members projected within \( r_{100} \) estimated from the caustic mass profile.

### 2.2. SZE Measurements

The SZE detections are primarily from Bonamente et al. (2008, hereafter B08), supplemented by three measurements from Marrone et al. (2009, hereafter M09). Most of the SZ data were obtained with the OVRO/BIMA arrays; the additional clusters from M09 were observed with the Sunyaev–Zel’dovich Array (SZA; e.g., Muchovic et al. 2007).

Numerical simulations indicate that the integrated Compton \( \gamma \)-parameter \( Y_{SZ} \) has smaller scatter than the peak \( \gamma \)-decrement \( \gamma_{peak} \) (Motl et al. 2005), so B08 and M09 report only \( Y_{SZ} \). Although \( \gamma_{peak} \) should be nearly independent of redshift, \( Y_{SZ} \) depends on the angular size of the cluster. The quantity \( Y_{SZ} D_A^2 \) removes this dependence. Thus, we compare our dynamical mass estimates to this quantity rather than \( \gamma_{peak} \) or \( Y_{SZ} \). Table 1 summarizes the SZ data and optical spectroscopy.

It is also critical to determine the radius within which \( Y_{SZ} \) is determined. B08 use \( r_{2500} \), the radius that encloses an average density of 2500 times the critical density at the cluster’s redshift; \( r_{2500} \) has physical values of 300–700 kpc for the massive clusters studied by B08 (470–670 kpc for the subsample studied here). M09 use a physical radius of 350 kpc because this radius best matches their lensing data.

To use both sets of data, we must estimate the conversion between \( Y_{SZ}(r_{2500}) \) measured within \( r_{2500} \) and \( Y_{SZ}(r = 350 \text{ kpc}) \) measured within the smaller radius \( r = 350 \text{ kpc} \). There are eight...
clusters analyzed in both B08 and M09 (five of which are in HeCS). We perform a least-squares fit to $Y_{SZ}(r_{2500}) - Y_{SZ}(r = 350\text{ kpc})$ to determine an approximate aperture correction for the M09 clusters. We list both quantities in Table 1.

3. RESULTS

We examine two issues: (1) the strength of the correlation between the SZE signal and the dynamical mass and (2) the slope of the relationship between them. Figure 2 shows the $Y_{SZ}-\sigma_p$ relation. Here, we compute $\sigma_p$ for all galaxies inside both the caustics and the radius $r_{100,c}$ defined by the caustic mass profile ($r_3$ is the radius within which the enclosed density is 3 times the critical density $\rho_c(z)$).

Because we make the first comparison of dynamical properties and SZE signals, we first confirm that these two variables are well correlated. A non-parametric Spearman rank-sum test (one-tailed) rejects the hypothesis of uncorrelated data at the 98.4% confidence level. The strong correlation in the data suggests that both $\sigma_p$ and $Y_{SZ}D_A^2$ increase with increasing cluster mass.

Hydrodynamic numerical simulations indicate that $Y_{SZ}$ (integrated to $r_{2500}$) scales with cluster mass as $Y_{SZ} \propto M_{500}^{\alpha}$, where $\alpha = 1.60$ with radiative cooling and star formation, and 1.64 for simulations with radiative cooling, star formation, and active galactic nucleus feedback ($\alpha = 1.70$ for non-radiative simulations; Motl et al. 2005). Combining this result with the virial scaling relation of dark matter particles, $\sigma_p \propto M_{200}^{\alpha \pm 0.03}$ (Evrard et al. 2008), the expected scaling is $Y_{SZ} \propto \sigma_p^{4.76}$ (we assume that $M_{100} \propto M_{500}$). The right panels of Figure 2 show this predicted slope (dashed lines).

The bisector of the least-squares fits to the data has a slope of $2.94 \pm 0.74$, significantly shallower than the predicted slope of 4.8.

We recompute the velocity dispersions $\sigma_{p,A}$ for all galaxies within one Abell radius (2.14 Mpc) and inside the caustics. Surprisingly, the correlation is slightly stronger (99.4% confidence level). This result supports the idea that velocity dispersions computed within a fixed physical radius retain strong correlations with other cluster observables, even though we measure the velocity dispersion inside different fractions of the virial radius for clusters of different masses. Because cluster velocity dispersions decline with radius (e.g., Rines et al. 2003; Rines & Diaferio 2006), $\sigma_{p,A}$ may be smaller than $\sigma_{p,100}$ (measured within $r_{100,c}$) for low-mass clusters, perhaps exaggerating the difference in measured velocity dispersions relative to the differences in virial mass (i.e., $\sigma_{p,A}$ of a low-mass cluster may be measured within $2r_{100}$ while $\sigma_{p,100}$ of a high-mass cluster may be measured within $r_{100}$; the ratio $\sigma_{p,A}$ of these clusters would be exaggerated relative to the ratio $\sigma_{p,100}$). Future cluster surveys with enough redshifts to estimate velocity dispersions but too few to perform a caustic analysis should still be sufficient for analyzing scaling relations.

Because of random errors in the mass estimation, the virial mass and the caustic mass within a given radius do not necessarily coincide. Therefore, the radius $r_{2500}$ depends on the mass estimator used. Figure 2 shows the scaling relations for two estimated masses $M_{100,c}$ and $M_{100,v}$; $M_{100,100}$ is the mass estimated within $r_{100,100}$ (where both quantities are defined from the caustic mass profile) and $M_{100,v}$ is the mass estimated within $r_{100,v}$ (both quantities are estimated with the virial theorem, e.g., Rines & Diaferio 2006). Similar to $\sigma_p$, there is a clear correlation between $M_{100,v}$ and $Y_{SZ}D_A^2$ (99.0% confidence with a Spearman test). The strong correlation of dynamical mass with SZE also holds for $M_{100,c}$ estimated directly from the caustic technique (99.8% confidence).

The bisector of the least-squares fits has a slope of $1.11 \pm 0.16$, again significantly shallower than the predicted slope of 1.6. This discrepancy has two distinct origins. By looking at the distribution of the SZE signals in Figure 2, we see that, at a given velocity dispersion or mass, the SZE signals have a scatter which is a factor of $\sim 2$. Alternatively, at fixed SZE signal, there is a scatter of a factor of $\sim 2$ in estimated virial mass. Unless the observational uncertainties are significantly underestimated, the data show substantial intrinsic scatter. Moreover, this scatter is comparable to the range of our sample and, therefore, the
error on the slope derived from our least-squares fit to the data is likely to be underestimated (see Andreon & Hurn 2010, for a detailed discussion of a Bayesian approach to fitting relations with measurement uncertainties and intrinsic scatter in both quantities).

Our shallow slopes may also arise in part from the fact that our sample, which has been assembled from the literature and whose selection function is difficult to determine, is likely to be biased against clusters with small mass and low SZE signal. Larger samples should determine whether unknown observational biases or issues in the physical understanding of the relation account for this discrepancy.

4. DISCUSSION

The strong correlation between masses from galaxy dynamics and SZE signals indicates that the SZE is a reasonable proxy for cluster mass. B08 compare SZE signals to X-ray observables, in particular the temperature $T_X$ of the intracluster medium (ICM) and $Y_X = M_{\text{gas}}T_X$, where $M_{\text{gas}}$ is the mass of the ICM (see also Plagge et al. 2010). Both of these quantities are measured within $r_{500}$, a significantly smaller radius than $r_{100}$ where we measure virial mass. M09 compare SZE signals to masses estimated from gravitational lensing measurements. The lensing masses are measured within a radius of 350 kpc. For the clusters studied here, this radius is smaller than $r_{2500}$ and much smaller than $r_{100}$. Numerical simulations indicate that the scatter in masses measured within an overdensity $\delta$ decreases as $\delta$ decreases (White 2002), largely because variations in cluster cores are averaged out at larger radii. Thus, the dynamical measurement reaching a larger radius may provide a more robust indication of the relationship between the SZE measurements and cluster mass.

The $Y_{SZ}D_A^2$–$M_{\text{lens}}$ data presented in M09 show a weaker correlation than our optical dynamical properties. A Spearman test rejects the hypothesis of uncorrelated data for the M09 data at only the 94.8% confidence level, compared to the 98.4%–99.8% confidence levels for our optical dynamical properties. One possibility is that $M_{\text{lens}}$ is more strongly affected by substructure in cluster cores and by line-of-sight structures than are the virial masses and velocity dispersions we derive.

Few measurements of SZE at large radii ($> r_{500}$) are currently available. Hopefully, future SZ data will allow a comparison between virial mass and $Y_{SZ}$ within similar apertures.

5. CONCLUSIONS

Our first direct comparison of virial masses, velocity dispersions, and SZE measurements for a sizable cluster sample demonstrates a strong correlation between these observables (98.4%–99.8% confidence). The SZE signal increases with cluster mass. However, the slopes of both the $Y_{SZ}$–$\sigma$ relation ($Y_{SZ} \propto \sigma^{2.94\pm0.07}$) and the $Y_{SZ}$–$M_{100}$ relation ($Y_{SZ} \propto M_{100}^{1.11\pm0.16}$) are significantly shallower (given the formal uncertainties) than...
the slopes predicted by numerical simulations (4.76 and 1.60, respectively).

This result may be partly explained by a bias against less massive clusters that could artificially flatten our measured slopes. Unfortunately, the selection function of our sample is unknown, and we are unable to quantify the size of this effect. More importantly, our sample indicates that the relation between SZE and virial mass estimates (or velocity dispersion) has a non-negligible intrinsic scatter. A complete, representative cluster sample is required to robustly determine the size of this scatter, its origin, and its possible effect on the SZE as a mass proxy.

Curiously, $Y_{SZ}$ is more strongly correlated with both $\sigma_p$ and $M_{100}$ than with $M_{\text{ems}}$ (M09). Comparison of lensing masses and cluster velocity dispersions (and virial masses) for larger, complete, objectively selected samples of clusters may resolve these differences.

The full HeCS sample of 53 clusters will provide a large sample of clusters with robustly measured velocity dispersions and virial masses as a partial foundation for these comparisons.

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