HIGH ANGULAR RESOLUTION OBSERVATION OF THE SUNYAEV–ZEL’DOVICH EFFECT IN THE MASSIVE \( z \approx 0.83 \) CLUSTER CI J0152–1357

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ABSTRACT

X-ray observations of galaxy clusters at high redshift \((z \gtrsim 0.5)\) indicate that they are more morphologically complex and less virialized than those at low redshift. We present the first subarcminute resolution synthesis observations at 18 GHz of the Sunyaev–Zel’dovich (SZ) effect for CI J0152–1357 using the Australia Telescope Compact Array. CI J0152–1357 is a massive cluster at redshift \( z = 0.83 \) and has a complex structure including several merging subclumps which have been studied at optical, X-ray, and radio wavelengths. Our high-resolution observations indicate a clear displacement of the maximum SZ effect from the peak of X-ray emission for the most massive subclump. This result shows that the cluster gas within the cluster substructures is not virialized in CI J0152–1357, and we suggest that it is still recovering from a recent merger event. A similar offset of the SZ effect has recently been seen in the “bullet cluster” and in RX J1347–1145. This non-equilibrium situation implies that high-resolution observations are necessary to investigate galaxy cluster evolution and to extract cosmological constraints from a comparison of the SZ effect and X-ray signals.

Key words: cosmological parameters – galaxies: clusters: individual (CI J0152-1357) – techniques: interferometric

1. INTRODUCTION

The Sunyaev–Zel’dovich (SZ) effect is the spectral distortion of the cosmic microwave background (CMB) due to inverse Compton scattering of CMB photons off a cloud of electrons (Birkinshaw 1999 and references therein). The increase of the photon energy implies a decrease of the CMB brightness at frequencies below 218 GHz and an increase at higher frequencies. The amplitude of the distortion depends only on the properties of the electron cloud: in the case of thermal electrons, it is proportional to the integral of the electron pressure (i.e., \( \Delta T_{\text{SZ}} \propto n_e T_e \)), where \( n_e \) is the electron density and \( T_e \) is the electron temperature) along the line of sight and is independent of distance. Galaxy clusters are massive structures permeated by hot, dense ionized gas that preserves the same cosmic baryonic fraction of the epoch of the cluster virialization, so they are the ideal targets for SZ effect observations and to infer pieces of information about cosmology.

The absolute X-ray luminosity from the hot cluster gas has a different dependence on gas properties (i.e., \( L_X \propto n_e^{2/3} T_e^{1/2} \)) and is dependent on the cluster redshift. For virialized clusters, where the distribution of density and temperature is easy to model with regular forms (e.g., isothermal and spherically symmetric), the different distance dependence provides a powerful method for extracting cosmological parameters by combining the two signals (Cavaliere et al. 1979; Cooray 1999; Carlstrom et al. 2002; Molnar et al. 2002).

The comparison of the two signals is also a particularly effective tool to estimate the gas mass, but the different dependence on density makes X-ray more susceptible to the gas clumping factor \( C = (n_e^{2/3}/n_e) \) that may be \( \gg 1 \) at high redshift. The SZ effect signal is a better tracer of less dense hotter region.

Current theories of structural formation predict that clusters form hierarchically via the merger of smaller structures (Borgani & Guzzo 2001). X-ray observations (Jeltema et al. 2005; Maughan et al. 2008) of high-redshift \((z \gtrsim 0.5)\) clusters revealed that they are more morphologically complex, less virialized, and dynamically more active than low-redshift clusters. Studies of \( z > 0.8 \) clusters show clumpy and elongated structures that suggest that they are close to the epoch of cluster formation (Rosati et al. 2004).

The study of the high-redshift cluster SZ effect can provide constraints on the theories of cluster formation and evolution. However, for these objects the temperature and density distributions might be so complex that the comparison of X-ray and SZ effect signals is seriously compromised. If this is the case, the information about cosmology or cluster evolution will be misleading.

In this Letter, we present the first subarcminute resolution 18 GHz observations of the SZ effect with the Australia Telescope Compact Array (ATCA) using the new wide bandwidth 4 GHz correlator (Ferris & Wilson 2002) for a high-redshift cluster. The properties of the cluster and a summary of its existing observations in radio, optical, and X-ray are described in Section 2. In Section 3 we present our new observations. Their comparison with other bands and the implications of our results are discussed in Section 4. To estimate distances we have adopted a flat \( \Lambda \) CDM cosmology with \( \Omega = 0.73 \) and \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. CL J0152–1357

CI J0152–1357 is one of the most massive \((M_{\text{tot}} = 1.1 \times 10^{15} M_\odot)\) galaxy clusters known at high redshift \((z \approx 0.83)\). It was discovered independently in the Wide Angle ROSAT Pointed Survey (Scharf et al. 1997; Ebeling et al. 2000), in the ROSAT Deep Cluster Survey (Della Ceca et al. 2000), and was also cataloged in the Bright SHARC survey (Romer et al. 2000).
X-ray images from BeppoSax (Della Ceca et al. 2000), Chandra, and XMM (Maughan et al. 2003 and 2006; Huo et al. 2004), optical images (Ellis & Jones 2004; Girardi et al. 2005; Demarco et al. 2005; Kodama et al. 2005; Jørgensen et al. 2005; Burbidge et al. 2006), IR images (Maughan et al. 2006; Marcillac et al. 2007), and weak lensing (Jee et al. 2005) observations all show a complex structure that appears to be far from virialized.

The cluster contains two main subclumps, 95 arcsec apart (corresponding to ~723 kpc), and several other smaller structures that may be merging. The two main subclumps are aligned in the NE–SW direction (and for this reason we will call them “NE” and “SW”). X-ray temperatures (Maughan et al. 2003) indicate that they have quite similar total masses, but the gas in the NE one may be more extended and slightly more massive than in the SW subclump. There is a suggestion in the X-ray of the presence of an excess of emission in the region in between them, possibly indicating that the two clumps are interacting and merging.

It has already been noted that the peaks of the galaxy mass distribution do not coincide with the X-ray emission peaks (Huo et al. 2004). The weak lensing signal shows a clumpy mass distribution (Jee et al. 2005). It generally agrees with the galaxy distribution and with some but not all the X-ray peaks. They note small displacements between the mass distribution and X-ray peaks and suggest this is further evidence for merging. Furthermore, a third smaller subclump in an SE region (see Girardi et al. 2005) may provide further possible explanations to these observations.

Burbidge et al. (2006) found a QSO at the same redshift 14 arcsec away (~6.45 Mpc) toward the northeast, indicating that this cluster is part of a much larger scale structure. A similar indication comes from the Subaru wide field imaging of the cluster field by Kodama et al. (2005).

Redshift distributions of the galaxies (Demarco et al. 2005) in the cluster region show that all the galaxies in the region of the X-ray clumps lie at z ≃ 0.83, but there is another group of galaxies at z ≃ 0.64 along the same line of sight to the cluster.

The cluster SZ effect was detected by Joy et al. (2001) with the Berkley–Illinois–Maryland Association millimeter interferometer at 28.5 GHz with a 2.4 ± 0.32 mJy beam−1 peak and a resolution of 151″ × 88″. This detection did not have high enough angular resolution to observe the effects of internal structure in this cluster. For the northern subclump of this cluster, Zemcov et al. (2007) may have detected the SZ increment from the SCUBA data at 350 GHz.

3. RADIO-FREQUENCY OBSERVATIONS

In 2005, we had a 24 hr observation with the “old” ATCA in its most compact configuration, Hybrid H75, with baselines from 30 to 75 m. In this experiment, we used two adjacent 128 MHz bands at 18.5 GHz. The primary beam FWHM was ≃2.4 arcmin with an angular resolution of 33″ × 33″. We made a mosaic of two pointings with centers on the X-ray position of each of the subclusters (NE 01h52m44s18, −13°57′15″.84; SW: 01h52m39.89; −13°58′27.48″). We detected at a low significance level (signal-to-noise ratio equal to 3.5) a negative peak in the region of the NE subclump, but ~35 arcsec displaced toward the northwest from the position of the X-ray peak. A 1.5σ dip at the position of the second main subclump suggests that the SZ peak of SW subclump may be in the region of its X-ray-expected position.

After the upgradation of the correlator of the ATCA to the new Compact Array Broadband Backend digital correlator in 2009 July (Ferris & Wilson 2002), we performed a new observing run with the same H75 configuration, but with 2 × 2 GHz adjacent bands in two orthogonal polarizations (i.e., an 8 GHz total bandwidth) between 16 and 20 GHz. The angular resolution is 35″ × 35″ (FWHM). We observed 27 hr on the position of the NE X-ray peak. The negative peak is −118.6 ± 11.53 μJy (i.e., signal-to-noise ratio 10.3) in the position 01h52m42.661−13°56′36″.40 (see Figure 1). The single pointing was chosen to optimize our sensitivity to check the possible displaced SZ effect signal seen in the previous observations of the NE subclump at the sacrifice of good sensitivity in the SW subclump region. Future deeper observations will be carried out to investigate the SW subclump.

Figure 2 shows the ATCA SZ effect image with X-ray contours by Maughan et al. (2006) superimposed. Figure 3 shows the same ATCA image with the galaxy density contours superimposed (Maughan et al. 2006).

The analysis of the signal on the ATCA longest spacings at 20 GHz (~0.5 arcsec resolution) did not show the presence of any compact active galactic nucleus (AGN) emitting above the noise level in the cluster region. We also observed for 3 hr at 1.4 GHz with a 35 arcmin FWHM field of view. The image has an rms of 4.8 mJy beam−1 and does not show any AGNs or diffuse emission within 2.5 arcmin of the cluster center. As pointed out in the literature (e.g., for the “bullet” cluster 1ES 0657–56, see Liang et al. 2000 and references therein) merging clusters often show non-thermal radio relics or haloes due to synchrotron emission in the region of the merging front. Since we observe no trace of any of these structures, we have no supporting evidence for strong merging in this system. We see two radio sources in our 1.4 GHz image which agree in position with NVSS sources. There are also weaker NVSS sources identified with X-ray AGN nearer the cluster center but too weak to affect our 18 GHz observations. Positions agree between all these sources.

4. DISCUSSION

4.1. The Comparison With Other Bands

From Figure 2 it is clear that the SZ effect from the NE subclump is shifted ~45 arcsec (~342 kpc) toward the north with respect to the X-ray peak of emission and is about
30 arcsec west of the main galaxy concentration (see Figure 3). A similar offset of the SZ effect has been recently seen in the “bullet cluster” by Malu et al. (2010) and by Mason et al. (2010) in RX J1347–1145.

In a relaxed structure, the shape of the gravitational potential close to the center of the mass distribution will determine both the X-ray and the SZ effect distribution. Hence, we expect the signal from the SZ effect and the free–free X-ray emission from the intracluster medium to peak in the same position. The position of the maximum SZ effect (ΔT ∝ n_e T_e) should trace the position of the gas pressure peak of this subclump, but the X-ray (free–free) emission (L_X ∝ n_e^2 T_e^{3/2}) is displaced 45 arcsec to the southeast. The X-ray emission agrees more closely with the weak-lensing-based mass distribution (Jee et al. 2005) so we need to explain this difference.

The angular resolution of both the X-ray and radio images is sufficient to resolve the offset structures, so the displacement cannot be a resolution effect. We also know from the agreement in radio and X-ray positions through detections of NVSS sources that the two coordinate systems are aligned to at least arcsecond accuracy.

The foreground group of galaxies at z ∼ 0.6 could affect the X-ray emission more than the SZ effect, because it is closer, but it is a relatively low-density group with a larger scale N–S distribution (see Figure 4 in Demarco et al. 2005) not clearly related to the observed X-ray emission. We thus consider it unlikely that the foreground structure is responsible for the observed SZ effect–X-ray offset.

The cluster is very dynamically complex, with five apparent X-ray clumps at the same redshift (Maughan et al. 2006). The NE subcluster appears to be at the intersection of two merger axes (suggested by the distribution and morphology of the X-ray emission and also discussed in Kodama et al. 2005), and may have undergone mergers along one or both axes recently. It is thus likely that the observed SZ effect–X-ray displacement is due to the impact of this merger activity on the distributions of electron density and temperature in the NE subclump region, related to this merger activity.

The X-ray surface brightness is extended toward the northwest of the system, across the SZ effect minimum, and the X-ray surface brightness residuals (after subtracting the best fitting elliptical β-models to the four main X-ray components; see Maughan et al. 2006 for details) show excess X-ray emission coincident with the SZ effect minimum. This suggests that the gas density in this region is higher than would be expected from those simple models. However, the X-ray surface brightness is still significantly lower than the NE subcluster peak (implying a significantly lower gas density), so a significantly higher gas temperature than that at the X-ray peak is required to explain the SZ effect minimum at this position.

In fact, the current X-ray data suggest a temperature at the SZ effect minimum that is similar to or lower than that at the NE X-ray peak (Maughan et al. 2006, Figure 10). However, it should be noted that the X-ray data are not deep enough for detailed spectral analysis in this region. If there were shock heating in the region of the SZ effect minimum due to a recent merger, then it is plausible that there is a mixture of cooler gas associated with the cluster and much hotter gas (including possibly very hot ∼20 keV gas that is hard to detect with XMM or Chandra as shown for the “bullet” cluster by Markevitch et al. 2002) associated with the merger, projected along the line of sight. Depending on the densities of these components, the X-ray and the SZ effect could respond very differently, with the hotter components going undetected in the current X-ray data. This, along with the relatively poor X-ray statistics in this region, could explain the lack of evidence for enhanced pressure at the SZ effect peak in the XMM data.

It is possible that an AGN, rather than a merger shock, could have locally heated the gas in the region of the SZ effect minimum. However we have no indication of either X-ray or radio AGN in this region, and the only cluster galaxies in the region are subluminous so this seems unlikely.

Thus, having ruled out astrometric errors and the influence of the foreground structure, we consider the most likely cause for the SZ effect–X-ray offset in this system to be the strong effect of merger activity in the system on the gas properties.
violent cluster merger has been considered the most plausible explanation for similar displacements between X-ray and high-resolution SZ signals observed in the bullet cluster (Malu et al. 2010) and in RX J1347−1145 (Kitayama et al. 2004). In the case of Cl J0152−1357, the offset could be due to the passage of a smaller clump (e.g., the one to the SE) through the denser NE clump. Maughan et al. (2006) suggested that an interaction along the NE–SW merger axis happened more recently than a merger with the SE group, relying on the fact that the projected separation of the substructures associated with the NE peak is much smaller than the separation between NE and SE subclumps, and because the X-ray morphology appears more disrupted along this NE–SW axis in the northern subcluster. However, the passage of the SE subclump through the NE one would destroy the equilibrium in the NE clump and could generate regions of shocked gas causing excess X-ray emission on one side (including also an elongation of the NE X-ray peak toward north, perpendicular to the crossing direction).

Deeper high-resolution SZ (including the SW peak) and X-ray observations, along with simulations of different merger scenarios, are planned in order to build a more conclusive description for the dynamics of this cluster.

4.2. The Impact on Cosmology

A clear consequence of our finding is that any cosmological conclusion based on the assumption that the SZ effect and the X-ray emission result from the same relaxed gas distribution could be wrong for clusters at high redshift like Cl J0152−1357. Low resolution SZ effect data do not allow the proper density and temperature distribution to be disentangled, with the risk that if the peak of the signal is blindly associated with the X-ray peak, an error in the estimation of cosmological parameters is introduced.

The cosmological parameters are usually estimated by comparing the angular diameter distance $D_A$ as estimated by the X-ray and the SZ effect. In order to determine the distance, it is necessary to properly model the structure of the intracluster medium, to connect the quantities determined among integrations along the cluster line of sight with the cluster appearance on the plane of the sky: typically isothermal and spherically symmetric density distributions are assumed in order to extract $D_A$ and cosmological parameters. The failures of the assumptions for several reasons—including mergers, asphericity, clumpiness, and non-isothermality—induce errors on the cosmological parameters, which increase with redshift: numerical simulations (Molnar et al. 2002; Yoshikawa et al. 1998; Inagaki et al. 1995; Roettiger et al. 1997; Mohr et al. 1999) have demonstrated that at $z \sim 1$ the cumulative effective of non-isothermality and asphericity, almost negligible at low redshift, can introduce an error of up to 20% in the estimation of the angular diameter distance and that the assumption of isothermality for merging subclusters overestimates $D_A$ by 15%–20%. The error introduced by the offset we observed is likely to be much larger.

The error is larger, the farther from virialization, hence clusters at higher redshift, which exhibit less virialized structures than local ones, could be more seriously affected. This has implications also on the studies of cluster evolution, because estimates of barionic mass and intracluster medium properties might be wrong.

In conclusion, we stress the importance that only virialized clusters can be of use for deriving cosmological parameters. Furthermore, wherever X-ray observations indicate that the structure of the cluster is not yet relaxed, the high-resolution SZ effect data are a powerful tool for the analysis of the cluster properties. In combination with X-ray observations of free–free emission it may provide a powerful tool to study the effects of shocks and other phenomena which will be important for our understanding of the evolution of galaxy clusters.

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