THE ASTROPHYSICAL JOURNAL, 466:L75–L78, 1996 August 1

ASCA OBSERVATIONS OF THE DISTANT CLUSTER A1204

MASAKAZU MATSUURA AND SHIGERU J. MIYOSHI
Department of Physics, Kyoto Sangyo University, Kamigamo-Motoyama, Kita-ku, Kyoto 603, Japan

KOUJUN YAMASHITA, YUZURU TAWARA, AND AKIHIRO FURUZAWA
Department of Astrophysics, Faculty of Science, Nagoya University, Chikusa-ku, Nagoya 464-01, Japan

ANTHONY N. LASENBY, RICHARD SAUNDERS, AND MICHAEL JONES
Mullard Radio Astronomy Observatory, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, England

AND

ISAMU HATSUKADE
Faculty of Engineering, Miyazaki University, 1-1 Gakuen-kibanadai-nishi, Miyazaki 889-21, Japan
Received 1995 September 1; accepted 1996 May 13

ABSTRACT

We report the results of *ASCA* and Ryle Telescope observations of the distant cluster of galaxies A1204. The X-ray image shows that this source is very compact and that the intracluster gas is strongly centrally concentrated. The brightness temperature decrement of the cosmic microwave background radiation toward this cluster (the Sunyaev-Zeldovich effect) was not detected by the Ryle Telescope, with a 1 σ upper limit of $|\Delta T| < 360\ \mu$K. The gas temperature is 3.6 keV, which is considerably lower than that expected from the bright X-ray luminosity in the *ROSAT* band and explains the lack of detection. The hot gas mass within 1 Mpc is estimated to be $\lesssim 7 \times 10^{13}$ $M_{\odot}$. In the wide window of the *ASCA* Gas Imaging Spectrometer, a very faint X-ray source was found at R.A. = $11^{\rm h}12^{\rm m}16^{\rm s}$, decl. = $+17°56'40''$ (J2000). The observed count rate was too small to identify the X-ray emission mechanism in the new source.

Subject headings: galaxies: clusters: individual (Abell 1204) — intergalactic medium — X-rays: galaxies

1. INTRODUCTION

The distant Abell cluster of galaxies A1204 is optically classified as richness class 1 and Bautz-Morgan type II–III (Abell, Corwin, & Olowin 1989). In the X-ray band, A1204 was not known as a bright cluster until the *ROSAT* All-Sky Survey (RASS) detected it as one of the most X-ray–bright distant clusters. In an optical follow-up study of RASS clusters, Allen et al. (1992) observed a dominant galaxy at the X-ray brightness center of this cluster. They have reported a precise value of redshift ($z = 0.1706 \pm 0.0003$) and the existence of optical (H_{α} + [N II] complex) line emission, which is rather common for clusters that have an X-ray–inferred cooling flow (Heckman et al. 1989).

Our *ASCA* observations of A1204 were motivated by a desire to determine the value of the Hubble constant, H_0, using the Sunyaev-Zeldovich (S-Z) decrement in the cosmic microwave background radiation (CMBR). This was expected to be measurable because of the cluster's high X-ray luminosity in the *ROSAT* band and the low radio luminosity in the immediate vicinity on the sky. The X-ray observations are needed to determine the distributions of the electron number density and the intracluster gas temperature. Details of the derivation of H_0's value from these quantities are in Jones (1994) [the last term $(1 + z)^{3/2}$ in his eq. (10) should be read as $(1 + z)^{5/2}$]. Since the results of the observations of the S-Z effect using the Ryle Telescope were marginal, here we report mainly the results of X-ray observations of A1204 with *ASCA*. The details of the *ASCA* observations, the data reduction, and the results of data analysis are in § 2 together with a short summary of radio observations, and the astrophysical meanings of these observational results are discussed in § 3. We summarize the present results in § 4.

2. OBSERVATIONS AND DATA REDUCTION

We observed A1204 with the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*) during 1994 May 21–22. The total exposure time was $\sim 4 \times 10^4$ s. The instruments aboard *ASCA* consist of four imaging telescopes; two solid-state imaging spectrometers (SIS) and two gas-scintillation proportional counter imaging spectrometers (GIS) (Tanaka, Inoue, & Holt 1994) are situated in the focal planes of identical grazing-incidence X-ray telescopes (XRTs) (Serlemitsos et al. 1995). In our observations, the SIS was operated in 1-CCD faint mode and the GIS was operated in pulse-height mode. The standard cleaning was applied to eliminate X-ray contaminations from the local environment.

Figure 1 shows the whole X-ray energy spectra of A1204 obtained with the SIS and the GIS. For the SIS, the on-source data were taken from the region within 3′ of the X-ray brightness center (R.A. $11^{\rm h}13^{\rm m}18^{\rm s}$, decl. 17°36′09″, J2000), and the background data were obtained from the outer region. The GIS on-source data were taken from a region within 5′ of the X-ray brightness center, and the background data were taken from the region on the opposite side across the window center. The net source count rates were 0.16 counts $\rm s^{-1}$ for the SIS 0.4–8 keV band and 0.11 counts $\rm s^{-1}$ for the GIS 0.5–9 keV band. The background-subtracted spectra were fitted to a one-temperature, thin thermal plasma model (Raymond & Smith 1977, with later modifications) with photoelectric absorption (Morrison & MacCammon 1983). As summarized in Table 1, this model is well fitted to the observed spectra, with reduced $\chi^2 = 1.09$. The obtained (mean) intracluster gas tem-

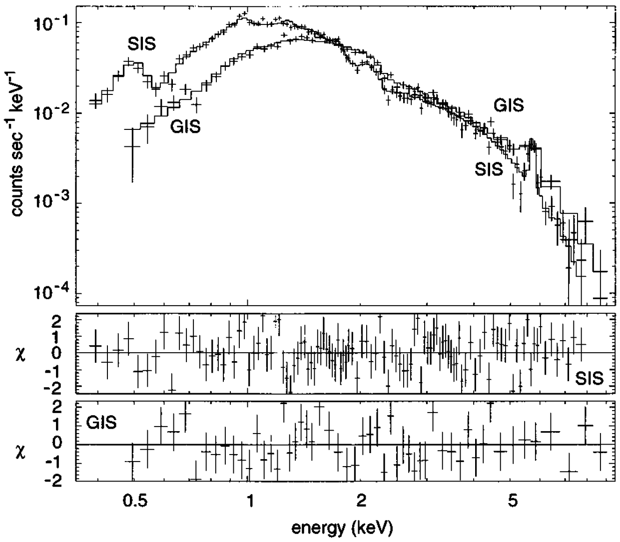

FIG. 1.—SIS and GIS energy spectra of A1204 (*crosses*) fitted by thin thermal plasma model with photoelectric absorptions (*solid lines*). The bottom panels show the residuals of fitting normalized to observational errors.

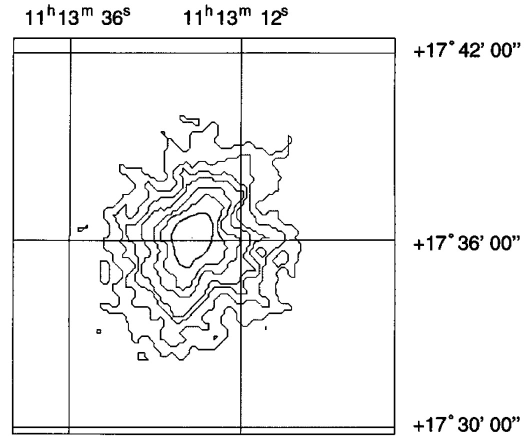

FIG. 2.—Contour map of A1204 SIS image. It is not corrected for the deformation by mirror. The sky coordinates are J2000 values.

perature is 3.59 ± 0.13 keV, and the iron abundance is 0.35 ± 0.06 relative to the solar abundance ratio of $n(\mathrm{Fe})/n(\mathrm{H}) = 4.68 \times 10^{-5}$. The redshift value of $z = 0.170 \pm 0.005$ obtained from the 6.7 keV ionized Fe line is in good agreement with the optical value noted in § 1. The most conspicuous point is that the intracluster gas temperature is considerably lower than those of distant clusters that have S-Z measurements.

As mentioned in § 1, there is an optical suggestion of cooling flow in A1204. We tried to fit the above spectra to the cooling-flow model of Mushotzky & Szymkowiak (1988). However, perhaps partly because of the poor statistics, the fitting program did not converge. In addition, there was no decrease in the reduced χ^2 compared with the one-temperature model fitting. These facts show that the *ASCA* X-ray data do not necessarily support the existence of a cooling flow in A1204.

In the wide field of view of GIS, a very faint source is centered on J2000 R.A. = $11^{\mathrm{h}}12^{\mathrm{m}}16^{\mathrm{s}}$, decl. = $+17°56'40''$. There is no counterpart in the NASA/IPAC Extragalactic Database. The number of observed X-ray photons is too small to identify the X-ray emission mechanism in this extra source. Using the Galactic N_{H}-value in this direction (1.4×10^{20} cm^{-2}), however, we tried to fit the energy spectrum to a power-law model and obtained a photon index of $\gamma = 2.6 \pm 0.3$ with reduced $\chi^2 = 1.24$ (22 degrees of freedom). This value of γ is common for BL Lac objects but not for QSOs or other active galactic nuclei. Fitting to a thin thermal bremsstrahlung model yields a temperature of 1.6 ± 0.5 keV with reduced $\chi^2 = 1.09$, which is common for elliptical galaxies (Ohashi & Tsuru 1992).

TABLE 1

BEST-FIT PARAMETER VALUES FROM SIS-PLUS-GIS COMBINED FITTING

Parameter	Best-Fit Value[a]
N_{H} (10^{20} cm^{-2})	7.4 ± 1.0
T (keV)	3.59 ± 0.13
Fe Kα line central energy (keV)	5.72 ± 0.03
Kα line equivalent width (eV)	390
Fe abundance (in solar units)	0.35 ± 0.06
Redshift of Fe line	0.170 ± 0.005
2–10 keV luminosity (10^{44} ergs s^{-1})	5.4
Reduced χ^2	173.0/164 = 1.09

[a] The errors are at the 90% confidence level.

The contour map of X-rays from A1204 obtained with the SIS, including the background and the deformation due to the XRTs, is shown in Figure 2. The contour map clearly shows the cross-shaped feature that is typical of pointlike sources. It therefore informs us that A1204 has a very compact distribution of hot gas. The background data obtained from several blank-sky fields were subtracted from the image. We then tried to fit the background-subtracted SIS image to an image obtained from an XRT ray-tracing simulation for the surface brightness distribution of a spherically symmetric, isothermal β-model of gas distribution,

$$\Sigma_{\mathrm{X}}(\theta) = \Sigma_{\mathrm{X}}(0)[1 + (\theta/\theta_C)^2]^{0.5-3\beta}\,. \quad (1)$$

Here $\Sigma_{\mathrm{X}}(\theta)$ is the X-ray surface brightness at θ, the projected angular separation from the cluster's center, and θ_C and β are fitting parameters. Because of the limited angular resolution, we could estimate the 90% confidence level upper limit of angular core size, $\theta_C^{\max}$, only for fixed values of β. The value of $\theta_C^{\max}$ thus obtained is $0\overset{'}{.}7$ for $\beta = 0.8$ and $0\overset{'}{.}2$ for $\beta = 0.6$. For the typical value of $\beta = 0.7$ (see, e.g., Jones & Forman 1984), $\theta_C^{\max} \sim 0\overset{'}{.}5$. This angular size is equivalent to the projected core radius, which is equal to the three-dimensional core radius, $R_C \sim 120$ kpc.[1] This is small compared with the typical value of 250 kpc for other well-studied clusters.

Under the assumption that the intracluster gas distribution is well described by the isothermal β-model, the integrated gas mass $M_g(<R_0)$ increases with R_C for fixed β and $R_0 \gg R_C$, where R_0 is a three-dimensional distance from the cluster's center. Then, adopting the parameter values $\beta = 0.7$, $\theta_C^{\max} = 0\overset{'}{.}5$, and $T = 3.6$ keV, the upper limit of the gas mass within $R_0 = 1$ Mpc that corresponds to the observed extent of the X-ray image is estimated to be $7 \times 10^{13}\ M_{\odot}$. For the values $\beta = 0.8$ and 0.6, the upper limits are 7×10^{13} and $6 \times 10^{13}\ M_{\odot}$, respectively. These values are consistent with the R_0-$M_g(<R_0)$ diagram based on the *Einstein* data (White & Fabian 1994).

In addition to the X-ray observations, we also observed

[1] In this Letter, we are using a Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1}.

A1204 in the radio band using the Ryle Telescope (RT) of the Cavendish Laboratory in order to detect the S-Z decrement of the CMBR due to the hot intracluster gas. The RT is an aperture-synthesis interferometer operating at 15.4 GHz ($\lambda = 19.5$ cm) and sensitive to angular scales of 30″–3′ that has been successfully used to detect the S-Z effect in several distant ($z > 0.14$) clusters (Jones 1994). A1204 was observed on 26 occasions between 1994 May 17 and 1994 November 8. The data were flux-calibrated using observations of 3C 48 or 3C 286 and phase-calibrated by observing an unresolved source, 1117 + 146, at intervals of ~20 minutes during each run. After calibrating, concatenating, and mapping all the data, we found a point source of flux density 1.37 mJy at R.A. = $11^h13^m20\overset{s}{.}6$, decl. = +17°35′44″ (J2000) coincident with the central cluster galaxy. After removing this source from the visibilities, there was no evidence of any further signal at any angular scale. The real part of the visibilities averaged over all baselines less than 1000 λ (expected to be most sensitive to any extended S-Z signal) was -38 ± 140 μJy beam^{-1}. Converting this to a CMBR brightness temperature decrement ΔT_b depends on the angular structure of the gas: for the isothermal β-model with $\beta = 0.7$ and $\theta_C = 0\overset{'}{.}5$, the temperature decrement is estimated to be $\Delta T_b = -100 \pm 360$ μK (for $\theta_C = 1'$, $\Delta T_b = -90 \pm 320$ μK). The meaning of this nondetection is discussed in the following section.

3. DISCUSSION

Here we investigate theoretically the dependence of the CMBR brightness temperature decrement ΔT_b at a Rayleigh-Jeans frequency on the mean gas temperature T, on the total X-ray luminosity L_X in the rest-frame frequency band $\nu_1 - \nu_2$, on the core radius R_C, and on the β of an assumed spherically symmetric isothermal β-model; we shall thus ignore any temperature gradient that may perhaps exist in the cluster. The following discussion should therefore be considered a qualitative one based on the zeroth-order approximation for temperature distribution. We also ignore the contribution of line emission.

First, for thin thermal bremsstrahlung radiation,

$$L_X \simeq \Lambda_0 F(T) \int_0^\infty 2\pi R\, dR \int_{-\infty}^{\infty} n_e(r)^2\, dl, \quad (2)$$

where R is the projected radius from the cluster's center, l is the coordinate along the line of sight separated by R from the cluster's center ($l^2 + R^2 = r^2$), and $n_e(r)$ is the electron number density at a three-dimensional distance r from the cluster's center, as given by

$$n_e(r) = n_e(0)[1 + (r/R_C)^2]^{-1.5\beta}. \quad (3)$$

Λ_0 and $F(T)$ are respectively given by

$$\Lambda_0 = \frac{32\pi}{3}\left(\frac{2\pi}{3}\right)^{0.5} \frac{e^6 \overline{Z^2}}{(m_e c^2)^{1.5}} \frac{4 - 3Y}{4 - 2Y}, \quad (4)$$

$$F(T) = (kT)^{-0.5} \int_{\nu_1}^{\nu_2} g_{\rm ff}(\nu, T) e^{-h\nu/kT}\, d\nu, \quad (5)$$

where m_e is the electron mass, c the velocity of light, Y the He mass fraction of the gas, e the electron charge, $\overline{Z^2}$ the mean square charge of ions, $g_{\rm ff}(\nu, T)$ the Gaunt factor of free-free transition, k the Boltzmann constant, and h the Planck constant. On the other hand, for an observed radio frequency ν_b in the Rayleigh-Jeans region of the CMBR, the brightness temperature decrement in the direction of the cluster's center is estimated by

$$\Delta T_b(0) \simeq \frac{T_b \sigma_{\rm T}}{m_e c^2}\left(x \frac{e^x + 1}{e^x - 1} - 4\right) kT \int_{-\infty}^{\infty} n_e(l)\, dl, \quad (6)$$

where $\sigma_{\rm T}$ is the Thomson scattering cross section, T_b is the CMBR brightness temperature, $x \equiv h\nu_b/kT_b$, and the integration is along the line of sight across the cluster's center. Eliminating $n_e(0)$ from equations (2) and (6) after the integration, we obtain

$$\Delta T_b(0) \simeq \frac{k\sigma_{\rm T}}{m_e c^2} T T_b B(\beta)\left(x \frac{e^x + 1}{e^x - 1} - 4\right) \times \left[\frac{L_X}{2\sqrt{\pi}\Lambda_0 R_C F(T)}\right]^{0.5}. \quad (7)$$

The β-dependence of $\Delta T_b(0)$ is summarized in $B(\beta)$ as

$$B(\beta) \equiv \frac{\Gamma[(3\beta - 1)/2]}{\Gamma(3\beta/2)} \left\{\frac{(6\beta - 3)\Gamma(3\beta)}{\Gamma[3\beta - (1/2)]}\right\}^{0.5}, \quad (8)$$

where Γ is the gamma function. We can see from numerical calculations that $B(\beta)$ is insensitive to β. For canonical values of β between 0.6 and 1, one has $B(\beta) \simeq 2.0$.

Observations have shown an obvious correlation between the mean intracluster gas temperature T and L_X(2–10 keV), the 2–10 keV X-ray luminosity of each cluster of galaxies (see, e.g., David et al. 1993). That is,

$$L_X(2\text{–}10 \text{ keV}) \simeq 0.011 \times 10^{44} \left(\frac{T}{1 \text{ keV}}\right)^{3.4} \text{ ergs s}^{-1}. \quad (9)$$

Inserting equation (9) into equation (7), for $\nu_b = 15$ GHz we obtain

$$\Delta T_b(0) \simeq -0.2 \frac{B(\beta)}{2.0}\left(\frac{R_C}{120 \text{ kpc}}\right)^{-0.5} f\left(\frac{T}{3.6 \text{ keV}}\right) \text{ mK}, \quad (10)$$

where $f(T)$ summarizes the T-dependence as

$$f(T) = T^{2.7}/\sqrt{F(T)}. \quad (11)$$

In Figure 3, we plot $-\Delta T_b$ observed so far (Rephaeli 1995; Herbig, Lawrence, & Readhead 1995; Jones 1994) versus $R_C^{-0.5} f(T)$, which we call the "S-Z measure," together with the theoretical relation obtained above (*dashed line*). Spearman's rank-order correlation coefficient for the observed data is 0.66, which indicates a significant correlation between $-\Delta T_b$ and the S-Z measure with 97% confidence. The observed data are distributed slightly below the theoretical line. This may be due to the adoption of a too simple (isothermal β) model. In any event, A1204 is settled in a reasonable position. The observed weak or absent CMBR temperature decrement for A1204, which seems to be unexpected from the high X-ray luminosity in the *ROSAT* band, is now understandable given the low gas temperature of A1204 obtained from *ASCA* observations.

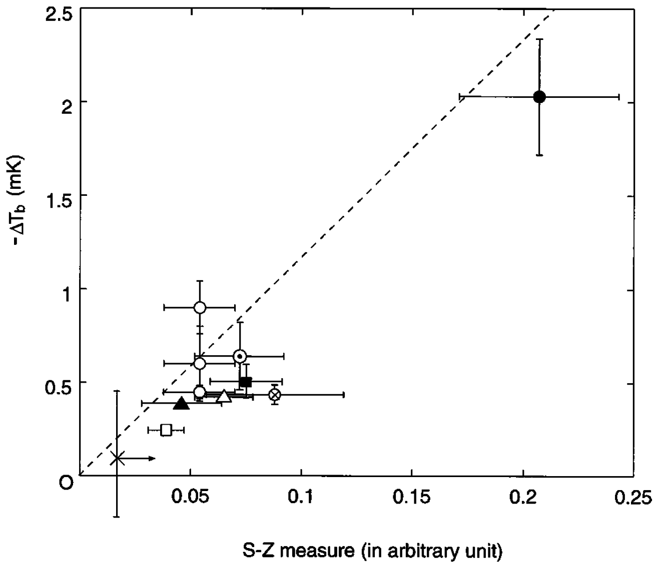

FIG. 3.—Observed S-Z decrement vs. S-Z measure, $R_C^{-0.5} f(T)$, together with the theoretical one (*dashed line*). The sources are A401 (*circled dot*), A478 (*filled triangle*), A665 (*circled cross*), A1204 (*cross*; present result), A1656 (*filled square*), A2142 (*open triangle*), A2163 (*filled circle*), A2218 (*open circles*), and A2256 (*open square*). Data are from Rephaeli (1995), Herbig et al. (1995), Jones (1994), and Furuzawa et al. (1994). Values of ΔT_b obtained from observations at different frequencies have been converted to the value at 15 GHz.

4. SUMMARY

We have observed the distant cluster A1204, using *ASCA* for the X-ray band and the Ryle Telescope for the radio band. The cluster has a quite low intracluster gas temperature (3.6 keV) and a very compact ($R_C < 120$ kpc) distribution of X-ray surface brightness. The integrated gas mass within 1 Mpc is estimated to be less than 7×10^{13} $M_\odot$ for canonical values of $\beta \gtrsim 0.6$. The radio observations with the RT attempted to detect the S-Z effect; however, the result obtained is not a significant detection ($\Delta T_b = -100 \pm 360$ μK). The low gas temperature of A1204 obtained from the *ASCA* data explains this negative result well. The existence of a temperature gradient expected for a cooling flow, which is suggested to exist in A1204 from optical observations, is not positively supported by the X-ray data.

In the window of the *ASCA* GIS, a new faint X-ray source was found at J2000 R.A. = $11^h12^m16^s$, decl. = $+17°56'40''$. The emission mechanism of this source cannot be identified because of its very low X-ray flux.

We are grateful to the *ASCA* team for their efforts on the design and operation of *ASCA* hardware and software. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration.

REFERENCES

Abell, G. O., Corwin, H. G., & Olowin, R. P. 1989, ApJS, 70, 1
Allen, S. W., et al. 1992, MNRAS, 259, 67
David, L. P., Slyz, A., Jones, C., Forman, W., & Vrtilek, S. D. 1993, ApJ, 412, 479
Furuzawa, A., Yamashita, K., Tawara, Y., Takana, Y., & Sonobe, T. 1994, in New Horizon of X-Ray Astronomy, ed. F. Makino & T. Ohashi (Tokyo: Universal Acad.), 541
Heckman, T. M., Baum, S. A., van Breugel, W., & McCarthy, P. 1989, ApJ, 338, 48
Herbig, T., Lawrence, C. R., & Readhead, A. C. S. 1995, ApJ, 449, L5
Jones, M. 1994, in Clusters of Galaxies, ed. F. Durret, A. Mazure, & J. Tran Thanh Van (France: Ed. Frontières), 231
Jones, C., & Forman, W. 1984, ApJ, 276, 38
Morrison, R., & McCammon, D. 1983, ApJ, 270, 119
Mushotzky, R. F., & Szymkowiak, A. E. 1988, in Cooling Flows in Clusters and Galaxies, ed. A. C. Fabian (NATO ASI Ser. C, 229) (Dordrecht: Kluwer), 53
Ohashi, T., & Tsuru, T. 1992, in Frontiers of X-Ray Astronomy, ed. Y. Tanaka & K. Koyama (Tokyo: Universal Acad.), 435
Raymond, J. C., & Smith, B. W. 1977, ApJS, 35, 419
Rephaeli, Y. 1995, ARA&A, 33, 541
Serlemitsos, P. J., et al. 1995, PASJ, 47, 105
Tanaka, Y., Inoue, H., & Holt, S. S. 1994, PASJ, 46, L39
White, D. A., & Fabian, A. C. 1994, in Cosmological Aspects of X-Ray Clusters of Galaxies, ed. W. C. Seitter (NATO ASI Ser. C, 441) (Dordrecht: Kluwer), 453