SYSTEMATIC OBSERVATION OF SUNYAEV-ZEL'DOVICH EFFECT TOWARD MEDIUM DISTANT GALAXY CLUSTERS AT 43 GHZ

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ABSTRACT

We have observed Sunyaev-Zel'dovich (S-Z) effect toward four distant galaxy clusters at 43 GHz using the focal-plane array SIS receiver installed in the Nobeyama 45-m telescope. The S-Z effects are −1.38±0.07 mK for CL0016+16, −0.95±0.11 mK for MS1358+62, −0.60±0.13 mK for MS1008-12, and −0.73±0.18 mK for A2218, respectively. The S-Z effect for MS1008-12 is a new detection. The derived Hubble constant is 68±11 $kms^{-1}Mpc^{-1}$. This is consistent with the value by Hubble Space Telescope (HST). On the contrary, assuming that the derived value is equal to that by HST, it suggests that the cosmological constant is around 0.7.

INTRODUCTION

The Sunyaev-Zel'dovich (S-Z) effect is the phenomenon that the photons of the cosmic microwave background (CMB) are scattered through inverse Compton process with the electrons in the hot gas of a galaxy cluster [1]. The S-Z effect makes a silhouette of the hot gas toward the CMB under 220 GHz, and an excess over 220 GHz. The observation of the S-Z effect had been one of the most difficult observations in radio astronomy because the temperature decrement of the silhouette is only on the order of 100 μK and it is extended over several arcminutes. The drastic improvement of the sensitivity and the reliability of radio telescopes during the last decades have, however, changed such a situation [2][3][4]. Then the measurement method of the Hubble constant by combining the S-Z effect and the X-ray surface brightness of the hot gas will be becoming a robust and reliable cosmological probe. The small beam size is important in the observations to avoid the beam-dilution of S-Z effect. The low side lobe level is also important because the distribution of the S-Z effect is affected by response of the side lobes. The reliability of zero level of the observed brightness temperature is important to estimate the absolute value of S-Z effect. In these points, large single-dish telescopes may be superior to interferometers with not large numbers of antenna. In addition, it is important to perform the observation at mm-wavelength because the contamination of weak point sources decreases steeply in mm-wave. These have motivated us to observe the S-Z effect of several distant galaxy clusters at 43 GHz using the Nobeyama 45-m radio telescope. The telescope is the best and largest single-dish radio telescope in the frequency range from 40 to 50 GHz.

OBSERVATIONS

The S-Z effect toward four distant galaxy clusters, CL0016+16 (z = 0.546, $\alpha_{1950} = 00^h16^m42^s.8$, $\delta_{1950} = 16°18'44''.5$)[5], MS1358+62 ($z$ = 0.328, $\alpha_{1950} = 13^h58^m20^s.6$, $\delta_{1950} = 62°45'33''.3$)[6], and MS1008-12 ($z$ = 0.301, $\alpha_{1950} = 10^h08^m05^s.4$, $\delta_{1950} = -12°24'44''.6$)[6], and A2218 ($z$ = 0.176, $\alpha_{1950} = 16^h35^m42^s.8$, $\delta_{1950} = 66°18'44''.5$)[7], were observed with the Nobeyama 45-m telescope until February 2001. It is clear that a focal plane array receiver system at millimeter wavelength is superior in the sensitivity to a single receiver system in spite of the difficulty of the beam-to-beam calibration of the focal plane array receiver. We developed a new 40 GHz-band focal-plane array SIS receiver for the Nobeyama 45-m telescope and used it in this observation. The receiver has 2x3 beams with 80" interval on the celestial sphere. The FWHMs of the beams were typically 40". The aperture and the main-lobe efficiencies at 43 GHz are typically 0.6 and 0.8, respectively. The Moon efficiency is typically 0.9. The detail description of the system was presented in the other publication [8]. The SSB system noise temperature, including atmospheric effects and antenna ohmic loss, was 160--220 K during the observations. Calibration of the antenna temperature was made by the chopper-wheel method yielding the antenna temperature (T_A*) corrected for both atmospheric and antenna ohmic losses. The receiver was rotated so that the beam grid rests for the AZ-EL coordinate system. A beam is pointed at the center position on the cluster. The off-axis beams sweep arc-like areas in the sky by changing of the parallactic angle of the source. Then the beams observed three areas with angular distances of 0", 80", and 117" from the center position. The telescope has two beams alternated at 15 Hz by the beam-switch of the telescope, which are an on-axis beam and an off-axis beam. The separation of the main beam and the reference beam is selected to be 6′30" in the azimuth direction. The telescope is position-switched simultaneously between one on-source position at $\Delta AZ/\cos EL$=0′ (ON1), where the cluster is observed by the "main beam", and the other on-source position at $\Delta AZ/\cos EL$=–6′30" (ON2), where the cluster is observed by the "reference beam" both for 8 s during each cycle. The off-source beams at these positions sweep arc-like areas in the sky by changing of the parallactic angle of the source. This ON1-ON2 switching scheme gives about twice as much signal as simple ON-OFF switching. The offset of the zero level was smaller than about ±50 μK [8]. The antenna temperature decrement, $\Delta T_{A,RJ}$, corrected for Rayleigh-Jeans (R-J) limit is estimated by

$$\Delta T_{A,RJ} = -2\Delta T_A^* / \xi \tag{1}$$

where $\xi = x^2\exp(x)[x\coth(x/2)-4]/[\exp(x)-1]^2$, and x is the normalized frequency, $x = h\nu/kT_0$. The telescope beam is assumed as the Gaussian shaped beam;

$$P_n(\theta) = \exp\left(-4\ln 2\,\theta^2 / FWHM^2\right) \tag{2}$$

Assuming that the hot gas in the cluster has isothermality and spherical symmetry, the β model brightness temperature distribution. The antenna temperature distribution, $\Delta T_{A,RJ}(\theta)$, should be shown by the convolution of the Gaussian shaped beam $P_n(\theta)$ and the β model S-Z effect distribution;

$$\Delta T_{A,RJ}(\theta_0) = \eta \Delta T_0 \int_{\theta \le 6'30''} \left[1 + (\theta/\theta_C)^2\right]^{(1-3\beta)/2} P_n(\theta - \theta_0) d\Omega \Big/ \int_{4\pi} P_n(\theta) d\Omega \tag{3}$$

where ΔT_0 is the S-Z brightness temperature decrement at the center position and η is given by

$$\eta = \int_{\theta \le 6'30''} P_n(\theta) d\Omega \Big/ \int_{4\pi} P_n(\theta) d\Omega . \tag{4}$$

If the beam is not extended over θ_{ref} = 6′30", η is nearly equal to the Moon efficiency. Then the observed antenna temperature distribution is given by (model 1)

$$\Delta T_{A,RJ,obs}(\theta_0) = \Delta T_{A,RJ}(\theta_0) - \Delta T_{A,RJ}(\theta_{ref}). \tag{5}$$

It is an open question where is the outer limitation. If the temperature decrement is negligible on the reference arc (model 2), the antenna temperature is given by

$$\Delta T_{A,RJ,obs}(\theta_0) = \Delta T_{A,RJ}(\theta_0). \tag{6}$$

Which model is suitable for the observing cluster? This selection depends on the extent in the S-Z effect of the individual cluster. In this observation, the model with smaller χ^2 was selected.

RESULTS

Fig. 1a shows the brightness temperature corrected for R-J limit, $\Delta T_{A,RJ}/\eta$, of CL0016+16. The filled circles show the brightness temperatures observed at θ = 0", 80", and 117". The temperature decreases, as it goes outside from the center position. We assume that the hot gas in the cluster has isothermal, spherical symmetry β model density distribution with β = 0.61 and θ_c = 33.5" [9]. The observed brightness temperatures are converted to the S-Z brightness by χ^2 fitting for models 1 and 2. In the case of CL0016+16, the χ^2 of model 2 is smaller than the χ^2 of model 1. The curve of model 2 is also shown in Fig. 1a. The reference arcs are located 2 times far from the virial radius [9]. Thus, the S-Z brightness temperature decrement at the center position at R-J limit is derived to be, ΔT_0 = –1.38±0.07 mK for CL0016+16. The central position is probably free from contamination of weak radio sources. This is consistent with the previous results for, ΔT_0 = –1.21±0.19 mK [5] and ΔT_0 = –1.24±0.11 mK [10]. Fig. 1b shows the brightness temperature corrected for R-J limit of MS1358+62. Assuming the isothermal and spherical β model of β = 0.46 and θ_c

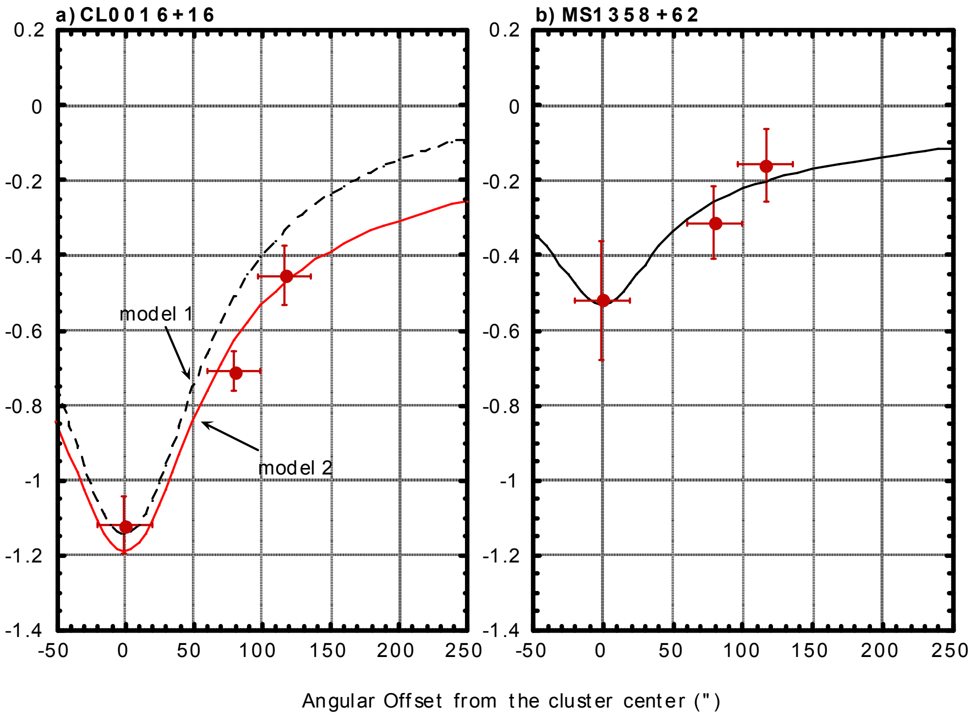

Fig.1. Brightness temperature distribution at R-J limit, a) CL0016+16 and b) MS1358+62

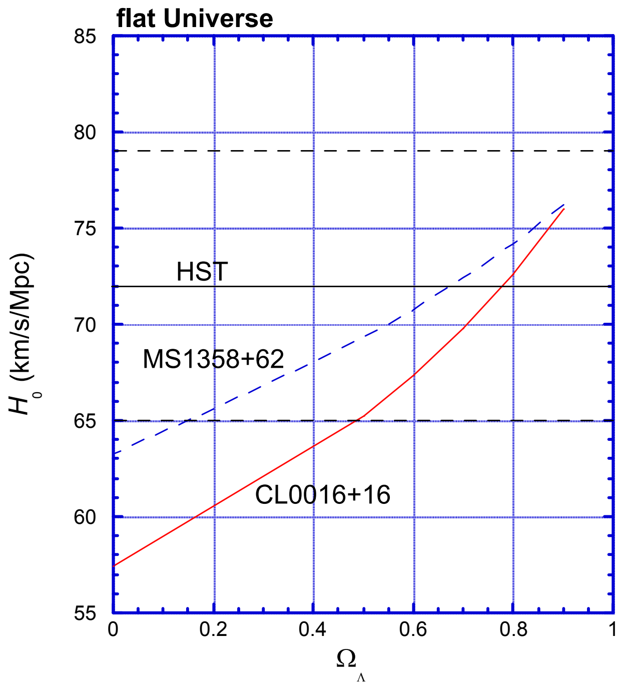

Fig. 2. Derived H_0 for CL0016+16 and for MS1358+62 vs Ω_Λ.

= 8.4" [9], the conversion from the observed brightness temperatures to the S-Z brightness temperature decrement is performed by the χ^2 fitting mentioned above. In the case of MS1358+62, the χ^2 of model 1 is almost equal to the χ^2 of model 2. The beam throw is 1.5 times larger than the virial radius [9]. The averaged curve is also shown in Fig. 1b. The S-Z brightness temperature decrement is derived to be ΔT_0 = –0.95±0.11 mK for MS1358+62. The observed brightness temperatures of MS1008-12 and A2218 are also converted to the S-Z brightness temperature decrement by the χ^2 fitting. The S-Z effect for MS1008-12 is a new detection. The observed brightness temperatures are converted to the S-Z brightness temperature decrement by the χ^2 fitting. Assuming the isothermal spherical β model of β = 0.61 and θ_c = 34.0" [9], the SZ effect for MS1008-12 is ΔT_0 = –0.60±0.13 mK. However, this may be suffered from the contamination of the point source. The value for A2218 becomes ΔT_0 = –0.73±0.18 mK for β = 0.71 and θ_c = 66.4" [9].

DISCUSSION

We performed a systematic estimate of H_0 by the comparison between of the observed S-Z effect and the X-ray data of the galaxy clusters. The angular diameter distance given by the comparison between of the observed S-Z effect and the X-ray data is given by

$$d_A = \left(\Delta T_0^2 \Lambda_{e0} m_e c^2\right) \Big/ \left[16\pi^{1/2}(1+z)^3 b_{x0}^2 kT_{e0}\sigma_T^2 T_{CBR}^2 \theta_C\right] \times \left[\Gamma(3\beta-1/2)/\Gamma(3\beta)\right] \Big/ \left[\Gamma(3\beta/2-1/2)/\Gamma(3\beta/2)\right]^2 \quad (7)$$

In the flat universe, the Hubble constant is given by

$$H_0 = c\int \left[(1+z)^2(1+\Omega_m z)+z(2+z)\Omega_\Lambda\right]^{-1/2} dz \Big/ d_A(1+z) \quad (8)$$

where Ω_m and Ω_Λ are matter density parameter and dimensionless cosmological constant, respectively[11].
In the case of Ω_m = 0.3 and Ω_Λ = 0.7, Hubble constants derived from individual clusters are H_0 = 69±6 kms^{-1}Mpc^{-1} for CL0016+16, H_0 = 72±17 kms^{-1}Mpc^{-1} for MS1358+62. H_0 = 89±38 kms^{-1}Mpc^{-1} for MS1008-12, and H_0 = 56±27 kms^{-1}Mpc^{-1} for A2218, respectively. The weighted mean value is H_0 = 68±11 kms^{-1}Mpc^{-1}. This value is consistent with the value of the HST key project [12] and the value derived previously from S-Z observations.

According to the formula in flat universe mentioned above, H_0 in distant universe of $z > 0.3$ depends on Ω_Λ. Fig. 2 shows H_0 for CL0016+16 and for MS1358+62 from the observed S-Z effect and the X-ray data as functions of Ω_Λ. On the contrary, the derived H_0 is assumed to be equal to the value from HST, a new knowledge for Ω_Λ is obtained. Thus the crossing points of these curves suggest that the cosmological constant, Ω_Λ, is about 0.7-8. This agrees with the value derived by supernova observation independently[13]. This supports the existence of the low Ω_m universe.

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