Tracing Cosmic Evolution with Galaxy Clusters
ASP Conference Series, Vol. 268, 2002
S. Borgani, M. Mezzetti, and R. Valdarnini, eds.

Masses of High-Redshift Clusters via SZ Effect Observations

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Abstract. We present Sunyaev-Zel'dovich Effect (SZE) observations of distant, highly X-ray luminous clusters of galaxies. We use the SZE data to constrain their total masses, independent of X-ray observations. To do this, we assume the clusters have the same gas mass fraction as that derived from SZE measurements of a sample of known massive clusters,

and then infer each cluster's mass from its SZE data. In the systems with published X-ray temperatures, we find good agreement between our SZE-derived temperatures and those inferred from X-ray spectroscopy; in the system without X-ray derived temperatures, the SZE data provide the first confirmation that it is indeed a massive system.

The abundance of clusters at high redshift is critically sensitive to the values of the cosmological parameters and so the demonstrated ability to determine cluster temperatures and masses from SZE observations independent of X-ray data illustrates the power of using deep SZE surveys to probe the distant universe.

1. Introduction

The existence of galaxy clusters at high redshift can place powerful constraints on the physical and cosmological parameters of structure formation models (Bahcall & Cen 1992; Luppino & Gioia 1995; Oukbir & Blanchard 1997; Donahue et al. 1998; Eke et al. 1998; Haiman, Mohr, & Holder 2001). The greatest leverage is provided by the most massive and distant clusters (e.g., Holder, Haiman & Mohr 2001); in fact to constrain Ω_Λ, one must use clusters with redshifts greater than 0.5. Ongoing and planned surveys will generate large numbers of massive cluster candidate objects. As the science proceeds into the realm of surveys, one outstanding technical problem will be how to best determine the masses of the high-redshfit candidate objects.

Most methods for cluster mass measurement become resource-intensive at large distances. For example, a cluster's mass can be estimated from a measurement of the temperature of its intracluster medium (ICM), which relates to its mass through an observationally-determined (c.f. Finoguenov, Reiprich, & Böhringer 2001; Horner, Mushotzky, & Scharf 1999) and theoretically-supported (c.f. Evrard, Metzler, & Navarro 1996) mass-temperature relation. To give a fiducial point, the X-ray spectrum from a 120 kilosecond observation of a massive ($kT_e \sim 7.5$ keV), distant (redshift z =0.783) cluster with the *Chandra* ACIS instrument yields a measurement of the ICM temperature to about 10% accuracy at 90% confidence. A temperature measurement of similar accuracy is expected to require an observation 5-10 times shorter with the *XMM* facility.

Weak gravitational lensing observations also permit a measurement of a cluster's total mass. (Mass densities which generate strong lensing events are confined to the cores of galaxy clusters; we require measurements of the cluster masses within radii as near as possible to the virial radius.) Deep imaging over large angular scales is required for weak lensing mass estimates, and the imaging efficiency decreases with cluster distance, as the surface brightness of the lensed galaxies decreases as well as the number of galaxies available to be lensed.

Here, we present a method for determining the mass of a galaxy cluster via a measurement of the cluster's Sunyaev-Zel'dovich Effect (SZE). This technique was originally presented in Joy et al. (2001). It is particularly valuable for distant clusters, as the surface brightness of the SZE is independent of distance. It is also independent of the X-ray spectral and gravitational lensing mass measurements;

together, these three mass determinations can provide checks on the acccuracy of and systematic uncertainties in each method.

The Sunyaev-Zeldovich Effect provides a measure of the ICM pressure integrated along the line of sight (Sunyaev & Zeldovich 1972; Birkinshaw 1999). The SZE is manifested as a change in the observed brightness temperature of the Cosmic Microwave Background (CMB) radiation that results from passage through the cluster's thermally ionized gas:

$$\frac{\Delta T_{thermal}}{T_{CMB}} = f(\nu, T_e)\frac{k_B \sigma_T}{m_e c^2}\int n_e T_e dl, \tag{1}$$

where T_{CMB} is the microwave background temperature; σ_T is the Thomson scattering cross section; and m_e, n_e, and T_e are the electron mass, density, and temperature. The frequency dependence of the SZE is contained in the factor $f(\nu, T_e)$, and includes relativistic effects; in the Rayleigh-Jeans regime of the CMB spectrum, $f(\nu) \sim -2$.

The integrated SZE flux is proportional to the gas mass in the cluster, weighted by the gas temperature:

$$\int d\Omega \Delta T \sim M_{gas}\langle T_e\rangle D_A^{-2}, \tag{2}$$

where D_A is the angular diameter distance to the cluster. The total gravitational mass of the cluster can be determined from $n_e(r)$, which is constrained by spatially-resolved SZE measurements, and the electron temperature. Therefore the gas mass fraction, f_{gas}, of the observed cluster can be determined directly from the measured SZE and the cluster's temperature. Under the assumption that the cluster gas mass fraction approaches a universal value, we can turn this relation around and instead estimate the cluster's ICM temperature (and thence the mass) as that which reproduces the universal f_{gas}.

We use this method to measure the masses of two distant clusters recently discovered in X-ray surveys, and a cluster at similar redshift of known ICM temperature and mass, to provide a test of the method.

2. Method

The gas mass fraction is calculated from an SZE observation as a function of the cluster's ICM temperature. If we parametrize the electron density distribution as an isothermal beta-model (Cavaliere & Fusco-Femiano 1976, 1981) with a core radius r_c

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

the spatial distribution of the gas density can be recovered from the projected SZE effect:

$$\Delta T(\theta) = \Delta T(0)\left(1 + \frac{\theta^2}{\theta_c^2}\right)^{\frac{1}{2}-\frac{3\beta}{2}}, \tag{4}$$

where $\theta = r/D_A$, $\theta_c = r_c/d_A$, and $\Delta T(0)$ is proportional to $n_{e0} \times T_e$. The central electron density can therefore be recovered from this relation:

$$n_{eo} = \frac{-\Delta T(0)}{T_{CMB}} \frac{m_e c^2}{2k\sigma_T} \frac{1}{T_e} \left(D_A \int_{-\infty}^{+\infty} \left(1 + \left(\frac{\theta}{\theta_c} \right)^2 \right)^{-3\beta/2} d\theta \right)^{-1} \tag{5}$$

where the integral, *dl*, is along the line of sight. The gas mass is simply the electron number density integrated through the cluster volume, multiplied by the mean atomic weight of the ionized species:

$$M_{gas} = \mu m_p \int n_e(r) dV. \tag{6}$$

If the ICM is in hydrostatic equilibrium in the cluster potential, the cluster's total mass can be determined from the gas density distribution:

$$M_{tot}(< r) = -\frac{k_B T_e r}{\mu m_p G} \left(\frac{d\ln n_e(r)}{d\ln r} \right). \tag{7}$$

To calculate μ, we assume the gas has solar metallicity as measured by Anders & Grevesse (1989). We also assume that μ is constant throughout the ICM. Therefore, the gas mass fraction as measured from a cluster is inversely proportional to the square of the gas temperature:

$$f_{gas} = \frac{M_{gas}}{M_{total}} \propto T_e^{-2} \tag{8}$$

We use the results from Grego et al. (2000) as the universal f_{gas}. This gas mass fraction was derived from SZE measurements and the published X-ray temperatures of 18 massive clusters, using the relations above. The clusters have kT_e >~5 keV, and range in redshift from $0.14 \leq z \leq 0.83$. The SZE data are interferometric, made at centimeter wavelengths (26-36 GHz) at the Owens Valley Radio Observatory (OVRO) and Berkeley-Illinois-Maryland Association (BIMA) millimeter-wave observatories. The mean f_g within r_{500} for these 18 clusters, is $0.081^{+0.009}_{-0.011} h^{-1}_{100}$ (statistical uncertainty at 68% confidence level, assuming Ω_M=0.3, Ω_Λ=0.7).

We use this mean value as the universal f_{gas}. We estimate the ICM temperature from new SZE observations of two distant and highly X-ray luminous clusters, recently discovered in deep ROSAT X-ray images. Cl J1226.9+3332, a cluster at redshift $z = 0.89$, was discovered in the WARPS survey (Ebeling et al. 2001; Scharf et al. 1997). Cl J0152.7−1357, at redshift $z = 0.83$, was detected in the RDCS, SHARC, and WARPS surveys (Della Ceca et al. 2000; Romer et al. 2000; Ebeling et al. 2000). Based on their X-ray luminosities ($L_X[0.5 - 2\mathrm{keV}] \gtrsim 2 \times 10^{44} \mathrm{h}_{100}^{-2}$ erg s^{-1}), these clusters are thought to be highly massive.

To provide a standard with which to compare our results on these clusters, we also determine the temperature of a well-studied cluster at a similar redshift ($z = 0.83$) and luminosity: MS 1054.4−0321, the most distant cluster discovered in the EMSS survey (Gioia & Luppino 1994; Donahue et al. 1998; Hoekstra et

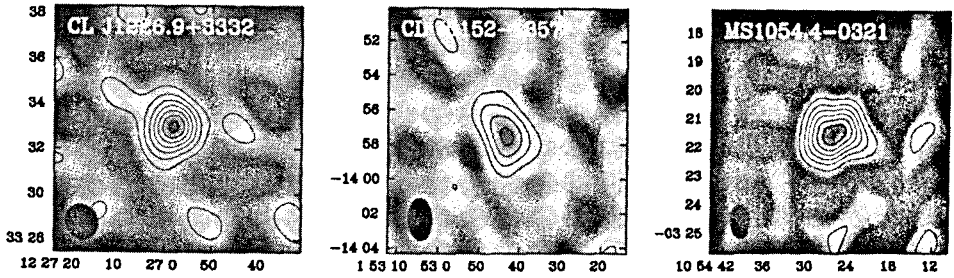

Figure 1. Synthesized images of the SZE decrement in Cl J1226.9+3332, Cl J0152.7−1357, and MS 1054.4−0321. Left panel: Synthesized image of Cl J1226.9+3332, obtained by applying a Gaussian taper with a half-power radius of 1 kλ to the interferometer $(u-v)$ data, yielding a resolution of 99.3″ × 87.4″ at position angle (p.a.) 32°. Contours are multiples of 290 μJ (1.5σ), and the rms is 190 μJ. Center panel: Synthesized image of Cl J0152.7−1357, obtained by applying a Gaussian taper with a half-power radius of 1 kλ to the $u-v$ data, yielding a resolution of 151″ × 87″.9 at p.a. 4°. Contours are multiples of 480 μJ (1.5σ), and the rms is 320 μJ. Right panel: Synthesized image of MS 1054.4−0321, obtained by applying a Gaussian taper with a half-power radius of 2 kλ to the $u-v$ data, yielding a resolution of 73″.1 × 45″.5 at p.a. 2°. Contours are multiples of 120 μJ (1.5σ), and the rms is 80 μJ.

al. 2000). The temperature of MS 1054.4−0321 was estimated by Donahue et al. from *ASCA* data to be $12.3^{+3.1}_{-2.2}$ keV.

The SZE images of these three clusters are shown in Figure 1. The derived temperatures and the total mass within 65″ for each cluster (via Equation 5) are reported in Table 1. The range in temperature and mass reflect the values which give a gas mass fraction within the sample mean of the Grego et al. (2000) f_{gas} value. We make a number of assumptions in these calculations: that the ICM is isothermal; is spherically symmetric; and that the gas is in hydrostatic equilibrium, supported only by thermal pressure. However, the gas mass fractions for Cl J1226.9+3332 and Cl J0152.7−1357 are calculated in exactly the same way as those used to determine the universal f_{gas}. We have used the universal value of f_{gas} in a comparative rather than an absolute way, and

Table 1. Cluster Properties derived from SZE measurements

Cluster Name	T_e^{Xray} (keV)	T_e^{SZ} (keV)	$M_{total}[<65'']$ $(10^{14}h^{-1}\mathrm{M}_\odot)$
Cl J1226.9+3332	–	$9.8^{+4.7}_{-1.9}$	2.7 ± 0.5
Cl J0152.7−1357	$6.5^{+1.7}_{-1.2}$	$8.7^{+4.1}_{-1.8}$	2.1 ± 0.7
MS 1054.4−0321	$12.3^{+3.1}_{-2.2}$	$10.4^{+5.0}_{-2.0}$	2.3 ± 0.3

Recent work confirms the accuracy of the SZE mass measurement method. Jeltema et al. (2001) analyzed a 91 ks *Chandra* ACIS-S observation of MS 1054.4 −0321 and find the emission-weighted temperature to be $10.4^{+1.7}_{-1.5}$ keV at 90% confidence, lower than but consistent with the temperature of $12.3^{+3.1}_{-2.2}$ keV inferred from ASCA data in Donahue et al. (1998). We also compare the total mass calculated for this cluster via the SZE method with the mass determined by weak lensing. Hoekstra et al. (2000) infer a total mass of $5.4 \pm 0.6 \times 10^{14} h_{100}^{-1}$ $M_{\odot}$ within a 94 ″ aperture. The SZE data imply a value of $M_{total}^{SZE}(< 94'') = 4.6 \pm 0.8 \times 10^{14} h_{100}^{-1}$ $M_{\odot}$, consistent with the lensing measurements. Thus we conclude that estimating cluster masses from SZE data and a measurement of the cluster redshift is a viable means of determining cluster temperatures and masses without X-ray or lensing data.

3. SZE Survey

A number of SZE-sensitive sky surveys are planned for the near future, with various depths and covered areas. The sensitivity of a SZE survey can be expressed as a redshift independent mass limit (Bartlett & Silk 1994; Barbosa et al. 1996; Holder et al. 2000). This follows from Equation 2 and the assumption of a universal f_{gas}.

SZE surveys can be grouped into two types of surveys: those which cover large areas to relatively shallow depths, similar to what can be expected with the Planck Surveyor Satellite; or smaller, relatively deep surveys, such as those expected with upcoming ground-based efforts. The left panel of Figure 2, from Carlstrom et al. (2000), shows the approximate expected limiting mass for the two types of surveys. The instrumental sensitivity used to represent the Planck-like survey is a limit on the integrated flux density of 15 mJy at 30 GHz. For the deep ground-based surveys, the flux density limit is 0.5 mJy. The SZE survey mass limits are also compared to an approximate mass limit for an XMM serendipitous survey, assuming a simple X-ray flux limit. A deep SZE survey will be able to probe somewhat lower masses at redshifts past $z \sim 1$, which promises to be a very interesting regime.

The right panels of Figure 2 show the expected cluster counts per square degree for a ΛCDM model ($\Omega_M = 0.3, \Omega_\Lambda = 0.7, h = 0.65, \sigma_8 = 1$). A deep SZE survey can expect to find roughly one cluster per square degree with $z > 1.5$. On the other hand, even though a shallow survey has a relatively high mass limit, a survey that covers half the sky would find ~10000 clusters.

The SZA (Sunyaev-Zel'dovich Effect Array), a project in development, will add eight 3.5 m telescopes to the existing array of six 10.4 meter telescopes comprising the OVRO Millimeter Array. The full array will have two receivers, to operate in the centimeter wavelength (26-36 GHz) and millimeter wavelength (75-115 GHz) regimes. The SZA will use a wideband digital correlator, which can correlate 8 GHz bandwith with about 20 MHz resolution. The 3.5 meter telescopes are specified to be built with rms surface accuracy of 30 μm, so that the array has the capability to operate at higher frequencies at an improved site. The SZA survey is expected to have sensitivity similiar to the curves labeled "0.5 mJy" in Figure 2.

Such a survey will be able to probe the universe to high redshift and clusters of a cosmologically interesting range of masses. As the cluster masses can be determined from the SZE data itself, the SZA survey can provide constraints on cosmological parameters independent of other determinations.

Acknowledgments. We thank Cheryl Alexander, Rick Forster, Steve Padin, Dick Plambeck, Steve Scott, David Woody, and the staff of the BIMA and OVRO observatories for their support, and Laurence Jones, Eric Perlman, and Caleb Scharf for providing data on Cl J1226.9+3332 prior to publication. ER gratefully acknowledges support from NASA GSRP Fellowship NGT5-50173. This work is supported by NASA LTSA grants NAG5-7986 (JC,MJ,WH) and NAG5-8253 (HE). Radio astronomy at the BIMA millimeter array is supported by NSF grant AST 96-13998. The OVRO millimeter array is supported by NSF grant AST96-13717. The funds for the additional hardware for the SZE experiment were from a NASA CDDF grant, a NSF-YI Award, and the David and Lucile Packard Foundation.

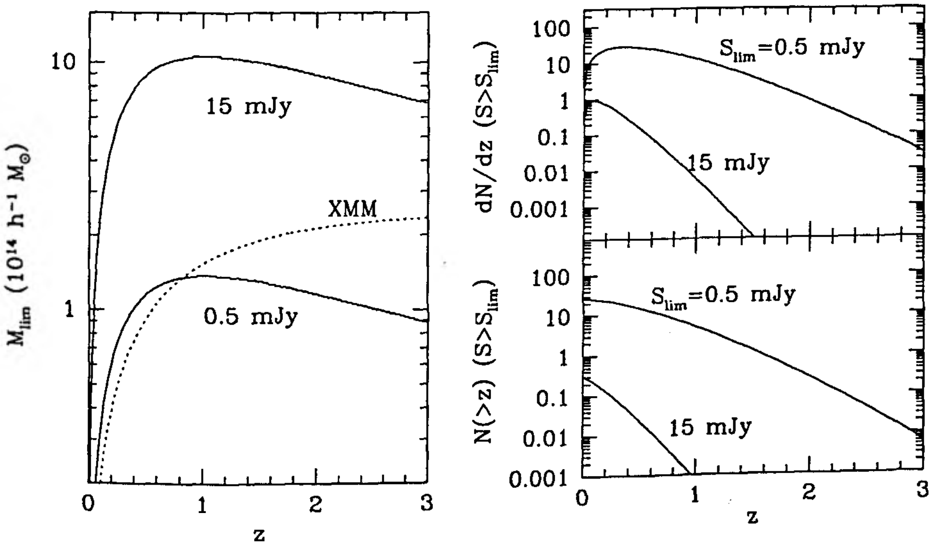

Figure 2. Illustration of the projected yield of SZE cluster surveys. Left: Mass limits as a function of redshift for a typical wide-field type of survey (sensitivity limit of ~ 15 mJy at 30 GHz) and for a typical deep survey (~ 0.5 mJy). The approximate XMM serendipitous survey limit is also shown. Right: Differential (top) and cumulative (bottom) counts per square degree as a function of redshift for the two SZE surveys shown at left, assuming a ΛCDM cosmology (Holder et al. 2000).

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