X-RAY AND SUNYAEV-ZELDOVICH EFFECT SCALING RELATIONS FROM A COMPLETE SAMPLE OF CLUSTERS AT $0.15 < z < 0.30$

1. Cluster masses and cosmology

One of cosmology's primary goals is the measurement of the mass distribution of galaxy clusters, the universe's largest gravitationally bound structures. The distribution of cluster masses with redshift provides a strong test for measuring the amount of matter (Ω_M), dark energy and its equation of state (Ω_Λ, ω), and level of primordial density fluctuations (σ_M or σ_8) in the universe. The number of clusters $d\mathcal{N}$ in the mass range $M, M+dM$ is related to the cosmological parameters via an equation of the form

$$\frac{d\mathcal{N}}{dz} = f(\sigma_{M,z}) \tag{1}$$

(see Carlstrom et al. 2002), where f is a function of $\sigma_{M,z}$, which is defined as the initial variance of the density field σ_M times the cosmology-dependent linear growth function $D(z)$, $\sigma_{M,z} = \sigma_M \cdot D(z)$. In order to use Eq. (1) for a precision measurement of the cosmological parameters, thousands of clusters at all redshifts are required (See Fig. 1, from Holder et al. 2001). Such a large number of clusters is expected to be detected using the SZE surveys that are now coming on-line, e.g., the South Pole Telescope (SPT), APEX, ACT and the Sunyaev-Zeldovich Array (SZA).

2. Measurement of cluster masses and the mass–SZE flux scaling relation

Cluster masses can be inferred from both X-ray (e.g., Vikhlinin et al 2006; Maughan et al. 2006) or SZE measurements [1] (Muchovej et al. 2007). X-ray data have the advantage of providing precise constraints on the gas density and temperature distribution, which result in the direct measurement of M_{gas}, and in the measurement of M_{tot} using the assumption of hydrostatic equilibrium between the gas and the dark matter,

$$M_{tot}(r) = -3.7\times10^{13} M_\odot T(r) r \left(\frac{dlog\rho_g}{dlog\ r} + \frac{dlogT}{dlog\ r}\right) \tag{2}$$

where T is in units of keV and r is in units of Mpc. X-ray measurements, however, are hampered at high redshift by the $(1+z)^{-4}$ cosmological dimming. The unique advantage of the SZE is that of being virtually independent of redshift (e.g., Carlstrom et al. 2002). The integrated SZE flux Y is defined as

$$\begin{aligned} Y &\equiv \int y d\Omega = D_A^2 \int y dA \\ \Rightarrow Y(r) \cdot D_A^2 &= 2\pi \int_0^r y(r') r' dr' \end{aligned} \tag{3}$$

in which the Compton-y parameter is defined as

$$y(r) = \frac{\sigma_T k_B}{m_e c^2} \int_0^\infty n_e(r') T_e(r') dl \tag{4}$$

and the integration is along the line of sight l.

An issue with SZE-only surveys is that the direct observable is the SZE flux Y, and *not* the cluster mass. An accurate mass reconstruction from the SZE data can be achieved using matching X-ray data which provide the necessary resolution to determine the detailed density and temperature structure. Such a joint X-ray/SZE analysis method has been performed by our group (La Roque et al. 2006) for a large sample of clusters with both X-ray Chandra data and SZE data from OVRO and BIMA. In order to measure the mass of clusters detected with SZE surveys, two avenues are therefore open: (1) obtaining X-ray data for all SZE-detected clusters or (2) establishing a calibration between SZE flux and cluster masses for a well-defined sample of clusters, and then using this relationship to infer masses from the observed SZE flux.

[1] Cluster redshifts are obtained from complementary optical and infrared photometry.

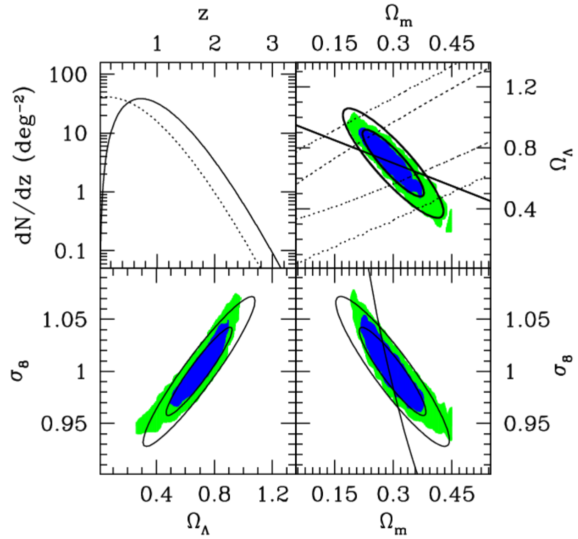

Fig. 1.— Expected cosmological constraints from the SPT survey (Holder et al. 2001).

With this proposal, we plan to carry out the joint analysis of Chandra and SZE data from the Sunyaev-Zeldovich Array (SZA) for a complete sample of 35 clusters, in order to establish the scaling relation between SZE flux and cluster masses. This mass-SZE flux relationship will be essential in interpreting the upcoming large-scale surveys of clusters with SPT and other SZE-only survey instruments, which will generally not have matching X-ray data.

3. Current knowledge of the mass–SZE flux scaling relation

The BIMA and OVRO interferometers have provided high resolution images of the SZE in clusters (e.g., Carlstrom et al. 2002). Using Chandra, OVRO and BIMA data for a sample of 38 clusters we measured the Hubble constant (Bonamente et al. 2006) [2], the gas fraction in clusters (La Roque et al. 2006), and have made a preliminary measurement of the relationship between the SZE flux and cluster mass (Bonamente et al. 2007, in preparation). The self-similar model of cluster formation and evolution (Kaiser 1986) predicts the following relationship between the SZE flux Y and mass (gas and total):

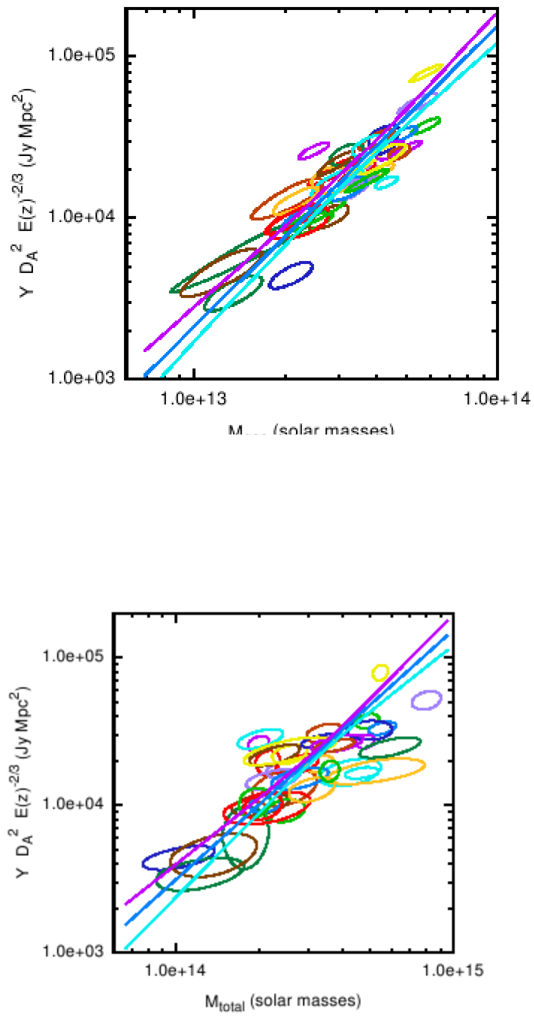

Fig. 2.— Best-fit scaling relation from Chandra-OVRO/BIMA ($M_{gas} - Y$ index $1.85\pm^{0.19}_{0.22}$. $M_{tot} - Y$ index: $1.69\pm^{0.23}_{0.21}$); ellipses are 68% confidence on 2 parameters.

$$YD_A^2 \propto M^{5/3}E(z)^{2/3} \tag{5}$$

where $E(z) = \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2}$. Our analysis indicates that the 38 clusters do in fact follow this relationship (Figure 2). Simulations also show that the X-ray equivalent of Y, $Y_x \equiv M_{gas} \cdot kT$ (Kravtsov et al. 2006) is indeed an excellent, low-scatter mass proxy, if measured near the virial radius.

[2]This work was supported by a Chandra cycle 7 Archival Grant.

The analysis based on the OVRO/BIMA clusters, however, has severe limitations:
(1) The sample had no uniform selection criteria, and no completeness can be claimed;
(2) The OVRO/BIMA sensitivity reaches approximately r_{2500}, a factor of several times short of the cluster's virial radius;
(3) A simple isothermal β model was used in the derivation of the scaling relation of Figure 2, and no attempt was made to account for temperature variations. The scatter in Fig. 2 may largely be due to the limitations in our current models, and in the inability to perform measurements at larger radii.
With this proposal, we plan to overcome these limitations, and obtain an accurate $Y-M$ scaling relation.

4. Analysis of a complete X-ray/SZE sample of galaxy clusters at $0.15 < z < 0.30$

The clusters we plan to analyze (Table 1) are the 35 brightest clusters detected by the ROSAT All-Sky survey for $0.15 < z < 0.3$. This is therefore a flux-selected, volume-limited sample with ∼90% completeness (Ebeling et al. 1998). The statistical completeness ensures that (i) the sample is representative, (ii) we can account for the selection bias by using the known selection function and (iii) we can investigate the intrinsic scatter in the scaling relations. Selecting a high-luminosity sample is the obvious first step in order to achieve the highest possible S/N, and we anticipate a future study of lower luminosity clusters to extend the determination of the scaling relations at lower masses. All clusters have Sunyaev-Zeldovich Array data that is already available or that will become available within the next few months. The SZA features small diameter dishes, which are sensitive to larger scales than OVRO/BIMA (∼ 12'; Muchovej et al. 2007), and an order of magnitude more bandwidth in its digital correlator for better coverage of the $u-v$ space, resulting in an improvement by a factor of several over OVRO/BIMA for the detection of the diffuse SZE from clusters. We propose to:
<u>(1) Reduce all Chandra X-ray data</u>, following the procedure of Bonamente et al. (2006) and La Roque et al. (2006), and derive X-ray surface brightness and projected temperature profiles.
<u>(2) Perform a joint analysis</u> of the SZE and X-ray data using our Monte Carlo Markov Chain (MCMC) analysis. For this purpose, we will extend our analysis to a non-isothermal model of the cluster gas. We propose to utilize the models of Vikhlinin et al. (2006), which reproduce accurately the X-ray surface brightness and temperature profiles of a large number of nearby clusters. This model is based on the following radial distribution of the density and temperature:

$$n^2(r) = n_{e0}^2 \left(1 + \frac{r^2}{r_c^2}\right)^{-3\beta+\alpha/2} \cdot \frac{(r/r_c)^{-\alpha}}{(1+(r/r_s)^{\gamma})^{\epsilon/\gamma}} + n_{e1}^2 \left(1+(r/r_c)^2\right)^{-3\beta_2}, \tag{6}$$

$$T(r) = T_0 \frac{(x + T_{min}/T_0)}{x+1} \cdot \frac{(r/r_t)^{-a}}{(1+(r/r_t)^b)^{c/b}} \tag{7}$$

in which $x = (r/r_{cool})^{a_{cool}}$. The ability of these models to follow a steepening with radius of the surface brigthness profiles is essential in deriving accurate masses (Vikhlinin et al. 2006). These models are projected along the line of sight to obtain the predicted X-ray surface brightness, temperature profile and SZE flux. Parameter estimation is performed using our MCMC software, which compares the observed and predicted quantities using Poisson statistics for the X-ray images and Gaussian statistics for the temperature profiles and the SZE data, the latter directly in Fourier space (Bonamente et al. 2006).
<u>(3) Establish mass-SZE flux scaling relations.</u>
With the SZE flux and masses available from our analysis, we can then proceed to the determination of the scaling relations and the assessment of their scatter. We also plan to use the Chandra information on cluster morphology to test the sensitivity of the scaling relations to the presence of mergers.

5. Summary of scientific goals

The project aims to establish that the SZE flux Y is a reliable proxy of the cluster masses. Our preliminary work based on lower-quality SZE data is encouraging, but confirmation is needed using a statistically well-defined sample, and using more accurate models that take into account the non-isothermality of the gas, now well established observationally (e.g. Vikhlinin et al. 2006). The success of this effort to establish a scaling relation between SZE fluxes and masses is critical to the success of using upcoming SZE-only surveys for cosmological purposes, e.g., the South Pole Telescope survey. It is virtually impossible that the thousands of clusters that the SPT or other SZE survey instruments will detect can be followed up individually with Chandra or other X-ray telescopes. The tool of an observationally-tested M-Y scaling relation will therefore be very valuable for cosmology at large.

Budget request and justification

We request a total of $50k for this one-year project: $16k for 1/2 year of support for a graduate student involved in the project at the University of Alabama in Huntsville, $26k for summer salary for the PI, and $8k for co-I M. Joy.

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Table 1. Chandra/SZA cluster sample

Cluster name	Redshift z	Chandra[a] (ks)	SZA[b]
A2204	0.15	20	S
RX J1720.1+2638	0.16	63	S
A586	0.17	10	O
A1914	0.17	30	O
A665	0.18	40	O
A115	0.20	50	S
A520	0.20	81	O
A963	0.21	40	O
A1423	0.21	10	S
A773	0.22	40	O
A2261	0.22	35	O
A267	0.23	30	O
A1682	0.23	10	S
A1763	0.23	20	S
A2111	0.23	10	O
A2219	0.23	40	O
A2390	0.23	120	O
Zw 5247	0.23	10	S
RX J2129.6+0005	0.23	10	S
RX J0439.0+0715	0.24	29	S
Zw 2089	0.24	10*	O
A1835	0.25	230	O
A68	0.26	10	O
MS1455+22	0.26	105	O
Zw 5768	0.27	10*	S
A697	0.28	30	O
A1758N	0.28	60	S
A2631	0.28	10	S
A611	0.29	40	O
RX J0437.1+0043	0.29	12*	S
Zw 3146	0.29	50	O
Zw 7215	0.29	14*	S
A781	0.30	10	O
A1576	0.30	15*	S
A2552	0.30	14	S

[a]– *: Chandra observation to become public in 2007 (all other observations already public).

[b]– O: Observed; S: scheduled for 2007.

Previous Chandra Programs

Dr. Bonamente was PI of one awarded cycle 7 Archival proposal, *Direct measurement of the Hubble flow at z=0.15-0.9 with X-ray and Sunyaev Zel'dovich Effect data of galaxy clusters*, This proposal was awarded for the study of the Hubble constant using Chandra and OVRO/BIMA data for a sample of 38 clusters.

(1) Publications based on the cycle 7 proposal:

1. Bonamente, Massimiliano; Joy, Marshall K.; LaRoque, Samuel J.; Carlstrom, John E.; Reese, Erik D.; Dawson, Kyle S., *Determination of the Cosmic Distance Scale from Sunyaev-Zel'dovich Effect and Chandra X-Ray Measurements of High-Redshift Galaxy Clusters*, ApJ 647, 25 (2006)
2. LaRoque, Samuel J.; Bonamente, Massimiliano; Carlstrom, John E.; Joy, Marshall K.; Nagai, Daisuke; Reese, Erik D.; Dawson, Kyle S. *X-Ray and Sunyaev-Zel'dovich Effect Measurements of the Gas Mass Fraction in Galaxy Clusters*, ApJ 652, 917 (2006)

(2) The results of the work performed as part of the cycle 7 proposal were featured in the NASA press release: *Chandra Independently Determines Hubble Constant*, CXC RELEASE 06-04, http://chandra.harvard.edu/press/06_releases/press_080806.html.

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Selected recent publications of PI M. Bonamente:

1. S. LaRoque, M. Bonamente, J. Carlstrom, M. Joy, D. Nagai, E. Reese, K. Dawson 2006, 'X-Ray and Sunyaev-Zel'dovich Effect Measurements of the Gas Mass Fraction in Galaxy Clusters', ApJ 652, 917
2. K. Coble, J. Carlstrom, M. Bonamente, K. Dawson, W. Holzapfel, M. Joy, S. LaRoque, E. Reese 2007, 'Radio Point Sources Toward Galaxy Clusters at 30 GHz', ApJ in press, astro-ph/0608274
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12. Bonamente, M., Lieu, R. and Mittaz, J. 2001, 'The Multiphase Nature of the Intracluster Medium of Some Clusters of Galaxies', ApJ, 546, 805