MEASUREMENT OF THE ELECTRON-PRESSURE PROFILE OF GALAXY CLUSTERS IN 3 YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (WMAP) DATA

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ABSTRACT

Using 3 year WMAP data at the locations of ∼700 X-ray–selected clusters, we have detected the amplitude of the thermal Sunyaev-Zeldovich (TSZ) effect at the 15σ level, the highest statistical significance reported so far. Owing to the large size of our cluster sample, we are able to detect the corresponding cosmic microwave background distortions out to large cluster-centric radii. The region over which the TSZ signal is detected is, on average, 4 times larger in radius than the X-ray–emitting region, extending to ∼3 $h_{70}^{-1}$ Mpc. We show that an isothermal β-model does not fit the electron pressure at large radii; instead, the baryon profile is consistent with the Navarro-Frenk-White profile, which is expected for dark matter in the concordance ΛCDM model. The X-ray temperature at the virial radius of the clusters falls by a factor ∼3–4 from the central value, depending on the cluster concentration parameter. Our results suggest that cluster dynamics at large radii is dominated by dark matter and is well described by Newtonian gravity.

Subject headings: cosmic microwave background — cosmology: observations — cosmology: theory

1. INTRODUCTION

The hot intergalactic X-ray-emitting gas distorts the cosmic microwave background (CMB) spectrum of those photons crossing the cluster. The CMB distortions are independent of redshift and arise from Thompson scattering; when electrons are nonrelativistic, they are caused by two different effects: (1) the thermal Sunyaev-Zel’dovich (TSZ) effect (Sunyaev & Zeldovich 1972) is due to the thermal motions of electrons in the cluster potential well, whereas (2) the kinematic Sunyaev-Zel’dovich (KSZ) effect is due to the motion of the cluster as a whole. Both effects contribute to the CMB radiation power spectrum, but their contribution is significant at $\ell > 10^3$ (Atrio-Barandela & Mücket 1999; Molnar & Birkinshaw 2000). For the most luminous clusters, relativistic corrections could become important, giving rise to the relativistic SZ effect (Wright 1979). The TSZ spectral signature appears as a temperature decrement in the WMAP frequency range. It has been measured for ∼100 individual clusters (Birkinshaw 1999; Carlstrom et al. 2002; LaRoque et al. 2006), whereas the KSZ effect, being of much smaller amplitude, has not yet been detected for individual systems. However, it can be detected statistically with large cluster samples (Kashlinsky & Atrio-Barandela 2000) by a method recently applied by us to measure the bulk motion of clusters on scales larger than 300 $h^{-1}$ Mpc (Kashlinsky et al. 2008).

Currently planned ground-based and space-borne CMB experiments like the South Pole Telescope, the Atacama Cosmology Telescope, and the Planck mission are expected to detect clusters via their TSZ signature in the near future. In the meantime, the first efforts to determine the TSZ contribution to the CMB fluctuations observed by WMAP across the entire sky (Spergel et al. 2007) were made by cross-correlating templates constructed from galaxy and cluster catalogs using first-year data (Hernández-Monteagudo & Rubiño-Martín 2004; Hernández-Monteagudo et al. 2004; Myers et al. 2004; Afshordi et al. 2005) and, more recently, third-year data (Afshordi et al. 2007). These studies report 2–8σ detections of an anticorrelation with various galaxies and cluster surveys, consistent with the expected TSZ signature at WMAP frequencies.

A more efficient detection of the SZ effect is possible by examining the WMAP data at the location of X-ray–detected clusters, because both the SZ effect and the X-ray data probe the same hot intracluster medium. In this Letter, we use the largest to-date all-sky cluster catalog, containing 782 clusters with well-measured X-ray parameters from ROSAT All-Sky Survey (RASS) data (Voges et al. 1999), to determine the TSZ amplitude present in the 3 year WMAP data and to evaluate the properties of the cluster SZ signal. We describe the catalog and WMAP data in § 2, present our results in § 3, and discuss their implications in § 4.

2. X-RAY CATALOG AND CMB DATA

Our analysis uses an all-sky cluster sample created by combining the ROSAT-ESO flux-limited X-ray (REFLEX) galaxy cluster survey (Böhringer et al. 2004) in the southern hemisphere, the extended Brightest Cluster Sample (eBPCS; Ebeling et al. 1998, 2000) in the north, and the clusters in the zone of avoidance (CIZA; Ebeling et al. 2002; Kocevski et al. 2007) sample along the Galactic plane. All three surveys are X-ray–selected and X-ray flux–limited using RASS data. A detailed description of the creation of the merged catalog is provided by Kocevski & Ebeling (2006).

For each cluster, the catalog lists the position, flux, and luminosity measured directly from RASS data and the X-ray electron temperature, derived from the $L_X$-$T_X$ relation of White et al. (1997), redshifts, and angular and physical extent of the region containing the measured X-ray flux. We determine the X-ray extent of each cluster directly from the RASS imaging data using a growth-curve analysis. The cumulative profile of the net count rate is constructed for each system by measuring the counts in successively larger circular apertures centered on the X-ray emission and by subtracting an appropriately scaled X-ray background. The latter is determined in an annulus from 2 to 3 $h_{70}^{-1}$ Mpc around the cluster centroid. The extent of each system is then defined as the radius...
at which the increase in the source signal is less than the 1σ Poissonian noise of the net count rate.

To obtain an analytic parameterization of the spatial profile of the X-ray–emitting gas and, ultimately, the central electron density, we fit a β-model (Cavaliere & Fusco-Femiano 1976) convolved with the RASS point-spread function to the RASS data for each cluster in our sample: \( S(r) = S_{0}[1 + (r/c_{\beta})^2]^{3/2 - 1/2} \) where \( S(r) \) is the projected surface brightness distribution and \( S_{0}, r_{c}, \) and \( \beta \) are the central surface brightness, the core radius, and the \( \beta \)-parameter characterizing the profile at large radii, respectively. Using the results from this model fit to determine the gas-density profile assumes the gas to be isothermal and spherically symmetric. In practice, additional uncertainties are introduced by the correlation between \( r_{c} \) and \( \beta \), which makes the results for both parameters sensitive to the choice of radius over which the model is fit, and by the fact that, for all but the most nearby clusters, the angular resolution of the RASS allows only a very poor sampling of the surface brightness profile (at \( z > 0.2 \), the X-ray signal from a typical cluster is only detected in perhaps a dozen RASS image pixels). In recognition of these limitations, we hold \( \beta \) fixed at the canonical value of 0.2 (Jones & Forman 1984). The resulting values for \( r_{c} \) are reassuringly robust in the sense that we find broad agreement with the empirical relationship between X-ray luminosity and \( r_{c} \) determined by Reiprich & Böhringer (1999). Our best-fit parameters, the cluster luminosity and electron temperature, are used to determine central electron densities for each cluster by use of equation (6) of Henry & Henriksen (1986), with the intracluster medium temperature estimated from the \( L_{X}/T_{X} \) relationship (White et al. 1997). Other sources of error of this parameterization—namely, the deviation from a \( \beta \)-profile at small radii due to cooling cores as well as the steepening of the profile often observed at large radii (Vikhlinin et al. 1999)—are unlikely to affect our results as a result of the low resolution and low signal-to-noise ratio (S/N) of the RASS data. Conversions between angular extents and the physical dimensions of clusters are made using the ΛCDM concordance cosmology (\( \Omega_{m} = 0.7, h = 0.7 \)).

In our analysis of the CMB data, we use maps from eight differencing assemblies (DAs) corresponding to the Q, V, and W bands of the “foreground-cleaned” 3 year WMAP data; Q1, Q2, V1, V2, and W1–W4 are available from the LAMBDA archive.1 We do not use the K and Ka bands, because foreground contamination is important at those frequencies (Bennett et al. 2003). The maps are written in the HEALPix (Gorski et al. 2005) nested format with resolution \( N_{side} = 512 \), corresponding to pixels of 7' on the side, significantly larger than the 0.75' pixels of the X-ray data, which makes our results insensitive to deviations from the spherical symmetry of the clusters in our sample. These bands correspond to frequencies 41, 61, and 94 GHz and angular resolutions \( \theta_{FWHM} = 0.5^\circ, 0.3^\circ, \) and 0.2°. All maps are multiplied by the Kp0 mask to remove microwave emission from the Galactic plane and foreground sources. The masking eliminates 120 clusters, leaving 674 clusters for our SZ analysis. Of those, 13 clusters did not have sufficient S/N in the ROSAT data to define an extent and were excluded from this analysis, leaving a total of 661 clusters.

### 3. RESULTS

To compute the TSZ signal from the 3 year WMAP data, we evaluate the mean temperature anisotropy at the cluster locations. The TSZ distortion scales as the electron density, \( n_{e} \), integrated along the line of sight, whereas the cluster X-ray emission is \( \propto n_{e}^2 \). Thus, the clusters’ SZ signal should exceed over an area significantly larger than the region within which X-ray emission is detectable. We probe the SZ extent by measuring the signal in regions of increasing radius \( \theta_{sz} \), from \( 10\theta_{c} \) to \( 60\theta_{c} \), where \( \theta_{c} \) is the angular extent of the respective cluster in the RASS data. The results from each DA were averaged with weights, which were inversely proportional to the pixel noise and the frequency-dependent amplitude of the SZ effect, and without weights. The differences between the results obtained with the different weighting schemes are smaller than 5%, and we quote results obtained using noise and frequency-weighted averages. We calculated the error bars by assigning 1000 random pseudocluster positions to the WMAP sky and computing the mean temperature anisotropy for each cluster template. The random positions are always placed outside the Kp0 mask and away from any of the cluster pixels.

In Table 1, we present our results for two subsamples: clusters with redshift \( z \leq 0.2 \) and clusters with luminosity \( L_{X}(0.1–2.4 \text{ keV}) \geq 3 \times 10^{44} \text{ ergs s}^{-1} \). The limit of \( z = 0.2 \) was chosen because this is the largest redshift out to which our cluster catalog is reasonably complete. We use the average values of the core radii and the radial cluster extent for each subsample. The TSZ signal is measured within (1) a disk of angular radius \( \theta \) and (2) a ring or annulus delimited by two consecutive disks, to differentiate the contribution coming from regions increasingly farther away from the cluster core. By design, the first disk and ring regions are identical. We measure a temperature decrement at the cluster pixels at the ~15σ level for the most X-ray–luminous clusters. The region that is from 3 to 4 times the X-ray extent still shows a nonnegligible contribution, while outside this region no statistically significant signal is detected.

### TABLE 1

| \( \theta \) (arcmin) | \( r_{c} \) (Mpc) | TSZ Disk (\( \mu K \)) | TSZ Ring (\( \mu K \)) |
|-----------------|-----------------|------------------|------------------|
| 4.4........ | 0.6 | -28.5 ± 2.3 | -28.5 ± 2.3 |
| 8.8........ | 1.3 | -20.3 ± 1.8 | -17.4 ± 2.0 |
| 13.2........ | 1.9 | -14.0 ± 1.6 | -8.4 ± 2.1 |
| 17.4........ | 2.5 | -9.5 ± 1.4 | -3.1 ± 2.1 |
| 21.7........ | 3.1 | -6.5 ± 1.3 | -0.5 ± 2.1 |
| 25.8........ | 3.8 | -4.6 ± 1.2 | 0.4 ± 2.2 |

Note.—The first two columns show the average angular and radial cluster extent for each subsample: the third and fourth columns correspond to the measured TSZ signal in the 3 year WMAP data at the cluster locations. In the disk, we measure the TSZ signal within a circle of angular radius \( \theta_{c} = (1 - 6)\theta_{c} \), in the ring, we measure the TSZ signal within an annulus of width \( 1\theta_{c} \) and increasing radius.

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1 See http://lambda.gsfc.nasa.gov.
toward cluster outskirts, making the KSZ dipole appear still more extended than the TSZ contributions.

In Figure 1, we show the TSZ amplitude for different cluster subsamples and regions of different radii. In Figure 1a, we plot the results for clusters within a progressively increasing upper redshift limit; the last data point includes all clusters. Except for the lowest redshift bins, the measured amplitude is roughly independent of the number of clusters. In Figure 1b, we show the frequency dependence of the measured TSZ signal for all clusters with redshift \( z \leq 0.2 \) by comparing the results for the three bands considered: Q, V, and W. The solid lines denote the frequency dependence of the KSZ and relativistic SZ effects, respectively, normalized to the amplitude measured at the V band.

In all cases, the vertical bars indicate the 1\(^\sigma\) errors. The lines were normalized by least-squares regression. The dashed and dot-dashed lines show the frequency dependence of the KSZ and relativistic SZ effects, respectively, normalized to the amplitude measured at the V band.

The discrepancy between data and the \( \beta = \frac{3}{2} \) prediction is less than a few microkelvins, or 10%–30% in the cluster centers, but increases with radius and reaches a factor of 2–3 at the largest radius probed in our study. It could be argued that a model with \( \beta = 1 \) would fit the data in the cluster outskirts. Such a high \( \beta \)-value would invalidate the values of \( r_c \) and central electron density derived directly from the RASS X-ray data, and would in fact be inconsistent with the shape of the X-ray surface brightness profile in the central region of essentially every cluster ever observed. Jones & Forman (1999) found that the average cluster surface brightness profile is well described by a \( \beta \)-model with \( r_c = 200 \) kpc and \( \beta \sim 0.6 \). Of 96 clusters analyzed in detail, they did not find a single one for which a \( \beta \)-value outside the range of 0.4–0.8 would provide an acceptable fit to the X-ray data.

Numerical hydrodynamic simulations suggest that the dark matter distribution in galaxy clusters is described by a universal density profile (the Navarro-Frenk-White [NFW] profile; Navarro et al. 1997): \( \rho_{\text{in}}(x) = \rho_s (1 + x)^{-3} \), where \( x = r/r_c \); here \( r_c \) and \( \rho_s \) are a characteristic scale radius and density, respectively. Usually \( r_c \) is given in terms of the concentration parameter \( c = r/r_v \), where \( r_v \) is the halo virial radius. This parameter depends only weakly on mass, with less massive systems being more concentrated, and thus having larger \( c \). While the electron density for the \( \beta = \frac{3}{2} \) model scales as \( r^{-2} \) at large radii, the NFW model is much steeper, scaling as \( r^{-3} \). If the gas distribution were to follow that of the dark matter, one would thus expect its radial profile to decline much more steeply, as observed and shown in Figure 2. The solid lines represent the electron-pressure profile of a single cluster computed using a \( \beta \)-model (upper solid line) and an NFW model (lower solid line), convolved with the 3 year WMAP beam. Our fits (\( \beta \)-model and NFW model alike) assume leads to biased estimates of the integrated Compton \( \gamma \)-parameter in the inner part of clusters. Since we measure the TSZ contribution outside the inner cluster region, we can test for a similar bias in the outskirts of clusters and assess the accuracy of the \( \beta \)-model. In Figure 2, a comparison is made between our measured radial SZ profile (filled circles; see also Table 1) and \( \beta \)-model predictions (diamonds). Predictions are computed with the same pipeline as the data from the eight DA maps generated by placing clusters on the sky with their measured angular size. To each pixel within a cluster, we assign the CMB temperature derived from the \( \beta \)-model TSZ profile, convolved with the WMAP beam for each DA. The angular scale \( \theta_{\text{LSZ}} \) is the area-weighted average extent of cluster.

The radial emission profiles derived from the SZ effect and from the X-ray observations of clusters do not necessarily follow the same \( \beta \)-model. Only a handful of clusters have measured radial SZ profiles, and the parameters obtained from X-ray data are often used in SZ analysis. Using numerical simulations, Hallman et al. (2007) showed that this approach...
a representative cluster redshift of $z = 0.12$, a value close to the mean redshift of both cluster subsamples. The best-fit values for the core radius of the $\beta$-model are $\theta_c = 1.5$ and 0.5 (Figs. 2a and 2b, respectively). We checked that no value of $r_p \in [0.5, 5]$ can make the $\beta$-model fit the measured pressure profile.

To generate the NFW profile, we follow Komatsu & Seljak (2001, 2002) and assume that the gas follows the dark matter distribution, is in hydrostatic equilibrium, and is well described by a polytropic equation of state. Fitting an NFW model yields best-fit concentration parameters of $(c = 8 \text{ (Fig. 2a)} \text{ and } c = 15 \text{ (Fig. 2b). In the Komatsu & Seljak (2001) model, these values correspond to polytropic indices } \gamma = 1.17 \text{ and } 1.2, \text{ respectively. This result reflects the fact that the most luminous clusters are, on average, farther away in a flux-limited sample than the whole population, so they subtend a smaller angular size and appear concentrated (smaller } r_p \text{ in the NFW model) or have a smaller core radius (in the } \beta \text{-model). In Figure 2, theoretical lines represent the TSZ signal of a single cluster; as such, they are not a fair representation of the cluster population as a whole. If } \theta_{sz} \text{ were not the area-weighted extent but the SZ emission–weighted center, the best-fit NFW and } \beta \text{-models—the solid lines in the figure—would correspond to slightly different model parameters, but this would not change the discrepancy between the measured profile and the } \beta \text{-model–predicted profile.}

The universal gas temperature profiles of Komatsu & Seljak (2001), compatible with our results, show a strong decline of gas X-ray temperature with radius. The central temperature decreases by a factor 2–4 at the virial radius, being steeper for the more concentrated (less massive) clusters. This result is in agreement with the recent analysis of the X-ray temperature profiles of 15 nearby clusters, carried out by Pratt et al. (2007) using XMM-Newton data. They measured temperature profiles declining by a factor $\sim 2$ at half the virial radius, in good agreement with numerical simulations outside the core region. To conclude, Figure 2 shows that the gas density has a steeper decline in the outer region than does an isothermal $\beta = \frac{1}{2}$ model; the slope is close to $-3$; i.e., the dynamical state of cluster outskirts is well described by an NFW profile.

4. CONCLUSIONS

Using the largest X-ray cluster catalog available today, we present an accurate measurement of the contribution of clusters of galaxies to the temperature anisotropies measured by the WMAP satellite in its 3 year data release. We find the TSZ signal to extend to, on average, $\sim 2-3 h_{100}^{-1}$ Mpc, i.e., radii much larger than the ones out to which X-ray emission is detectable. The TSZ signal measured in the cluster cores shows deviations from the expected TSZ frequency behavior. These are likely caused by the different angular resolutions of the WMAP Q, V, and W channels, which probe the SZ decrement from different parts of the clusters. However, when the TSZ contribution from the outer cluster regions is included, the signal is consistent with the frequency dependence of a TSZ spectrum.

The measurement indicates that the gas profile of the cluster population in the outer region is compatible with the NFW model. Our results suggest that the cluster temperature profile declines with radius, in agreement with numerical simulations of clusters and recent XMM-Newton data. We are currently re-deriving the NFW data parameters from the X-ray images to compare the TSZ signal predicted for the cluster population, using X-ray–derived quantities, with the signal at WMAP frequencies. The radial profile of the measured TSZ signal suggests that, all the way to the cluster outskirts, baryons are settled in hydrostatic equilibrium within the dark matter potential well and follow the same density distribution. As shown by numerical simulations, the profile of collapsed dark matter halos is a direct consequence of the Newtonian gravity, with a suitably chosen initial density field (corresponding to the concordance $\Lambda$CDM model). Hence, our results also provide further, albeit indirect, evidence for the existence of dark matter and the validity of Newtonian dynamics.

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