PHYSICAL PROPERTIES OF FOUR SZE-SELECTED GALAXY CLUSTERS IN THE SOUTHERN COSMOLOGY SURVEY

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ABSTRACT

We present the optical and X-ray properties of four clusters recently discovered by the South Pole Telescope (SPT) using the Sunyaev-Zel’dovich effect (SZE). The four clusters are located in one of the common survey areas of the southern sky that is also being targeted by the Atacama Cosmology Telescope (ACT) and imaged by the CTIO Blanco 4-m telescope. Based on publicly available griz optical images and XMM-Newton and ROSAT X-ray observations we analyse the physical properties of these clusters and obtain photometric redshifts, luminosities, richness and mass estimates. Each cluster contains a central elliptical whose luminosity is consistent with SDSS cluster studies. Our mass estimates are very likely massive systems with \( M \gtrsim 5 \times 10^{14} M_\odot \).

Subject headings: cosmic microwave background — cosmology: observations — galaxies: distances and redshifts — galaxies: clusters: general — large-scale structure of universe

1. INTRODUCTION

Galaxy clusters serve as important cosmological probes as their formation and evolution rate depend on cosmological parameters and the kinematics of the dark matter. They are the observational counterparts of dark matter halos and their abundances and masses as a function of redshift are quite sensitive to the growth of structure in the Universe offering a potentially powerful probe of dark energy (Carlstrom et al. 2002). Galaxy clusters also harbor a significant fraction of the visible baryons in the Universe. Hydrogen gas, heated as it falls into the dark-matter potential well of a cluster, forms an intracluster medium too hot to be bound by individual galaxies. The hot intracluster gas leaves an imprint on the Cosmic Microwave Background Radiation (CMBR) through the Sunyaev-Zel’dovich effect (SZE) (Sunyaev & Zel’dovich 1972) in which CMB photons are inverse-Compton scattered by the hot intracluster gas. It is this SZE signal that two new ground-based mm-band telescopes, the Atacama Cosmology Telescope (ACT) (Kosowsky 2006; Fowler et al. 2007) and the South Pole Telescope (SPT) (Ruhl et al. 2004), have been designed to detect through its frequency-dependence: these experiments will measure intensity shifts of the CMB radiation corresponding to a decrement below and an increment above the “null” frequency around 220 GHz. Both telescopes are now actively acquiring data over large areas of the southern sky that will ultimately cover several hundreds to thousands of square degrees.

Recent results from the SPT collaboration (Staniszewski et al. 2008) have yielded the first blind detection of SZE clusters in one of the common southern survey regions centered near right ascension \( 05^h 30^m \) and declination \( -53^\circ \). This area has also been scanned by ACT and has been optically imaged in the optical (griz) with the CTIO Blanco 4-m telescope as part of the Blanco Cosmology Survey (BCS) (Menanteau et al. 2008; Staniszewski et al. 2008). Prompted by these results, here we present a detailed study of the physical properties of these first four SZE-detected clusters based on publicly available optical imaging and archival X-ray data. Throughout this paper we assume a flat cosmology with \( H_0 = 100 h \) km s\(^{-1}\) Mpc\(^{-1}\), \( h = 0.7 \) and matter density \( \Omega_M = 0.3 \).

2. SZE OPTICAL COUNTERPARTS

The positions of the four SZE-selected clusters reported by the SPT team are contained within the region surveyed by the BCS in 2005 and 2006. These observations have been publically available for about a year or more now. We have processed and analyzed them using an independent software pipeline developed by us at Rutgers University. We refer the reader to Menanteau et al. (2008) where we provide a full description of the observing strategy, pipeline and data products and some results on new massive galaxy clusters discovered in the BCS survey field centered near 23hr. Here we use the identical software pipeline to generate data products from which we characterize the optical properties of the four SZE clusters. First, we identify the optical counterparts, which appear as clearly visible overdensities of early-type galaxies near the sky locations of the SZE decrements (see Table 1 from Staniszewski et al. 2008). Roughly centered within each overdensity is a bright elliptical, which we take to be the brightest Cluster Galaxy (BCG). In Figure 1 we show the gri color images of the four systems, centered on the location of the BCG. Each system shows a dominant population of early-type galaxies with very similar colors that can easily be identified by visual inspection. In all cases the offset between the BCG and the SZE decrement, shown as red ellipses and green crosses respectively, is less than \( \sim 30 \) arcsec.

2.1. Photometric Redshift Determination

We determine photometric redshifts from the four-band optical images using BPZ (Benitez 2000) following the same procedure as in Menanteau et al. (2008). To avoid contamination by non-cluster members we use the BCG to estimate the photometric redshift of each
system. The BCG is, by definition, indisputably part of the cluster, resides in a quasi-central location and always provides the strongest signal and the best colors since such galaxies are generally several times brighter than $L_\star$ at any given redshift. Moreover, the luminosities and particularly the colors of BCGs are well constrained as they are very bright elliptical galaxies dominated by old metal-rich stellar populations for which multi-color spectral energy distribution (SED) fitting techniques are well suited yielding precise and reliable results. In the bottom panel of Figure 2, we show the output BPZ photometric redshift probability density function (pdf) for each BCG. The differences between the BPZ Bayesian and Maximum Likelihood (ML) predicted redshifts are small ($\delta z \approx 0.01$) in all cases and therefore we will employ ML photometric redshifts hereafter as the addition of a prior is not justified when, as is the case here, the BCG SEDs are fitted unambiguously. We note that occasionally BCGs host radio-loud active galactic nuclei (Best et al. 2007). Although we have no indication of this, if any of our BCGs do harbor AGN then we would expect some blueness of the colors causing our photo-z’s to be slightly over-estimated.

Only one of the clusters, SPT-CL 0517−5430, has been previously reported; it is the optically-rich cluster Abell S0520 (Abell et al. 1989) which is also the X-ray cluster RXC J0516.6−5430 (Bohringer et al. 2004). Its published spectroscopic redshift of $z = 0.294$ (Guzzo et al. 1999) is in excellent agreement with our photometric redshift for that BCG, $z = 0.27 \pm 0.02$, but somewhat different from the value of $z = 0.35$ quoted by Staniszewski et al. (2008) for the cluster which came from the peak of their photo-z distribution of red-sequence galaxies using the same BCS imaging. In Table 1, we present the clusters’ optical positions based on the BCG locations and photometric redshifts with 1-$\sigma$ uncertainties.

2.2. BCG luminosities

The range in brightness of BCGs has been observationally established from galaxy clusters in the SDSS up to redshifts of 0.36 (see, for example, Loh & Strauss 2006; Koester et al. 2007). This can be used to determine whether the BCGs we identify in the SZE clusters have luminosities consistent with SDSS BCGs. In Figure 2 (2nd panel from top) we show the total $r$-band observed magnitude of each cluster’s BCG as a function of
This as strong evidence in support of them being bona
model curve (i.e., are intrinsically brighter) and we take
in all cases the BCGs in the SZE clusters are below the
et al. 2008; Mei et al. 2008). We see from the figure that
z
sively evolved since
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whelming evidence that ellipticals in clusters have pas-
redshift. Error bars in the figure represent
±
at the location in the curve for SPT-CL 0517–5430’s spectroscopic
probability distribution function for each BCG and with a cross
r
r
redshift compared to a parametrization of the observed
r-band magnitudes of SDSS BCGs (dashed line) (Fig-
2 in Loh & Strauss 2006). The curve corresponds to the simple prescription
\( M^* - 1.5 \) where \( M^* \) is taken from Blanton et al. (2003) and the model includes passive
evolution with redshift. We have extrapolated the SDSS
BCG luminosity model beyond \( z = 0.36 \) as there is over-
whelming evidence that ellipticals in clusters have pas-
vously evolved since \( z \approx 1 \) Blakeslee et al. 2003, Lidman
et al. 2008, Mei et al. 2008. We see from the figure that
in all cases the BCGs in the SZE clusters are below the
model curve (i.e., are intrinsically brighter) and we take
this as strong evidence in support of them being bona

fid BCGs. It is worth noting that SPT-CL 0509–5342
at \( z = 0.36 \) is the least luminous of the four, just slightly
brighter than the luminosity predicted by the model. As
we will see in the next section this cluster also has a
lower mass and X-ray luminosity compared to the other
systems. In Figure 2 we also show the range of absolute
magnitudes of the BCGs as a function of redshift. Here
we again see that SPT-CL 0509–5342 is the least lumin-
ous object, \( \approx 1 \) magnitude fainter than the other BCGs
which all have about the same luminosity.

3. CLUSTER MASS ESTIMATIONS

The new SZE experiments aim to deliver mass-selected
samples of galaxy clusters out to large redshifts which can
be used to probe the growth of structure in the Universe
and to study cluster physics. Current N-body plus hy-
drodynamics simulations (Motl et al. 2005, Nagai 2006
Sehgal et al. 2007) predict robust scaling relations be-
tween the SZE signal (i.e., the \( y \)-distortion due to inverse
Compton scattering) and cluster mass. However, a funda-
mental step before using SZE clusters as cosmological
probes is to observationally establish the relationship be-
tween \( y \) and mass using mass estimates independent of
the SZE measurements. SZE-selected clusters will almost
surely be the focus of intense efforts to obtain mass esti-
mates using X-ray images and spectra, weak and strong
lensing and velocity dispersions. In the following, we
present the first independent mass estimates for these
new SZE-selected clusters from archival optical and X-
ray data.

3.1. Optical Cluster Masses

Here we use optically observed parameters of galaxies
to predict the cluster mass from weak lensing richness-
mass scaling relations established from the SDSS (John-
ston et al. 2007, Reyes et al. 2008). We apply the state-
of-the-art mass tracer (Reyes et al. 2008) built from the
SDSS maxBCG cluster sample (Koester et al. 2007) of
\( \approx 13,000 \) optically-selected clusters. Here we briefly
describe our procedure and refer the reader to our earlier
study (Menanteau et al. 2008) for complete details. The
quantities, \( N_{200}^\text{gal} \), \( L_{200} \), and \( L_{BCG} \), are the observational
values needed as input to the cluster mass scaling rela-
tion. The cluster richness, \( N_{200}^\text{gal} \), is the number of E/S0
galaxies within \( R_{200} \) with colors and luminosities that
satisfy specific conditions for membership. \( R_{200} \) is the
estimated cluster size defined as the radius where the
class galaxy density is \( 200\rho_\text{crit} \) times the mean space
density of galaxies in the present Universe. Similarly,
\( L_{200} \) is the total rest-frame integrated r-band luminos-
ity of all member galaxies included in \( N_{200}^\text{gal} \) and \( L_{BCG} \)
is the rest-frame r-band luminosity of the BCG. Reyes
et al. (2008) provide power-law functions for both the
luminosity-mass and richness-mass relations (see section
5.2.1 in their paper), although here we only use the rela-
tion based on luminosity, which should be more robust
than that based on richness. In Table 1 we present the
cluster mass estimates and luminosities where \( M(L_{200}) \) is
the mass observational equivalent of \( M_{200}^\text{gal} \). For the two

\( M_{200}^\text{gal} \) is the halo mass enclosed within a radius of spherical
volume within which the mean density is 200 times the critical
density.
higher redshift clusters, SPT-CL 0528−5300 at z = 0.70 and SPT-CL 0547−5345 at z = 0.88 we quote lower-limit estimates as some fraction of low luminosity galaxies fall below our magnitude-limit (i ≃ 22.5). If we make the assumption that the two higher redshift clusters have luminosity functions that are similar to SPT-CL 0517−5430 at z = 0.29, then we estimate that we are missing 15% and 58% of the luminosity for SPT-CL 0528−5300 and SPT-CL 0547−5345 respectively. The mass estimates in Table 1 include these corrections.

3.2. X-ray Properties and Masses

The nearby cluster SPT-CL 0517−5430 has accurate measurements of its X-ray luminosity ($L_{\text{bol}} = 9.2 \pm 1.2 \times 10^{44}$ ergs s$^{-1}$) and temperature ($kT = 7.5 \pm 0.3$ keV) from XMM-Newton observations (Zhang et al. 2006). There is also a hydrostatic mass estimate of $M_{\text{500}} = 6.4 \pm 2.1 \times 10^{14} M_{\odot}$ (note this is at an overdensity of 500 times the critical density). The cluster’s X-ray morphology is strongly elongated: it has an axial ratio of 1.4−1.7 with its major axis aligned ∼14° from north (see Fig. 1).

We utilize the ROSAT All Sky Survey (RASS) to obtain X-ray information on the other three clusters. As noted by Staniszewski et al. (2008), faint RASS sources lie close to the locations of SPT-CL 0509−5342 and SPT-CL 0547−5300. For purposes of determining X-ray fluxes and luminosities we will assume that these RASS sources are indeed the X-ray counterparts to the SZ clusters. Starting with the raw X-ray photon event lists and exposure maps from the MPE ROSAT Archive2 we determined count rates for the band covering PI channels 52 to 201. Extraction regions were optimized to obtain all detected source photons (a radius of 3′ was sufficient) and, for the background estimation, to reduce statistical fluctuations (using an annular region between 5′ and 25′). The X-ray source position was used for the two SZ clusters with apparent counterparts; for SPT-CL 0528−5300, the quoted SZ position was used to derive upper limits.

The background-subtracted count rates (SPT-CL 0509−5342: 0.025 cts/s; SPT-CL 0528−5300: < 0.015 cts/s; SPT-CL 0547−5345: 0.007 cts/s) were converted to fluxes assuming a hard thermal spectrum ($kT \sim 5$ keV) and accounting for each cluster’s Galactic absorbing column density (Dickey & Lockman 1990); values fell in the range $6.1 \times 10^{20}$ atoms cm$^{-2}$ to $7.8 \times 10^{20}$ atoms cm$^{-2}$ for all sources. A k-correction was also applied to convert fluxes to the standard 0.1−2.4 keV ROSAT band in the rest frame of each cluster. These fluxes are plotted in Fig. 2 (2nd panel from bottom). The upper limit for SPT-CL 0528−5300 is at 2σ and the soft 0.1−2.4 keV band flux for SPT-CL 0517−5430 was converted from the bolometric luminosity quoted by Zhang et al. (2006). We denote the region (at the high flux end) that corresponds approximately to the Bright Source Catalog from the RASS. Also shown are curves of the expected X-ray fluxes for clusters with masses of $M_{\text{200}} = 1 \times 10^{15} M_{\odot}$ (solid) and $3 \times 10^{14} M_{\odot}$ (dotted). These curves assume the low redshift luminosity-mass (specifically $L_X(0.1-2.4$ keV) vs. $M_{\text{200}}$) relation from Reiprich & Böhringer (2002) and, for simplicity, no redshift evolution.

4. SUMMARY

We have established that the central ellipticals associated with the four SZE clusters have luminosities consistent with those of BCGs from the SDSS. We have also determined cluster masses using two different mass estimators based on the luminosity of the optical galaxies and the X-ray emitting gas. These mass tracers are reasonably consistent within the uncertainties given by the scatter in the X-ray luminosity-mass relation ($\sim 0.2$ in the log) and the estimated factor of 2 uncertainty in the mass derived from the optical luminosity of the galaxies (Menanteau et al. 2008). Based on this evidence, all four clusters are fairly massive ($M \gtrsim 5 \times 10^{14} M_{\odot}$) and therefore well above the nominal detection limit of both SPT and ACT (e.g., Sehgal et al. 2007). Although this is an important step in identifying the optical and X-ray counterparts to the SZ clusters, it cannot be considered definitive. In addition the RASS count rates could well be contaminated by X-ray emission from an AGN or other unrelated source. Thus the conservative reader could conclude that the X-ray luminosities and derived masses for the three higher redshift SPT sources represent upper limits to their true values. Approved Chandra observations will within the next year resolve any doubts about the X-ray emission of these clusters. Deeper optical imaging and spectroscopy should also be pursued in order to better constrain the masses of these clusters.

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| ID          | R.A.      | DEC.      | $z_{\text{photo}}$ | $\Delta_{\text{gal}}^{200}$ | $[10^{12}L_\odot]$ | $[10^{10}L_\odot]$ | $[10^{15}M_\odot]$ | $[10^{44} \text{ erg s}^{-1}]$ | $[10^{15}M_\odot]$ |
|-------------|-----------|-----------|-------------------|-------------------------------|-------------------|--------------------|-------------------|------------------------|-------------------|
| SPT-CL 0517–5430 | 05:16:37.4 | -54:30:01.5 | 0.27$^{+0.02}_{-0.02}$ | 168.9 ± 15.3 | 6.53 ± 0.15 | 31.20 | 1.7 | 3.5 ± 0.5 | 0.8 |
| SPT-CL 0509–5342 | 05:09:21.4 | -53:42:12.3 | 0.36$^{+0.02}_{-0.02}$ | 76.1 ± 9.2 | 2.24 ± 0.05 | 9.07 | 0.4 | 2.2 ± 0.8 | 0.6 |
| SPT-CL 0528–5300 | 05:28:05.3 | -52:59:52.8 | 0.70$^{+0.03}_{-0.02}$ | 69.3 ± 9.8 | 8.62 ± 1.20 | 23.00 | ≥ 2.1 | < 5.5 | < 1.1 |
| SPT-CL 0547–5345 | 05:46:37.7 | -53:45:31.1 | 0.88$^{+0.08}_{-0.04}$ | 12.7 ± 3.7 | 1.99 ± 0.25 | 17.90 | ≥ 0.4 | 4.7 ± 2.3 | 1.0 |

**Note.** — Physical properties of SZE selected clusters in the SCS regions. Redshifts represent the photometric redshift from the bright elliptical in the center of the cluster with ±1σ limits. The cluster position is based on the BCG.

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