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A SUNYAEV-ZELDOVICH MAP OF THE MASSIVE CORE IN THE LUMINOUS X-RAY CLUSTER RX J1347−1145

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ABSTRACT

We have mapped the Sunyaev-Zeldovich (SZ) decrement in the direction of the most luminous X-ray cluster known to date, RX J1347−1145, at $z = 0.451$. This has been achieved with an angular resolution of about 23″ using the Diabolo photometer running on the IRAM 30 m radio telescope. We present here a map of the cluster central region at 2.1 mm. The Comptonization parameter toward the cluster center, $y_c = (12.7^{+2.9}_{-3.1}) \times 10^{-4}$, corresponds to the deepest SZ decrement ever observed. Using the gas density distribution derived from X-ray data, this measurement implies a gas temperature of $T_e = 16.2 \pm 3.8$ keV. The resulting total mass of the cluster is, under hydrostatic equilibrium, $M(r < 1\ \mathrm{Mpc}) = (1.0 \pm 0.3) \times 10^{15}\ M_\odot$ for a corresponding gas fraction $f_{\rm gas}(r < 1\ \mathrm{Mpc}) = 19.5\% \pm 5.8\%$.

Subject headings: cosmic microwave background — cosmology: observations — galaxies: clusters: individual (RX J1347−1145) — intergalactic medium

1. INTRODUCTION

The hot intergalactic gas (10^6–10^8 K) is, with the galaxies themselves and the gravitational effects on background objects, one of the tools used to derive mass distributions within clusters of galaxies. It can be detected at X-ray wavelengths via its bremsstrahlung emission. From submillimeter to centimeter wavelengths, the cosmic microwave background (CMB) blackbody spectrum is distorted in the direction of the cluster by the so-called Sunyaev-Zeldovich (SZ) effect (Sunyaev & Zeldovich 1972). This characteristic distortion is due to the inverse Compton scattering of the CMB photons by the intracluster electrons (see Birkinshaw 1999 for a detailed review on the SZ effect).

In this Letter, we report the SZ measurement of the X-ray cluster RX J1347−1145 with the ground-based Diabolo millimeter instrument. This cluster has been observed with the *ROSAT* PSPC and HRI instruments by Schindler et al. (1995, 1997). At a redshift of $z = 0.451$, it appears as the most luminous X-ray cluster ($L_{\rm Bol} = 21 \times 10^{45}$ ergs s^{-1}) and, so far, one of the most massive [$M_{\rm tot}^{\rm X\text{-}ray}(r < 1\ \mathrm{Mpc}) = 5.8 \times 10^{14}\ M_\odot$]. It is also a relatively hot and very dense cluster (temperature: $T_e = 9.3 \pm 1$ keV, central density: $n_0 = 0.094 \pm 0.004$ cm^{-3}). Optical studies of the gravitational lensing effects toward RX J1347−1145 have also been performed by Fischer & Tyson (1997) and Sahu et al. (1998). The results have pointed out a discrepancy between the total mass obtained from the optical and the X-ray data, with a surface lensing mass toward the core ($r < 240$ kpc) being 1–3 times higher than the X-ray mass estimates. Because the SZ effect also directly probes the projected gas mass, which is not the case for X-ray masses, the comparison with SZ measurements might help to discriminate between the optical and the X-ray determination.

In § 2, we describe the Diabolo instrument and our observations of RX J1347−1145. The data reduction is explained in § 3. The map of the cluster core is presented in § 4. The physical parameter values are extracted from the data analysis in § 5.

2. OBSERVATIONS

Diabolo is a millimeter photometer that provides an angular resolution of about 23″ when installed at the focus of the IRAM 30 m radio telescope at Pico Veleta, Spain. It uses two wavelengths channels centered at about 1.2 and 2.1 mm. The detectors are bolometers cooled at 0.1 K with an open cycle ^{4}He-^{3}He dilution refrigerator (Benoit et al. 1999). Two thermometers associated to a heater and a proportional-integral-derivative (PID) digital control system are used to regulate the temperature of the 0.1 K plate. There are three adjacent bolometers per channel, arranged in an equilateral triangle at the focus of the telescope. For a given channel, each bolometer is co-aligned with one bolometer of the second channel, both looking toward the same sky direction. Detections of the SZ effect have already been achieved with Diabolo on nearby clusters (A2163, 0016+16, and A665) with a single, large throughput bolometer per channel at 30″ resolution. The experimental setup is described in Désert et al. (1998). The only difference between the present configuration and the one described in Désert et al. is the increase in the number of bolometers per wavelength channel and the slight decrease of the beam FWHM from 30″ to 23″. With three bolometers at the focus of the telescope, there is no longer just one detector on the central optical axis. With the 30 m telescope focus being of Nasmyth type, the rotation of the field has to be taken into account in the reconstruction of the sky maps.

RX J1347−1145 has been observed in 1997 December. Our observations are pointed on the *ROSAT* HRI X-ray emission center reported by Schindler et al. (1997): $\alpha_{2000} = 13^{\rm h}47^{\rm m}31^{\rm s}$, $\delta_{2000} = -11°45'11''$. The observations have been performed using the wobbling secondary mirror of the IRAM telescope at a frequency of 1 Hz and with a modulation amplitude of 150″. An elementary observation sequence is a 120″ × 55″ map in right ascension, declination coordinates for a duration of 277 s each. This is obtained using the right ascension drift provided by the Earth rotation so that the telescope

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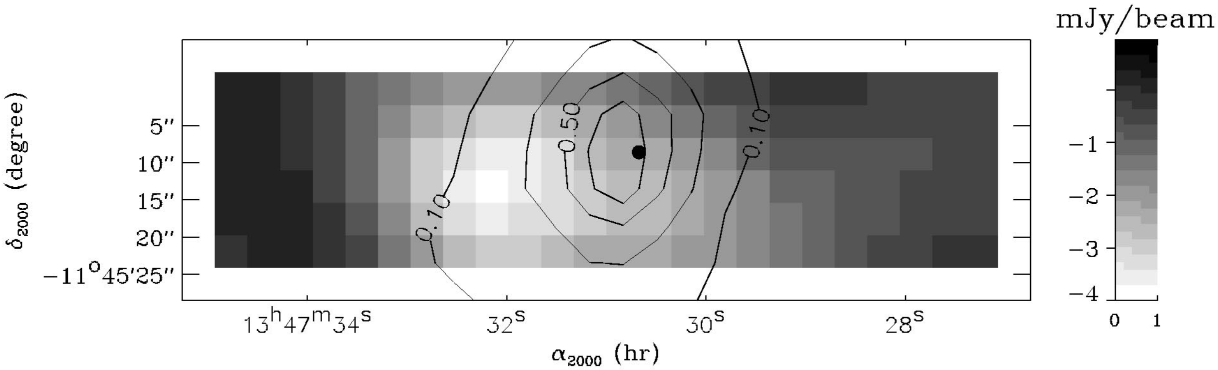

FIG. 1.—A 2.1 mm map of the RX J1347−1145 central region obtained with Diabolo. The map has been smoothed with a 25″ FWHM Gaussian filter. The 1 σ noise is about 1 mJy beam^{-1}. The X-ray contours have been overplotted. The filled circle indicates the radio source position.

could be kept fixed during the measurement. This was done to minimize microphonic noises and electromagnetic influences from the motors driving the IRAM 30 m antenna. The map of the cluster is obtained by stepping in declination between two consecutive lines. The line length is 120″ with a step of 5″. The wobbling is horizontal, and thus it is not aligned with the scan direction. However, the wobbling amplitude is large enough for the reference field to be always farther out of the cluster. In order to remove systematic signal drifts that are produced by the antenna environment, we used, alternatively, the positive and negative beam to map the cluster. We performed 208 such individual maps on the cluster, for a total duration of 16 hr.

Another target of Diabolo's 1997 run was the direction of the decrement detected at 8.44 GHz by Richards et al. (1997). We refer to this source as VLA 1312+4237 in the following. Richards et al. (1997) measured a flux decrement of -13.9 ± 3.3 μJy in a 30″ beam. The presence of two quasars in this direction led them to claim the possible existence of a cluster at a redshift of $z = 2.56$. Campos et al. (1999) have reported the detection of a concentration of Lyα-emitting candidates around the quasars. They argued that the probability for such a clustering to be random is 5×10^{-5}. Our pointing direction was $\alpha = 13^h12^m17^s$, $\delta = 42°37'30''$. We performed 287 individual maps on this target for a total time of about 20 hr.

3. DATA REDUCTION AND CALIBRATION

The reduction procedure includes the following main steps: (1) We remove cosmic-ray impacts. (2) A synchronous demodulation algorithm is applied, taking into account the wobbling secondary frequency and amplitude. (3) We remove from the 2.1 mm bolometer time line the signal that is correlated with the 1.2 mm bolometer that is looking at the same sky pixel. This correlated signal is mainly due to the atmospheric emission whose spectral color is very different from the SZ effect. (4) Correction for opacity is done from the bolometer total power measurements and its calibration by sky dips. (5) To eliminate the low-frequency detector noises, a baseline is subtracted from each line of the map. The baseline is a 1° polynomial. It is fitted to 60% of the data points: 30% at each end of the line. (6) Each map is then resampled on a regular right ascension/declination grid, taking into account the field rotation in the Nasmyth focal plane. (7) An average map is computed for each bolometer. Since the weather conditions were not permanently ideal, the noise quality of the individual maps is not homogeneous, particularly at 1.2 mm. We thus exclude from the average the maps in which the rms pixel-to-pixel fluctuation is larger than 1.5 times the median rms value of all the individual maps. (8) A single map is then produced for each channel (1.2 and 2.1 mm) by the co-addition of the three bolometer average maps.

During the run, pointing verifications and the mapping of reference sources have been performed. We have used the planet Mars as a calibration target. The apparent angular diameter of Mars was 5″, so that we can consider it as a point source with respect to Diabolo's beam. The accuracy of the absolute calibration obtained is on the order of 25% at 1.2 mm and 15% at 2.1 mm. Mars observations are also used for the characterization of Diabolo's beams. The measured FWHMs are 24″ and 22″ at 1.2 and 2.1 mm, respectively. Mars has been observed in an azimuth-elevation mapping mode with a scanning speed that is slower than the natural drift speed of the cluster observation mode. This later speed is fast enough compared with the wobbler period to spread the signal in the scanning direction (i.e., right ascension) significantly. The resulting beam FWHM for the cluster mode along this direction is 28″. It has been experimentally determined by the observation of a quasar lying at about the same declination as the cluster.

4. RESULTS

The final map of RX J1347−1145 at 2.1 mm is shown on Figure 1. The X-ray contours have been overplotted. The average right ascension profile at 2.1 mm is plotted in Figure 2. The profile obtained for the VLA 1312+4237 direction, using the same data processing, has been overplotted. The map and the profiles have been smoothed with a Gaussian filter of 25″ FWHM to maximize the signal-to-noise ratio. The 2.1 mm RX J1347−1145 map presents a very strong decrement. For a thermal SZ effect, this corresponds to a Comptonization parameter on the order of 10^{-3}. The decrement that we measure is not centered on the cluster X-ray maximum. We will show in the analysis that this effect can be explained by the superposition of the SZ decrement from the intracluster gas and a positive emission from a known radio source slightly shifted west off the cluster center.

We have no detection for the direction of VLA 1312+4237. Our 3 σ upper limit is $y < 1.5 \times 10^{-4}$. This is actually compatible with the decrement measured by Richards et al. (1997) that translates into a central Comptonization parameter on the

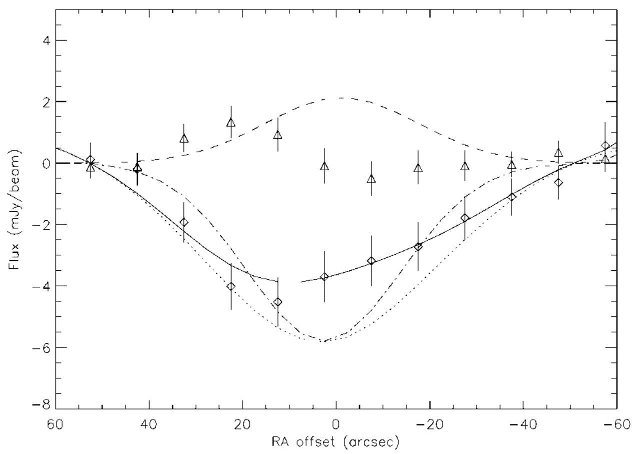

FIG. 2.—A 2.1 mm right ascension profile of RX J1347−1145 (data smoothed with a 25″ FWHM Gaussian). The data points have been plotted (*diamonds*) with their 1 σ error bars. The best-fit model (*solid line*) combines an SZ component (*dotted line*) with a point-source component (*dashed line*). The dot-dashed line draws a point-source profile with the same amplitude as the SZ effect. It shows that the decrement we observed is more extended than a point source. The VLA 1312+4237 average profile (no detection; see text) is shown with triangles.

order of 7×10^{-5} for a thermal SZ effect. If this decrement is in fact due to a kinetic SZ effect, then we expect a signal at 2.1 mm that is equivalent to a thermal SZ effect of $y_c = 1.4 \times 10^{-4}$, still within our 3 σ limit.

Actually, we have used the VLA 1312+4237 data set to obtain a reliable assessment of the error bars on RX J1347−1145. The individual maps have been averaged over increasing durations in order to evaluate the effective scatter of the average signal over independent data sets. The maximum duration that could be checked with this method is about 5 hr, corresponding to an average of 64 individual maps. We have checked that for all bolometers, the rms pixel noise scales as the square root of the integration time. The error bars extrapolated from this analysis to longer integration times are consistent with the error bars derived from the internal scatter of the data averaged for RX J1347−1145. The typical sensitivity reached in the 2.1 mm channel is on the order of 1 mJy in a 25″ beam.

5. DATA ANALYSIS

In the following, we have used for the intracluster gas density a spherical β-model with the parameter values derived from the X-ray analysis of Schindler et al. (1997): core radius $r_c = 8''.4$ (57 kpc), $\beta = 0.56$, central density $n_0 = 0.094\ \mathrm{cm}^{-3}$, and temperature $T_e = 9.3$ keV. We choose to cut off this distribution at a radial distance of $r_{\mathrm{cut}} = 15 r_c$. We assume the same cosmological parameters too, $H_0 = 50\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ and $\Omega_0 = 1$ ($\Lambda = 0$). With such a model, the measured SZ skymap reads

$$I(\bar{\nu}, \mathbf{\Omega}) = y_c \int \tau(\nu) \mathrm{SZ}(\nu, T_e) d\nu \int P(\mathbf{\Omega}) L(\mathbf{\Omega} - \mathbf{\Omega}') d\mathbf{\Omega}', \quad (1)$$

where $y_c = (k/m_e c^2)\, \sigma_{\mathrm{T}} \int T_e n_e(r) dl$ is the Comptonization parameter toward the cluster center; $n_e(r) = n_0[1 + (r/r_c)^2]^{-3\beta/2}$ is the β-radial distribution of the gas density; $\tau(\nu)$ is the normalized Diabolo band spectral efficiency (given in Désert et al. 1998); and $\mathrm{SZ}(\nu, T_e)$ is the spectral density of the thermal SZ distortion for a unit Comptonization parameter, including the relativistic weak dependence on T_e (see Pointecouteau, Giard, & Barret 1998). In fact, for a 9.3 keV cluster, the use of relativistic spectra avoids making errors on the SZ flux estimations of 45% and 10% at 1.2 and 2.1 mm, respectively. We did not include any kinetic SZ contribution, which is generally weak (Birkinshaw 1999); k, m_e, c, and σ_{T} are, respectively, the Boltzmann constant, the electron mass, the speed of light, and the Thomson cross section. $P(\mathbf{\Omega})$ and $L(\mathbf{\Omega})$ are the normalized angular distributions of the cluster and the experimental beam, respectively. $P(\mathbf{\Omega})$ has no analytical expression; it is numerically computed by the integration of the gas density β-profile on the line of sight.

Two radio sources are known from the NRAO VLA Sky Survey in the neighborhood of the cluster (Condon et al. 1998). One, at $(\alpha, \delta) = (13^{\mathrm{h}}47^{\mathrm{m}}30^{\mathrm{s}}.67, -11°45'8''.6)$, is very close to the cluster center and is likely to correspond to the central Cd galaxy. Komatsu et al. (1999) have compiled observations of this radio source at 1.4, 28.5, and 105 GHz. They have derived the following power law for the radio source spectrum: $F_\nu(\mathrm{band}) = (55.7 \pm 1.0)\,(\nu/1\ \mathrm{GHz})^{-0.47 \pm 0.02}$ mJy. So the extrapolated millimeter flux should be $F_\nu(1.2\ \mathrm{mm}) = 3.7 \pm 0.4$ mJy beam^{-1} and $F_\nu(2.1\ \mathrm{mm}) = 4.9 \pm 0.5$ mJy beam^{-1}.

To analyze the data properly, we have performed a realistic simulation of the Diabolo observations on the skymap of the SZ model (eq. [1]). The whole set of observed individual maps has been simulated by taking into account the 150″ wobbling amplitude and the proper sky rotation at the Nasmyth focus. The simulated data have been processed through the same pipeline as the observed data set in order to obtain averaged model maps.

Finally, using this simulated data set, we have simultaneously fitted the SZ decrement amplitude and the point-source flux on the 2.1 mm profile with y_c and $F_\nu(2.1\ \mathrm{mm})$ as free parameters. The best-fit parameters are $y_c = (12.7^{+2.9}_{-3.1}) \times 10^{-4}$ and $F_\nu(2.1\ \mathrm{mm}) = 6.1^{+4.3}_{-4.8}$ mJy beam^{-1} with a reduced χ^2 of 1.3. Results are given at a 68% confidence level. The absolute calibration error, 25% and 15% at 1.2 and 2.1 mm, respectively, is not included. $F_\nu(2.1\ \mathrm{mm})$ is compatible with the value expected from radio observations. The best fit is overplotted on the data (see Fig. 2). It reproduces the asymmetric profile. This asymmetry is due to the point-source contribution that fills part of the SZ decrement.

During a second time, we fixed the radio point-source flux at the expected value deduced from Komatsu et al. (1999), $F_\nu(2.1\ \mathrm{mm}) = 4.9$ mJy beam^{-1}, and we fitted with a maximum likelihood method both the central Comptonization parameter y_c, and the angular core radius θ_c. We have found $y_c = (13.2^{+0.2}_{-2.6}) \times 10^{-4}$ and $\theta_c = 7.2^{+7.3}_{-7.2}$ arcsec with a reduced χ^2 of 1.2. The Comptonization parameter value is consistent with the previous one. The angular core radius is consistent with the X-ray value within the 68% confidence level.

6. CONCLUSION

We confirm through our SZ detection that RX J1347−1145 is an extremely massive and hot cluster. We have measured the deepest SZ effect ever observed. It corresponds to a very large Comptonization parameter, $y_c = (12.7^{+2.9}_{-3.1}) \times 10^{-4}$. This is almost twice the value expected from the X-ray data: $y_{\mathrm{X\text{-}ray}} = (7.3 \pm 0.7) \times 10^{-4}$ if we use the cluster gas parameters derived by Schindler et al. (1997). Although our result points to a mass higher than the X-ray mass, as is the case for gravitational lens measurements, the uncertainties do not allow us to conclude firmly that there is a discrepancy. The X-ray flux toward the cluster center is actually dominated by the very strong cooling flow in the core. The average temperature of the gas that contributes to the SZ effect is thus likely to be higher than the temperature derived from the X-ray data, $T_e = 9.3 \pm 1$ keV. The gas temperature that is needed to produce the thermal SZ effect that we have observed is $T_e = 16.2 \pm 3.8$ keV, assuming all other parameters are kept unchanged. In a reanalysis that takes into account the heterogeneity of the cluster, Allen & Fabian (1998) have actually derived for this cluster a very high gas temperature: $T_e = 26.4^{+7.8}_{-12.3}$ keV, which is indeed consistent with our measurement. Under the hypothesis of hydrostatic equilibrium, a higher gas temperature implies a higher total cluster mass, thus decreasing the gas fraction if all other cluster parameters are kept unchanged. For $T_e = 16.2 \pm 3.8$ keV, the total mass of RX J1347−1145 within 1 Mpc is considerable, $M_{\rm tot}(r < 1\ {\rm Mpc}) = (1.0 \pm 0.3) \times 10^{15}\ M_{\odot}$, and the corresponding gas fraction is $f_{\rm gas}(r < 1\ {\rm Mpc}) = 19.5\% \pm 5.8\%$.

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