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SUBMILLIMETER DETECTION OF THE SUNYAEV-ZELDOVICH EFFECT TOWARD THE MOST LUMINOUS X-RAY CLUSTER AT $z = 0.45$

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ABSTRACT

We report on the detection of the Sunyaev-Zeldovich (SZ) signals toward the most luminous X-ray cluster RX J1347−1145 at the Nobeyama Radio Observatory (21 and 43 GHz) and with the James Clerk Maxwell Telescope (350 GHz). In particular, the latter is the first successful detection of the SZ temperature increment in the submillimeter band that resolved the profile of a cluster of galaxies. Both the observed spectral dependence and the radial profile of the SZ signals are fully consistent with those expected from the X-ray observation of the cluster. The combined analysis of the 21 and 350 GHz data reproduces the temperature and core radius of the cluster that are determined with *ROSAT* and *ASCA* when we adopt the slope of the density profile from the X-ray observations. Therefore, our present data provide the strongest and most convincing case for the detection of the submillimeter SZ signal from the cluster as well as in the Rayleigh-Jeans regime. We also discuss briefly the cosmological implications of the present results.

Subject headings: cosmic microwave background — cosmology: observations — distance scale — galaxies: clusters: individual (RX J1347.5−1145) — X-rays: galaxies

1. INTRODUCTION

The Sunyaev-Zeldovich (SZ) effect (Zeldovich & Sunyaev 1969; Sunyaev & Zeldovich 1972), which is a change in the apparent brightness of the cosmic microwave background toward a cluster of galaxies, provides important probes for cluster gas properties, the global cosmological parameters, and the peculiar velocity field on large scales (see, e.g., Silk & White 1978; Sunyaev & Zeldovich 1980; Rephaeli & Lahav 1991; Kobayashi, Sasaki, & Suto 1996; Yoshikawa, Itoh, & Suto 1998; Birkinshaw 1999). While the temperature decrement due to the SZ effect is observed for tens of clusters in the Rayleigh-Jeans regime, there is no unambiguous SZ detection in the Wien region (i.e., the submillimeter band) where the apparent brightness increases. Andreani et al. (1996, 1999) and Holzapfel et al. (1997) reported the detection of the SZ temperature increment of the clusters RX J0658−5557 and A2163, respectively, at the wavelength $\lambda = 1.1$–1.2 mm. Although their total fluxes are consistent with the SZ signals from the clusters, it is not clear to what extent the obtained signals are affected by other possible contaminations, including the dust in our Galaxy and submillimeter sources in the cluster field (Smail, Ivison, & Blain 1997; Hughes et al. 1998). This question also applies to a recent claim of the submillimeter SZ detection (Lamarre et al. 1998) toward A2163 that is based solely on the spectral dependence because its beam size is very large ($2'$–$3'$).

This simply implies that the mapping observation of the SZ effect is essential. At centimeter wavelengths, more than a dozen of the clusters have been mapped already with interferometers, but this technique is not yet feasible at submillimeter bands. In the present Letter, we describe our successful SZ mapping observation of the X-ray cluster RX J1347−1145 ($z = 0.45$) at 350 GHz (0.85 mm) with the Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) as well as the scanning observations (at 21 and 43 GHz) at the Nobeyama Radio Observatory.

2. OBSERVATION OF THE SZ EFFECT TOWARD RX J1347−1145 AT CENTIMETER, MILLIMETER, AND SUBMILLIMETER BANDS

2.1. *The Target Cluster RX J1347−1145*

ROSAT and *ASCA* revealed that RX J1347−1145 at $z = 0.45$ is the brightest X-ray cluster of galaxies observed so far (Schindler et al. 1997). With the additional *ROSAT*/HRI data acquired recently, the total exposure time of the cluster in the X-ray observation of RX J1347−1145 is now 36.5 ks. We have reanalyzed the new X-ray radial profile and found that it is well fitted by the isothermal β model:

$$I_{\rm X}(\theta) \propto n_{e0}^2 \theta_c [1 + (\theta/\theta_c)^2]^{1/2-3\beta}, \quad (1)$$

with the following parameters: the central electron density $n_{e0} = (9.3 \pm 0.4) \times 10^{-2}$ cm^{-3}, the core radius $\theta_c = 8\farcs4 \pm 1\farcs0$, and $\beta = 0.57 \pm 0.02$, where quoted errors represent 90% statistical uncertainties (unless otherwise stated, we assume $H_0 = 50$ km s^{-1} Mpc^{-1} and $\Omega_0 = 1.0$ with vanishing cosmological constant $\lambda_0 = 0$). Since the corresponding SZ radial profile is given by

$$I_{\rm SZ}(\theta) \propto T_e n_{e0} \theta_c [1 + (\theta/\theta_c)^2]^{1/2-3\beta/2}, \quad (2)$$

the cluster is definitely an ideal SZ target because of its unusually large central density and high temperature, $T_e = 9.3^{+1.1}_{-1.0}$ keV (Schindler et al. 1997). In addition, its small core radius should enable us to map the radial profile at 350 GHz within the field of view ($160''$) of the SCUBA while retaining a reasonable angular resolution (the beam size $\sigma_{\rm FWHM}$ of SCUBA is $15''$). This is the reason why we selected the cluster

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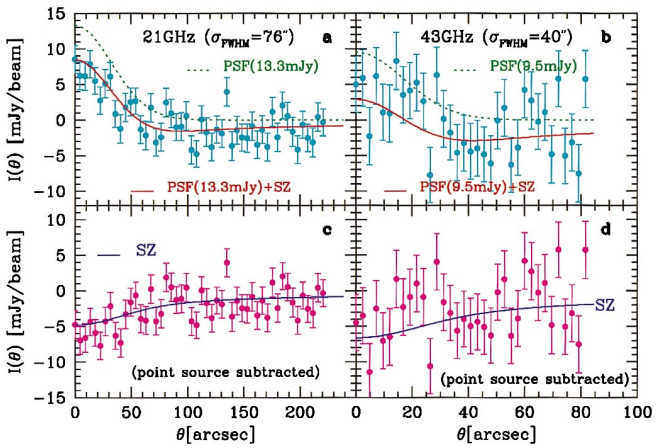

FIG. 1.—Radial intensity profile toward RX J1347 at 21 GHz (*left panels*) and 43 GHz (*right panels*) observed at NRO. The lower panels show the data in which the estimated contribution of the central radio source (13.3 mJy at 21 GHz, and 9.5 mJy at 43 GHz plotted in green dotted lines) is subtracted. The filled circles indicate our data with 1 σ error bars. The red (blue) solid lines in the upper (lower) panels are the prediction of the signal with (without) the point-source contribution using the best-fit parameters in the X-ray observation.

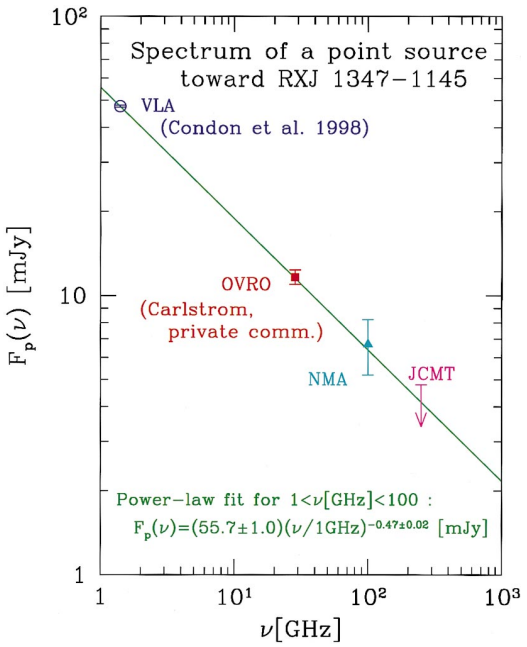

FIG. 2.—Spectrum of the central radio source. The data labeled NMA are the average of the results at 93 and 105 GHz.

RX J1347−1145 as our SZ target at 350 GHz with the JCMT/SCUBA as well as at 21 and 43 GHz at the Nobeyama Radio Observatory (NRO).

2.2. *The* 21 *and* 43 GHz *Observation with the Nobeyama* 45 m *Telescope*

First we observed RX J1347−1145 at 21 (43) GHz with the HEMT amplifier (SIS mixer) mounted on the Nobeyama 45 m telescope between 1998 March 3 and 15. The observation was performed in the cross-scan mode with a 4′ and 45″ chop throw in azimuth, and NGC 7027 was used to calibrate the flux (estimated calibration error is less than 10%). The total exposure time is 16.2 (14.4) ks, and the beam size of the point-spread function (PSF) is $\sigma_{\rm FWHM} = 76''$ (40″), at 21 (43) GHz. To cut the lower frequency noise that is due to the sky variation, the data were high-pass–filtered with a time constant of 30 (21) s, and then integrated and averaged over radial bins. The resulting radial profiles of the cluster at 21 and 43 GHz (the upper panels in Fig. 1) indicate the presence of a point source near the cluster center, in addition to the SZ signal. In fact, the radio source was also detected in the National Radio Astronomy Observatory 1.4 GHz sky survey (Condon et al. 1998) and in the Owens Valley Radio Observatory serendipitous survey of the SZ effect at 28.5 GHz (Cooray et al. 1998; J. E. Carlstrom 1998, private communication). The former suggests that the radio source is located at (α, δ) = ($13^{\rm h}47^{\rm m}30\overset{\rm s}{.}67$, −11° 45′ 8″.6) (J2000). This is 2″.08 away from the optical center ($13^{\rm h}47^{\rm m}30\overset{\rm s}{.}54$, −11°45′9″.4), which is defined as the location of the central galaxy. This 2″ offset is within a relative positional error between our radio frame (Johnston et al. 1995) and the optical frame (MacGillivray & Stobie 1985) adopted in Schindler et al. (1995).

Since the accurate flux of the point source is crucial for properly extracting the SZ signal, we observed the central source at 93 and 105 GHz simultaneously with the Nobeyama Millimeter Array (NMA) between 1998 May 19 and 21 (15 hr exposure at each frequency) and at 250 GHz in the photometry mode of SCUBA (Holland et al. 1998) on 1998 May 30 and 3 (2 hr exposure). Since the thermal SZ effect vanishes at around 250 GHz (Rephaeli & Lahav 1991), the latter signal, if any, is expected to be dominated by the point source. We detected the point-source flux of 5.0 ± 1.5 mJy at 100 GHz, while the 250 GHz observation placed a 2 σ upper limit of 4.8 mJy. These results are summarized in Figure 2. We have corrected the point-source fluxes for the SZ decrement at the corresponding frequency, although the contamination is comparable to or less than the quoted 1 σ error bars in Figure 2.

We fitted the three data of the point source at $\nu \le 100$ GHz to a single power law:

$$F_p(\nu) = (55.7 \pm 1.0)(\nu/1\ \text{GHz})^{-0.47\pm0.02}\ \text{mJy}, \qquad (3)$$

where the quoted errors represent 1 σ. Since equation (3) yields a fairly accurate approximation for the flux at 21 and 43 GHz, we subtract the corresponding contribution of the point source from our data. Most radio sources with a spectrum index less than ~0.5 are known to exhibit a small amount of time variation (Eckart, Hummel, & Witzel 1989). Therefore, it is unlikely that the total flux estimated from equation (3) varies significantly because of the possible variability of the source. The corrected radial profiles of the cluster plotted in the lower panels of Figure 1 clearly exhibit an extended negative intensity that is characteristic of the SZ signal. They are quite consistent with those expected from the X-ray observation, especially at 21 GHz where the signal-to-noise ratio is significantly higher than at 43 GHz.

2.3. *The* 350 GHz *Observation with JCMT/SCUBA*

We observed the cluster at 350 GHz with SCUBA in the jiggling mode on 1998 May 30 and 31. Unfortunately, the weather conditions during our observation were bad (the zenith optical depth at 350 GHz ranged around $\tau_{350} = 0.46$–0.60). The observation was performed over 64 independent points over the sky that were spaced 3″.09 from each other with a 120″ chop throw in azimuth. A total exposure time amounts to 18.6 ks. The primary flux calibration and beam measurement were

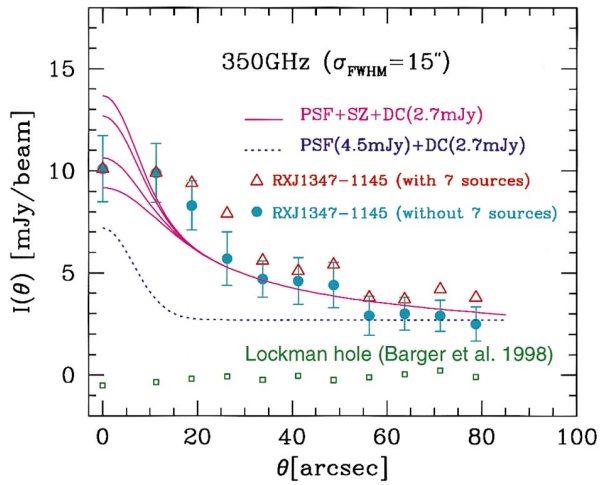

FIG. 3.—Radial intensity profile toward RX J1347 at 350 GHz observed at JCMT/SCUBA. The open triangles (filled circles) indicate our data with (without) the seven spurious sources described in the text. The 1 σ error bars are shown only for the latter. The solid curves plot the SZ profiles from the best-fit parameters in the X-ray observation and the point-source contribution with F_p = 4.5 mJy (a conservative 2 σ *upper* limit from eq. [3]), 3.5 mJy (extrapolated from eq. [3]), 1.5 mJy (best fit in Table 1), and 0 mJy (*from top to bottom*). We applied the identical reduction procedure to the Lockman Hole data (Barger et al. 1998), and the results are plotted in small squares for reference (the 1 σ error is smaller than the size of the symbol itself). The dotted curve shows the PSF of a 4.5 mJy source with a 2.7 mJy DC offset.

carried out using Uranus, and the secondary calibrations were performed at the beginning and the end of each observation using IRC +10216 and 16293−2422, respectively, to check the stability of the gain. The resulting PSF has a beam size of $\sigma_{FWHM} = 15''$, and the calibration error is less than 15%. The beam profile was approximately Gaussian, but our analysis takes account of the effect of the residual beam wing as well.

First we analyzed the raw data using REMSKY (Jenness, Lightfoot, & Holland 1998) in the SURF package (Jenness & Lightfoot 1998) in order to remove spatially correlated sky noise. With REMSKY, we subtract the sky noise at each integration from the entire map using the median value of the bolometers (except for very noisy ones). Therefore, the zero level of the resulting map after all integrations is still uncertain depending on the sky condition. We estimated the 1 σ error of our base level or DC offset to be as large as 2.9 mJy beam^{-1} because of the bad weather conditions. Then the data were reduced and converted to the image using SURF, version 1.2. The resulting image turned out to contain several bright point sources in the field. We detected seven spurious contamination sources above a threshold of 3 σ using the SExtractor package (Bertin & Arnouts 1996). While some of them might simply be due to the sky noise, others could be real sources; in fact, the previous SCUBA deep surveys toward clusters of galaxies (Smail et al. 1997, 1998) and blank fields (Hughes et al. 1998; Barger et al. 1998) detected many submillimeter sources in their fields (but with less than 10 mJy typically). Since it is premature to discuss further the reality of the "sources" at this point, we consider the cases with and without the seven sources, separately.

The radially averaged profile of the image is plotted in Figure 3. We confirmed that the presence of the extended feature, which is comparable to the cluster extension, is robust, even when retaining the seven sources. In this plot, we adopted the cluster center as the position of the optical center. It should be noted that the error bars in the inner annuli are smaller than those in the outer annuli, despite the smaller effective area. This is true for the following reason: several noisy bolometers, located at the outer annuli, contribute significantly to the noise level of the corresponding annuli. Thus, the noise level is in fact dependent on the angular radius. These complex noise properties of the SCUBA should be kept in mind when interpreting the result below.

TABLE 1

SUMMARY OF THE BEST-FIT PARAMETERS AT 350 GHz

Seven Sources	SZ	F_p (mJy)	I_{DC} (mJy beam^{-1})	Reduced χ^2
No	No	7.4	4.0	3.6
Yes	No	6.1	5.1	3.6
No	Yes	1.5	2.7	0.73
Yes	Yes	0.2	3.8	0.79

In fitting our observed profile to the model prediction at 350 GHz, we have to take account of the DC offset mentioned above, I_{DC}, and the possible contribution of the central point source F_p. In what follows, we mainly consider three values for the point flux so as to take into account the associated uncertainties: F_p = 3.5 mJy (extrapolated from eq. [3]), 4.5 mJy (a conservative 2 σ *upper* limit from eq. [3]), and 0. We adopt the latter since many radio sources are known to exhibit a steep decline of flux around submillimeter bands (see, e.g., Gear et al. 1994). Incidentally, F_p = 4.5 mJy is similar to the flux level reported for the submillimeter emission from two central galaxies in luminous X-ray clusters (Edge et al. 1999). Thus, the analysis using F_p = 4.5 mJy may also be useful in understanding the effect of the possible dust emission from the central galaxy. Then we always treat the DC offset as a free-fitting parameter. Note that the central feature of our data is significantly more extended than the PSF of the beam, even for the case with F_p = 4.5 mJy (*blue dotted curve* in Fig. 3). The best-fit parameters for F_p and I_{DC} are listed in Table 1, together with the corresponding value of the reduced χ^2. Table 1 indicates that the fit is unacceptable without including the SZ profile, while the agreement with the SZ profile is insensitive to the seven sources.

We applied the same reduction procedure for the Lockman Hole data with SCUBA (Barger et al. 1998) and found no central extended signal or significant DC offset. This confirms that our signal profile does not suffer from any systematic effects in the reduction procedure. In addition, it supports our suspicion that our large DC offset is due to the relatively large sky noise during our observing run; our and their noise levels are typically 8 and 0.8 mJy beam^{-1}, respectively.

We repeated the similar fitting analysis at 21 and 43 GHz as well. The results are summarized in confidence contours on the T_e-θ_c plane (Fig. 4). Figures 4*a*–4*c* indicate that the profile in each band is consistent with the other profiles and is actually in good agreement with the parameters estimated from the X-ray observation. The combined data analysis at 21 and 350 GHz further improves the agreement and puts more stringent constraints on T_e and θ_c (Fig. 4*d*). Therefore, our present data provide the strongest and most convincing case for the detection of the submillimeter SZ signal from the cluster as well as in the Rayleigh-Jeans regime.

3. DISCUSSION

The detection of the SZ signals in multibands for one particular cluster has important cosmological implications; com-

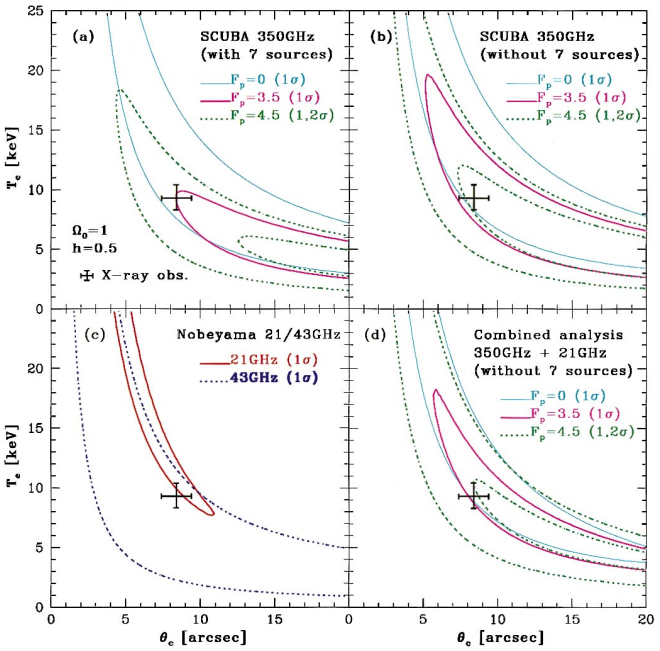

FIG. 4.—Confidence contours on the gas temperature T_e and the core radius θ_c from the SZ data analysis, assuming $\Omega_0 = 1.0$ and $h = 0.5$ for definiteness. The cross indicates the parameters determined from X-ray observations with *ROSAT* and *ASCA*. (*a*) The 350 GHz data with the seven spurious *sources* described in the text; (*b*) the 350 GHz data without the seven spurious sources; (*c*) the 21 and 43 GHz data; and (*d*) the combined analysis with the 21 and 350 GHz (without the seven spurious sources) data. In (*a*), (*b*), and (*d*), we adopt $F_p = 0$ mJy (*thin solid curve*), $F_p = 3.5$ mJy (*thick solid curve*), and $F_p = 4.5$ mJy (*thick dotted curve*) for the flux of the point source at 350 GHz as explained in the text.

bining our X-ray, 21 and 350 GHz data of RX J1347, we estimated the angular diameter distance at $z = 0.451$ as $1897 \pm 317 \pm 246$ Mpc, assuming $F_p = 3.5$ mJy and the spherical symmetric profile of the cluster (Silk & White 1978; Kobayashi et al. 1996; Birkinshaw 1999). The first and second quoted errors come from the uncertainties of the observed SZ intensity and of the parameters from the X-ray observation, respectively. This angular diameter distance is translated into $H_0 = 37 \pm 6 \pm 5$ and $44 \pm 7 \pm 6$ km s^{-1} Mpc^{-1} for $(\Omega_0, \lambda_0) = (1.0, 0.0)$ and (0.3, 0.7), respectively. While the estimates still have fairly large errors compared with those from optical observations, it is encouraging that they fit in a reasonable range, and we expect to improve the estimates by observing the cluster again (hopefully in much better weather conditions). Then it will be feasible to separate the kinematic and thermal SZ effects by a simultaneous fit to the 21 and 350 GHz data, which will yield an estimate of the peculiar velocity of the cluster (Rephaeli & Lahav 1991; Yoshikawa et al. 1998; Birkinshaw 1999).

In the above discussion, we have neglected several issues that, in principle, could affect our interpretation of the detection of the SZ signal from the cluster, including a possible variability of the central point source, a nonsphericity and nonisothermality (Yoshikawa et al. 1998; Makino, Sasaki, & Suto 1998; Suto, Sasaki, & Makino 1998; Yoshikawa & Suto 1999), a cooling flow (Fabian 1994; Allen 1998; Allen & Fabian 1998), a contribution of submillimeter dust (Lamarre et al. 1998; Edge et al. 1999), unresolved lensed sources, and a peculiar velocity of the cluster. To some extent, these would definitely contribute to putting additional uncertainties on the best-fit parameters of the cluster. Nevertheless, it is almost impossible to explain both the spectral dependence in three bands and the radial profile in each band simultaneously by the combination of those effects alone without the SZ effect, as clearly demonstrated in Figure 4. Detailed analysis that takes into account those issues will be presented elsewhere (Komatsu et al. 1999).

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