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JOINT FITTING OF CLJ1226.9

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ABSTRACT

We present pressure profiles of galaxy clusters determined from high resolution

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1. INTRODUCTION

Galaxy clusters are the largest gravitationally bound objects in the universe and thus serve as ideal cosmological probes and astrophysical laboratories. Within a galaxy cluster, the gas in the intracluster medium (ICM) constitutes 90% of the baryonic mass (Vikhlinin et al. 2006) and is directly observable in the X-ray due to bremsstrahlung emission. At millimeter and submillimeter wavelengths, the ICM is observable via the Sunyaev-Zel'dovich (SZ) effect (Sunyaev & Zel'dovich 1972): the inverse Compton scattering of cosmic microwave background (CMB) photons off of the hot ICM electrons. The thermal SZ is observed as an intensity decrement relative to the CMB at wavelengths longer than ∼1.4 mm (frequencies less than ∼220 GHz). The amplitude of the thermal SZ is proportional to the integrated line-of-sight electron pressure, and is often parameterized as Compton y: $y = (\sigma_T/m_e c^2) \int P_e dl$, where σ_T is the Thomson cross section, m_e is the electron mass, c is the speed of light, and P_e is the electron pressure.

Cosmological constraints derived from galaxy cluster samples are generally limited by the accuracy of mass calibration of galaxy clusters (e.g. Hasselfield et al. 2013; Reichardt et al. 2013), which is often calculated via a scaling relation with respect to some integrated observable quantity. Scatter in the scaling relations will then depend on the regularity of clusters and the adopted integration radius of the clusters. Determining pressure profiles of galaxy clusters provides an assessment of the relative impact and frequency of various astrophysical processes in the ICM and can refine the choice of extent of galaxy clusters to reduce the scatter in scaling relations.

In the core of a galaxy cluster, some observed astrophysical processes include shocks and cold fronts (e.g. Markevitch & Vikhlinin 2007), sloshing (e.g. Fabian et al. 2006), and X-ray cavities (McNamara & Nulsen 2007). It is also theorized that helium sedimentation should occur, most noticeably in low redshift, dynamically-relaxed clusters (Abramopoulos et al. 1981; Gilfanov & Syunyaev 1984) and recently the expected helium enhancement via sedimentation has been numerically simulated (Peng & Nagai 2009). This would result in an offset between X-ray and SZ derived pressure profiles if not accounted for correctly.

At large radii ($R \gtrsim R_{500}$),[6] equilibration timescales are longer, accretion is ongoing, and hydrostatic equilibrium (HSE) is a poor approximation. Several numerical simulations show that the fractional contribution from non-thermal pressure increases with radius (Shaw et al. 2010; Battaglia et al. 2012; Nelson et al. 2014). For all three studies, non thermal pressure fractions between 15% and 30% are found at ($R \sim R_{500}$) for redshifts $0 < z < 1$. Additionally, clumping is expected to increase with radius (Kravtsov & Borgani 2012), and is expected to increase the scatter of pressure profiles at large radii (Nagai & Lau 2011) as well as biasing X-ray derived gas density high, and thus X-ray derived thermal pressure low (Battaglia et al. 2015).

However, the intermediate region, between the core and outer regions of the galaxy cluster, is often the best region to apply self-similar scaling relations derived from HSE to describe simulations and observations (e.g. Kravtsov & Borgani 2012). Moreover, both simulations and observations find low cluster-to-cluster scatter in pressure profiles within this intermediate radial range (e.g. Borgani et al. 2004; Nagai et al. 2007; Arnaud et al. 2010; Bonamente et al. 2012; Planck Collaboration et al. 2013; Sayers et al. 2013).

There are many existing facilities capable of making SZ observations, but most have angular resolutions of one arcminute or larger. In recent years, the SZ community has adopted the pressure profile presented in Arnaud et al. (2010) (hereafter, A10), who derive their pressure profiles from X-ray data from the REXCESS sample of 31 nearby ($z < 0.2$) clusters out to R_{500} and numerical simulations for larger radii. The adoption of the A10 pressure profile has allowed for the extraction of an integrated observable quantity which, via scaling relations, can then be used to determine the mass of the clusters. In this paper, we use high resolution SZ data to test the validity of this pressure profile in our sample of 14 clusters at intermediate redshifts.

The MUSTANG camera (Dicker et al. 2008) on the 100 meter Robert C. Byrd Green Bank Telescope (GBT, Jewell & Prestage 2004) with its angular resolution of 9″(full-width, half-maximum FWHM) is one of only a few SZ effect instruments with sub-arcminute resolution. However, MUSTANG's instantaneous field of view

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[6] R_{500} is the radius at which the enclosed average mass density is 500 times the critical density, $\rho_c(z)$, of the universe

(FOV) limits its sensitivity to scales larger than $1'$. To probe a wider range of scales we complement our MUSTANG data with SZ data from Bolocam (Glenn et al. 1998). Bolocam is a 144-element bolometer array on the Caltech Submillimeter Observatory (CSO) with a beam FWHM of $58''$ at 140 GHz and circular FOV with $8'$ diameter, which is well matched to the angular size of R_{500} ($\sim 4'$) of the clusters in our sample.

This paper is organized as follows. In Section 2 we describe the MUSTANG and Bolocam observations and reduction. In Section 3 we review the method used to jointly fit pressure profiles to MUSTANG and Bolocam data. We present results from the joint fits in Section 4 and compare our results to X-ray derived pressures in Section ??. Throughout this paper we assume a ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Sample*

2.2. *NIKA Observations and Reduction*

2.3. *MUSTANG Observations and Reduction*

MUSTANG is a 64 pixel array of Transition Edge Sensor (TES) bolometers arranged in an 8×8 array located at the Gregorian focus on the 100 m GBT. Operating at 90 GHz (81–99 GHz), MUSTANG has an angular resolution of $9''$and pixel spacing of $0.63 f\lambda$ resulting in a FOV of $42''$. More detailed information about the instrument can be found in Dicker et al. (2008).

Our observations and data reduction are described in detail in Romero et al. (2015), and we briefly review them here. Absolute flux calibrations are based on the planets Mars, Uranus, or Saturn, nebulae, or the star Betelgeuse (α_{Ori}).
[7]

2.4. *Bolocam Observations and Reduction*

Bolocam is a 144-element camera that was a facility instrument on the Caltech Submillimeter Observatory (CSO) from 2003 until 2012. Its field of view is $8'$ in diameter, and at 140 GHz it has a resolution of $58''$ FWHM (Glenn et al. (1998); Haig et al. (2004)). The clusters were observed with a Lissajous pattern that results in a tapered coverage dropping to 50% of the peak value at a radius of roughly $5'$, and to 0 at a radius of $10'$. The Bolocam maps used in this analysis are $14' \times 14'$. The Bolocam data [8] are the same as those used in Czakon et al. (2015) and Sayers et al. (2013); the details of the reduction are given therein, along with Sayers et al. (2011). The reduction and calibration is similar to that used for MUSTANG, and Bolocam achieves a 5% calibration accuracy and $5''$ pointing accuracy.

3. JOINT MAP FITTING TECHNIQUE

3.1. *Overview*

The joint map fitting technique used in this paper is described in detail in Romero et al. (2015). We review it briefly here. The general approach follows that of a least squares fitting procedure, which assumes that we can make a model map as a linear combination of model components.

This linear combination can be written as:

$$\vec{d_m} = \mathbf{A}\vec{a}_m, \tag{1}$$

where d_m is the total model, each column in $\mathbf{A}$ is a filtered model component (Section ??), and $\vec{a}_m$ is an array of amplitudes of the components. There are up to four types of components for which fit: a bulk component, point source(s), residual component(s), and a mean level. Of these, we produce a sky model for the bulk component and point source to be filtered. The residual component is calculated directly as a filtered component.

We wish to fit $\vec{d_m}$ to our data, $\vec{d}$, and allow for a calibration offset between Bolocam and MUSTANG data. We therefore define our data vector as:

$$\vec{d} = [\vec{d_B}, k\vec{d_M}, k], \tag{2}$$

where $\vec{d_B}$ is the Bolocam data, $\vec{d_M}$ is the MUSTANG data, and k is the calibration offset of MUSTANG relative to Bolocam, with an RMS uncertainty of 11.2%.

We use the χ^2 statistic as our goodness of fit:

$$\chi^2 = (\overrightarrow{d} - \overrightarrow{d}_m)^T \mathbf{N}^{-1} (\overrightarrow{d} - \overrightarrow{d}_m), \tag{3}$$

where $\mathbf{N}$ is the covariance matrix; however, because we wish to fit for k in addition to the amplitude of model components, we no longer have completely linearly independent variables, and thus we employ MPFIT (Markwardt 2009) to solve for these variables.

3.2. *Preprocessing*

3.3. *Mean Level*

Similar to Czakon et al. (2015), we wish to account for a mean level (signal offset) in the MUSTANG maps. We do not wish to fit for a mean level simultaneously as a bulk component given the degeneracies. Therefore, to determine the mean level independent of the other components, we create a MUSTANG noise map and calculate the mean within the inner arcminute for each cluster. This mean is then subtracted before the other components are fit.

3.3.1. *Point Sources*

For MUSTANG, point sources are treated in the same manner as in Romero et al. (2015). A point source is identified by NIKA (Adam et al. 2015) in CLJ1226, which is posited to be a submillimeter galaxy (SMG) behind the cluster.

For the Bolocam image

3.3.2. *Centroid*

The default centroids used when gridding our bulk ICM component are the ACCEPT centroids. Given the offsets between ACCEPT and Bolocam centroids (Table 1), we perform a second set of fits where we grid the bulk ICM component using the Bolocam centroids. The ACCEPT centroid are taken to be the X-ray peaks unless their centroiding algorithm produced a centroid more than 70 kpc from the X-ray peak, in which case they adopt that centroid (Cavagnolo et al. 2008).

[7] MUSTANG data is publicaly available at Hi

[8] Bolocam data is publicaly available at http://irsa.ipac.caltech.edu/data/Planck/release_2/ancillary-data/bolocam/

Table 1
CLASH cluster properties

Cluster	z	M_{500} ($10^{14} M_{\odot}$)	P_{500} (keV/cm^3)	R_{500} (kpc)	T_x^a (keV)	T_x^b (keV)	T_{mg} (keV)	Dynamical state	Δr_0 ($''$)
CLJ1226	0.888	7.8	0.01184	1000	12.0	11.7	8.39	–	15.3

Note. — z, M_{500}, and T_X^a are taken from Mantz et al. (2010): T_X^a is calculated from a single spectrum over $0.15R_{500} < r < R_{500}$ for each cluster. T_X^b is from Morandi et al. (2015), and is calculated over $0.15R_{500} < r < 0.75R_{500}$. T_{mg} is a fitted gas mass weighted temperature, determined by fitting the ACCEPT (Cavagnolo et al. 2009) temperature profiles to the profile found in Vikhlinin (2006). The dynamical states: cool core (CC) and disturbed (D) are taken from (and defined in) Sayers et al. (2013). The bolded clusters are the 14 clusters in our sample. Δr_0 denotes the offset between the ACCEPT and Bolocam centroids.

Table 2
Bolocam and MUSTANG observational properties.

Cluster	z	R.A. (J2000)	Decl. (J2000)	$T_{obs,B}$ (hours)	Noise$_B$ μK_{CMB}-amin	A10$_B$ (σ)	$T_{obs,M}$ (hours)	Noise$_M$ μJy/bm	A10$_M$ (σ)
CLJ1226	0.888	12:26:57.9	+33:32:49	11.8	22.9	13.7	4.9	85.6	9.43

Note. — Subscripts $_B$ and $_M$ denote Bolocam and MUSTANG properties respectively. Noise$_B$ and $T_{obs,B}$ are those reported in Sayers et al. (2013). Noise$_M$ is calculated on MUSTANG maps with $10''$ smoothing, in the central arcminute. T_{obs} are the integration times (on source) for the given instruments. A10$_B$ and A10$_M$ values indicate the significance (in σ) of P_0 when we fit a spherical A10 (Arnaud et al. 2010) profile (see Section **??**).

3.4. *Parametric Fits: gNFW*

The cluster is taken to be a spherically symmetric 3D electron pressure profile as parameterized by a generalized Navarro, Frenk, and White profile (hereafter, gNFW Navarro et al. 1997; Nagai et al. 2007):

$$\tilde{P} = \frac{P_0}{(C_{500}X)^{\gamma}[1 + (C_{500}X)^{\alpha}]^{(\beta-\gamma)/\alpha}} \quad (4)$$

where $X = R/R_{500}$, and C_{500} is the concentration parameter; one can also write $(C_{500}X)$ as (R/R_s), where $R_s = R_{500}/C_{500}$. $\tilde{P}$ is the electron pressure in units of the characteristic pressure P_{500}. This pressure profile is integrated along the line of sight to produce a Compton y profile, given as

$$y(r) = \frac{P_{500}\sigma_T}{m_e c^2} \int_{-\infty}^{\infty} \tilde{P}(r,l) dl \quad (5)$$

where $R^2 = r^2 + l^2$, r is the projected physical radius, and l is the distance from the center of the cluster along the line of sight. Once integrated, $y(r)$ is gridded as $y(\theta)$ (θ being the angular radius) and is realized as two maps with the same astrometry as the MUSTANG and Bolocam data maps (pixels of $1''$ and $20''$ on a side, respectively). In each case, we convolve the Compton y map by the appropriate beam shape. For Bolocam we use a Gaussian with FWHM = $58''$, and for MUSTANG we use the double Gaussian as determined in Romero et al. (2015).

3.4.1. *Parameter Space*

As in Romero et al. (2015), we fix MUSTANG's centroid, but allow Bolocam's pointing to vary by $\pm 10''$ in RA and Dec with a prior on Bolocam's radial pointing accuracy with an RMS uncertainty of $5''$. Our approach to find the absolute calibration offset between Bolocam and MUSTANG is the same as in Romero et al. (2015) (see also Section 3.1).

In Romero et al. (2015), we performed a grid search over γ and C_{500}, marginalizing over P_0, where α and β are fixed to values determined from previous studies. We find that fixing α and β at different values, the pressure profiles are in very good agreement with one another and that the differences in χ^2 values between these fits is not significant. Thus, for our fits we assume the values of α and β given in A10.

We search over $0 < \gamma < 1.3$ in steps of $\delta\gamma = 0.1$, and over $0.1 < C_{500} < 3.3$ in steps of $\delta C_{500} = 0.1$. To create models in finer steps than $\delta\gamma$ and δC_{500}, we interpolate filtered model maps from nearest neighbors from the grid of original filtered models.

3.5. *Non Parametric Fits: radial pressure bins*

3.6. *Geometric Deprojection*

4. SZ PRESSURE PROFILE CONSTRAINTS

We have constrained the gNFW parameters P_0, C_{500}, and γ.

4.1. *Systematics*

5. INTEGRATED COMPTON Y SCALING RELATIONS

6. CONCLUSIONS

We developed an algorithm to jointly fit gNFW pressure profiles to clusters observed via the SZ effect with MUSTANG and Bolocam. We apply this algorithm to 14 clusters and find the profiles are consistent with a universal pressure profile found in Arnaud et al. (2010). Specifically, the pressure profile is of the form:

$$\tilde{P}_e = \frac{P_0}{\ldots}$$

where we fixed α and β to values found in Arnaud et al. (2010).

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APPENDIX

.1. *CLJ 1226 (z=0.89)*

CLJ 1226 is a well studied high redshift cluster (e.g. Mroczkowski et al. 2009; Bulbul et al. 2010; Adam et al. 2015). Adam et al. (2015) find a point source at RA 12:12:00.01 and Dec +33:32:42 with a flux density of 6.8 ± 0.7 (stat.) $\pm$ 1.0 (cal.) mJy at 260 GHz and 1.9 ± 0.2 (stat.) at 150 GHz. This is not the same point source seen in Korngut et al. (2011), which is reported as a point source with 4.6σ significance in surface brightness, and can be fit in our current analysis as a point source with a flux density of 0.33 ± 0.13 mJy. A short VLA filler observation (VLA-12A-340, D-array, at 7 GHz) was performed to follow up this potential source. To a limit of $\sim 50\mu$Jy nothing is seen, other than the clearly spatially distinct radio source associated with the BCG at the cluster center (1 mJy at 7 GHz and 3.2 mJy in NVSS). In contrast, the point source found in Adam et al. (2015) is fit to our data with a flux density of 0.36 ± 0.11 mJy. Given the slight increase in significance of the point source from Adam et al. (2015), we adopt that point source location for our pressure profile analysis of CLJ 1226.

In the previous analysis of the MUSTANG data, Korngut et al. (2011) find a ridge of significant substructure after subtracting a bulk SZ profile (N07, fitted to SZA data). They find that this ridge, southwest of the cluster center, alongside X-ray profiles, are consistent with a merger scenario. However, in this work, we do not find any significant substructure after fitting a bulk component.

A. DATA PRODUCTS

We have made MUSTANG data products for the sample of clusters analysed in this paper available at: https://safe.nrao.edu/wiki/bin/view/GB/Pennarray/MUSTANG_CLASH. Links to accompanying Bolocam and ACCEPT data are available from this website as well. In particular, we have publicized the final data maps, noise maps, and signal-to-noise (SNR) maps used in this analysis, as well as transfer functions for individual clusters. Further documentation is available on the website.

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