An Improved Model for fitting SZE + X-ray observations of Galaxy Clusters

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Abstract

We demonstrate the utility of a new model, recently shown to be a robust, self-similar pressure profile, for fitting current and future generations of Sunyaev-Zel'dovich effect (SZE) observations of galaxy clusters. Modern SZE imaging instruments such as the Sunyaev-Zel'dovich Array (SZA) are sensitive to arcminute scales ($\sim 1-6'$), meaning they are capable of probing out to r_{500} for most clusters above redshift $z \gtrsim 0.2$. The need for a model that can describe a cluster's pressure profile at all observable radii has become crucial to the study of the SZE from clusters. Therefore, a new pressure profile motivated by simulations and detailed X-ray observations has been developed and tested on simulated and real observations. We find that we are able to constrain this model with current SZ data, without relying on X-ray determined density model shape parameters. We find this model provides an unbiased recovery of SZE flux from simulations, and, when combined with X-ray imaging to constrain the density, it yields an electron temperature profile that agrees with X-ray spectroscopic temperatures, without relying on any X-ray spectroscopic information. In addition to yielding more accurate relationships between cluster observables and physical cluster properties, this model could prove to be a useful tool in helping to constrain the temperatures of high redshift clusters.

I. Background

The Sunyaev-Zel'dovich Effect (SZE)

- The SZE is the inverse Compton scattering of cosmic microwave background (CMB) photons off the hot intracluster medium (ICM).
- A fraction of CMB photons are scattered to higher energies, leaving a decrement (~1 mK) at frequencies below ~ 217 GHz.

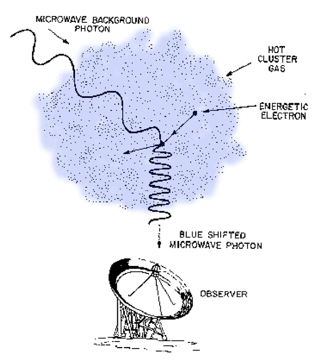


Image from Leon van Speybroeck (1987).

- The SZ decrement dT is a measure of the ICM electron pressure, integrated along the line of sight through the cluster (l). At 30 GHz, $dT/T_{cmb} \sim -2y$, where Compton $y \propto \int_{-\infty}^{\infty} P_e(l)dl$.

The Sunyaev-Zel'dovich Array (SZA)

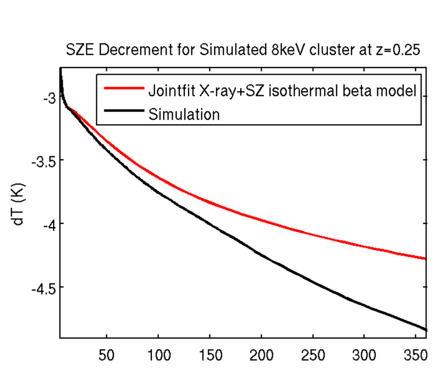
- The SZA comprises eight 3.5 m antennas, with six in the compact inner array.
- The inner array of the SZA probes arcminute (~ 1'-6') scales when operating at 30 GHz. This mode optimizes sensitivity to clusters at z $\gtrsim$ 0.2.

The SZA (inner array)

- The two outer antennas are used to constrain unresolved radio sources, which could otherwise mask the SZ decrement.
- The SZA 90-GHz receivers, which are now operational, will allow us to perform more detailed cluster studies.
- Large correlator bandwidth (8 GHz) to optimize detection efficiency.

The need for a new SZ model

- We set out to find an SZ pressure model that could accurately recover Y_{int}, the intrinsic integrated Compton y-parameter. We define Y_{int} as y integrated over the solid angle the cluster subtends, multiplied by the square of the angular diameter distance of the cluster (D_A^2). This scales as SZ cluster luminosity.
- Traditionally, the isothermal β-model has been used in SZ cluster studies, where higher significance X-ray observations were required constrain the cluster shape parameters, β and r_c.
- High resolution X-ray images from *Chandra*, XMM, and Suzaku, show that the isothermal β model is a poor description of ICM density over a large range of radii.
- The assumption of isothermality forces the pressure to have the same shape as density, ICM temperature declines at large radius. This leads to an increasing discrepancy between $n_e(r)$ and $P_e(r)$.
- The current generation of SZE experiments can constrain more than just the normalization (dT_0) of a β-model.
- By fitting the isothermal β-model to simulated clusters (which do not yet accurately capture cluster core physics), we found it overpredicts the SZ decrement, as seen in $log_{10}(dT)$ plot to the right ($6' \sim r_{500}$ for high mass clusters at z~0.25).

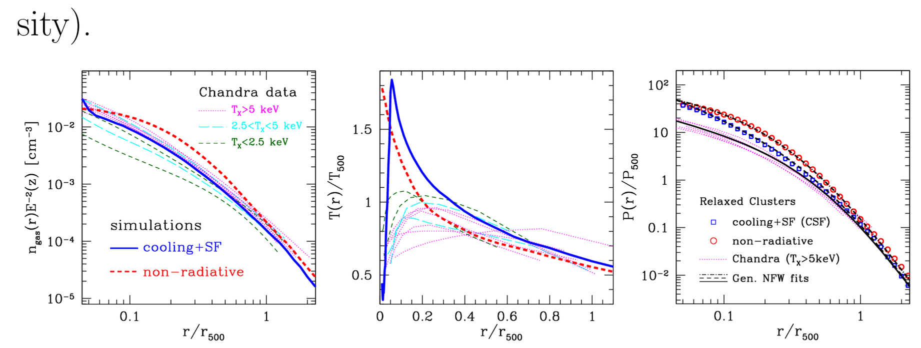


- It has become necessary to develop an SZ pressure profile that is no longer tied to the X-ray density model's shape.

II. The new model

Learning from X-ray Cluster Studies and Simulations

- Detailed X-ray cluster studies and simulations show pressure is simpler than its components, density and temperature.
- Nagai et al. (2007) show that cluster pressure is *self-similar* (over a broad range of masses and redshifts, pressure profiles exhibit the same shape when scaled to a fiducial overdensity).



Above: Red (adiabatic) and Blue (cooling+star formation) lines are average densities (**left panel**), temperatures (**middle**), and pressures (**right**) from 16 simulated clusters (Kravtsov et al. (2005)). All other lines are real cluster density and temperature fits (and derived pressures) for 11 nearby relaxed clusters with high-quality *Chandra* data, performed by Vikhlinin et al. (2006), who fit 9-parameter density and temperature profiles, i.e., they use 18 parameters total to describe density and temperature. Image from Nagai et al. (2007)

- Pressure self-similarity can be intuitively understood: Pressure integrates to thermal energy, which, to the extent that the cluster is virialized, tracks gravitational energy.
- Gravitational energy tracks dark matter, which resides in NFW halos, so it is not surprising that pressure profiles have an NFW-like form.
- Nagai et al. (2007) found that pressure is well-fit by a 5-parameter generalized NFW profile.
- Nagai et al. (2007) were able to further reduce the profile to 2 free parameters by fixing the slopes to their best-fit values (plotted as black lines in right panel, in above figure).

We call this profile the **Nagai 07 (N07) Pressure Profile**:

$$P_e(r) = \frac{P_{e,0}}{(r/r_p)^c \left[1 + (r/r_p)^a\right]^{(b-c)/a}} \qquad (1)$$

Getting Density from X-ray imaging

- X-ray surface brightness S_x scales as the ICM density squared: $S_x \propto \int_{-\infty}^{\infty} n_e(l)^2 \Lambda_{ee}(T_e(l), \mu) dl$
- S_x is a weak function of temperature, where the temperature dependence is contained in the emissivity function $\Lambda_{ee} \sim T_e^{1/2}$.
- For our density model, we choose a simplified core-cut version of the Vikhlinin et al. (2006) density model, . High-z cluster studies typically cannot constrain many parameters in a model, fewer cool-core clusters are seen at higher redshifts, and the simulated clusters simply do not reflect realistic cluster core properties.

$$n_e(r) = n_{e0} \left[1 + (r/r_c)^2\right]^{-3\beta/2} \left[1 + (r/r_s)^3\right]^{-\frac{\varepsilon}{6}} \qquad (2)$$

- We arrive at a modified β-model, with the terms r_s and ε able to account for the steepening slopes of clusters at large radii, where the β-model typically fails.

Combining SZE and X-ray Imaging

- With pressure constrained by the SZ, and density constrained by X-ray surface brightness, we use the ideal gas law to derive temperature (used in the surface brightness fits). We know $P_e = n_e k_B T_e$, and we get n_e from X-ray and P_e from SZE measurements, so we place no X-ray spectroscopic priors on our SZ fits.

III. Testing the models against simulations

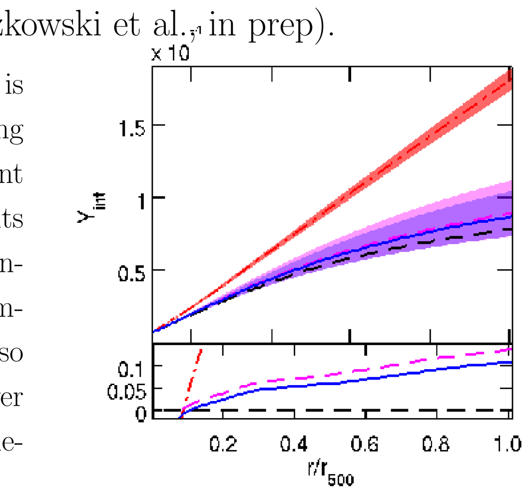
- We chose a few clusters of varying masses and relaxation states, simulated with radiative cooling and stellar formation feedback, from the Nagai et al. (2007) and Kravtsov et al. (2005) sample to determine the accuracy with which we could recover cluster parameters from model fits to mock SZA and *Chandra* X-ray observations.
- We use a Monte Carlo Markov Chain (MCMC) technique for all model fitting; the MCMC jointly maximizes the likelihood of the fits to the available data without getting stuck in local minima. MCMC also returns the probably density of the model fits, providing a convenient way to compute errorbars on derived cluster parameters.
- We fit the interferometric SZ data directly in Fourier space, building the line-of-sight projected SZ cluster model in image space and transforming it for the comparison.

Recovery of Y_{int} and T_e

We provide here results of fits to one simulated cluster, as an example to highlight the model.

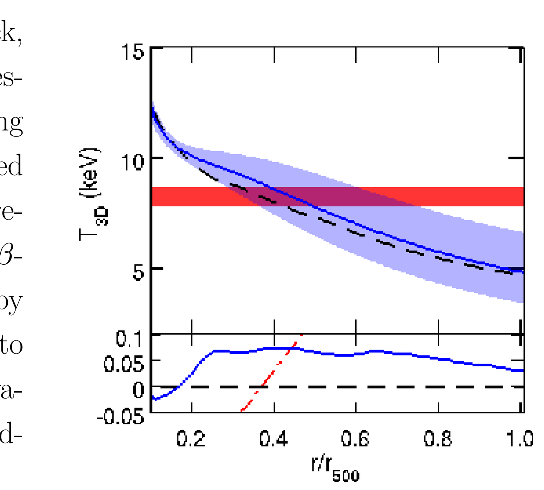
Below: Y_{int}, the integrated Compton y-parameter, recovered from fits to a mock SZA 30 GHz observation of a simulated relaxed 8 keV cluster (Mroczkowski et al., in prep).

The true Y_{int} from the simulation is the black, dashed line. Overlapping blue and magenta regions are joint (SZA+X-ray) and the SZA-only fits of the N07 Pressure Profile (68% confidence). The figure shows for comparison the isothermal β-model, also jointly fit with X-ray, in red. Lower panel shows residual errors on median true values.



Below: $T_e(r)$, the 3D electron temperature profile, recovered from joint X-ray and SZ fits.

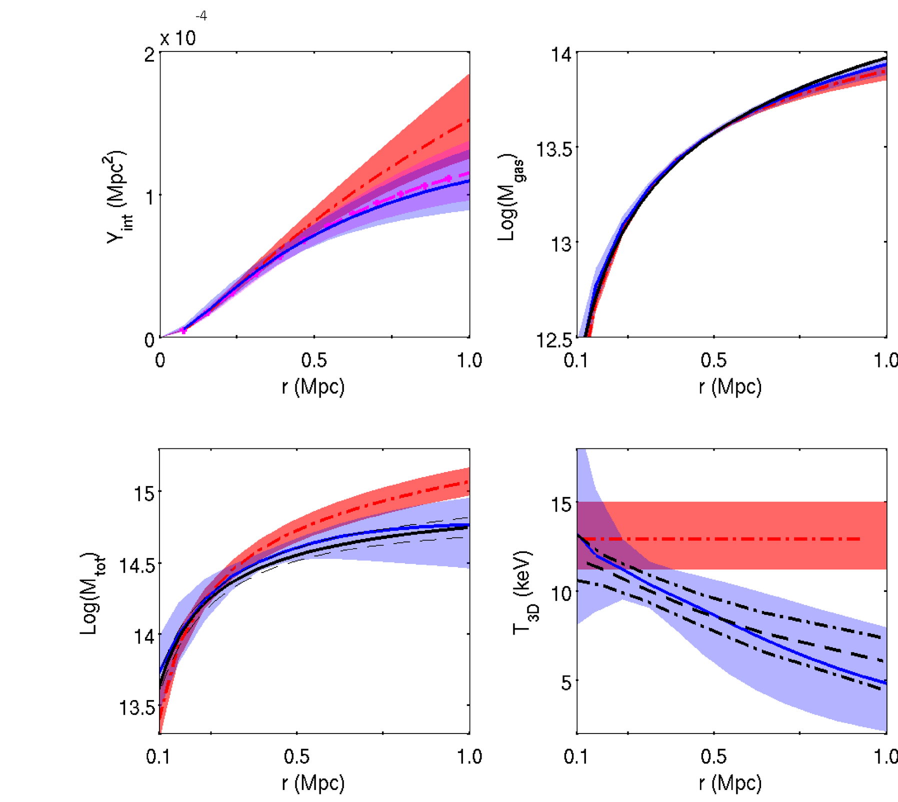
The 3-D, radially-averaged temperature from the simulation is the black, dashed line. The best-fit N07 Pressure Profile recovers the underlying temperature profile when combined with the X-ray density fit (blue region). We show the isothermal β-model's temperature, determined by 100 kpc core-cut spectroscopic fit to the mock Chandra X-ray observation, in red. Lower panel shows residuals errors on median values.



- The best-fit N07 Pressure Profile slopes introduce minimal (<10%) biases in derived SZ parameters.
- We find the new model accurately recovers Y_{int} and T_e (without relying on spectroscopic data).
- The SZ signal predicted by the jointly constrained X-ray+SZ isothermal beta model includes a significant amount of SZ flux at larger scales than we probe. The integral for SZ flux from a β-model is divergent for $\beta < 1$. This would predict an infinite thermal energy content within a cluster, using typical X-ray density constraints to model the pressure.
- The simulations do not accurately capture core astrophysics (see section II), leading to a larger discrepancy between the N07 and β-model fits than is observed in real clusters.
- The derived temperature profile gives a way to evaluate priors intrinsic to modeling the cluster.

IV. Fitting Real Observations

We have tested the model on a set of well-studied X-ray clusters, and present fits to a relaxed massive cluster below.



A comparison of SZA + *Chandra* joint analyses with an X-ray analysis for CL J1226+3332, a relaxed massive cluster at z=0.89. All colored regions represent 68% confidence. The solid lines represent the median derived quantities. Black dashed lines in 2nd-4th panel come from fits to the *Chandra* and *XMM Newton* observations presented in Maughan et al. (2007), with 68% confidence regions denoted by dot-dashed black lines. **Upper left panel** shows Y_{int} (integrated Compton y) for SZA-only (magenta) and the joint SZA + *Chandra* (blue) fits of the N07 pressure profile, compared to the isothermal β-model (red). **Upper right panel** shows gas mass, obtained by integrating the density fits. All M_{gas} estimates agree well for all model fits to the X-ray surface brightness (even when using SZE+X-ray derived temperatures, below). **Lower left panel** $M_{tot(<R)}$, the total mass obtained from each model assuming HSE. **Lower right panel** shows the temperature derived from joint *Chandra* and SZA analysis using the N07 Pressure Profile (blue, 68% confidence region), not using the spectroscopic information (Mroczkowski et al., in prep).

Conclusions / Future Work

- We have shown that the new N07 pressure profile accurately recovers SZ flux.
- On real clusters, we observe a systematic ~15-30% positive discrepancy in recovered SZ flux within r_{500} when using the isothermal β-model.
- By comparing the derived SZ + X-ray temperature with spectroscopic fits to high-quality X-ray data, we can diagnose the validity of the SZ fits using the N07 pressure profile.
- The temperature agreement confirms that SZ + X-ray imaging can be combined with X-ray spectroscopic data to further tighten constraints on cluster temperature. For high redshift clusters lacking deep X-ray observations, it is difficult to constrain more than a single spectroscopic temperature. Ground-based SZ instruments could prove to be a powerful complement to X-ray, since the SZE is redshift-independent.
- In addition to tightening constraints on ICM temperature, including spectroscopic information would allow the new, less-biased model to compute the angular diameter distance of a cluster (as has been done with the isothermal β-model, e.g. Bonamente et al. (2006)).
- Alternatively, this model could be used to compute cluster Helium abundances when cosmology is assumed (see Markevitch (2007)).
- The (thermal) SZE measures thermal energy content, and can thus provide an independent probe of the hot gas fraction in clusters.
- Assured that we can recover Y_{int} with minimal (10%) biases due to projection effects, we will use the model to determine SZ scaling relations (i.e. relate Y_{int} to total mass).

References

Bonamente, M., Joy, M. K., LaRoque, S. J., Carlstrom, J. E., Reese, E. D., & Dawson, K. S. 2006, ApJ, 647, 25.
Kravtsov, A. V., Nagai, D., Vikhlinin, A., 2005, ApJ, 625, 588.
Markevitch, M., 2007, ArXiv Astrophysics e-print 0705.3289
Maughan, B. J., Jones, C., Jones, L. R., & Van Speybroeck, L. 2007, ApJ, 659, 1125
Nagai, D., Kravtsov, A. V., & Vikhlinin, A. , 2007, ApJ, 668, 1
van Speybroeck, L. P., 1987, ApL&C, 26, 127
Vikhlinin, A., Kravtsov, A., Forman, W., Jones, C., Markevitch, M., Murray, S. S., & Van Speybroeck, L. 2006, ApJ, 640, 691.