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X-RAY STUDY OF NGC 1399 IN THE FORNAX CLUSTER OF GALAXIES

Y. IKEBE,[1] T. OHASHI,[1] K. MAKISHIMA,[1] T. TSURU,[1] G. FABBIANO,[2] D.-W. KIM,[2] G. TRINCHIERI,[3]
I. HATSUKADE,[4] K. YAMASHITA,[5] AND H. KONDO[5]

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ABSTRACT

Observations of the cD galaxy NGC 1399 in the Fornax cluster of galaxies with *Ginga* have detected extended X-ray emission out to a radius of more than ~360 kpc. The energy spectrum of this emission is well fitted with an optically thin thermal spectrum with $kT = 1.46^{+0.05}_{-0.21}$ keV with a strong iron emission line corresponding to an iron abundance of $1.1^{+1.3}_{-0.5}$ times solar. The mass of the hot gas responsible for the X-ray emission is nearly the same as the total stellar mass of the cluster. Therefore, the presence of iron at near-solar abundance suggests that the mass of the hot gas ejected from galaxies is comparable to the total stellar mass. This result indicates that most of the hot gas in a very poor cluster is created through ejections from galaxies, rather than being primordial.

Subject headings: galaxies: individual (NGC 1399) — galaxies: intergalactic medium — X-rays: galaxies

1. INTRODUCTION

The X-ray emission of X-ray-bright elliptical galaxies and of clusters of galaxies is dominated by a hot gaseous component with temperatures in the range of 1–10 keV (Sarazin 1988; Fabbiano 1989). It is generally accepted that the hot interstellar medium of galaxies is the result of normal stellar evolution. However, it is being debated how much of the intracluster gas is ejected from galaxies (e.g., Fabbiano 1988) and how these fractions depend on cluster properties. Recently, Hatsukade (1989) found that iron abundance of the hot intracluster medium (ICM) is negatively correlated with cluster temperature. These results suggest that cool poor clusters have a relatively larger content of gas ejected from galaxies (White 1991). Observations of very poor clusters provide a direct means of examining this question.

NGC 1399 is a cD galaxy in the Fornax cluster of galaxies, a nearby very poor cluster. The *Einstein* IPC observations have been analyzed by Killeen & Bicknell (1988, hereafter KB) and more recently by Fabbiano, Kim, & Trinchieri (1992, hereafter FKT) as part of a catalog of galaxies. The *Einstein* data show that the X-ray surface brightness extends throughout the entire IPC field, yielding a total luminosity $L_X \sim 2 \times 10^{42}$ ergs s^{-1} in the 0.5–4.5 keV band at a distance of 27 Mpc (FKT). The radial profile of the X-ray surface brightness was described by KB with an empirical isothermal model (Cavaliere & Fusco-Femiano 1976) with a core radius of 3$'$.8 and $\beta = 0.41$. KB fitted the spectral data with a temperature $kT = 2.6^{+2.9}_{-1.1}$ keV. However, a recent reanalysis of these data (Kim, Fabbiano, & Trinchieri 1991) suggests a temperature $kT > 1.1$ keV at 90% confidence.

The *Einstein* data are limited to the soft X-ray range and do not allow one to explore the question of the iron abundance. For this reason, we have observed NGC 1399 with the LAC instrument (Turner et al. 1989) on board *Ginga*, and we report here the results of this observation.

2. OBSERVATIONS AND RESULTS

The Fornax cluster was first observed in the scanning mode during 1989 November 15–17. A pointed observation of NGC 1399 was then made in 1989 November 17–19. A source-free nearby region of the sky (3^h20^m, $-36°$) was observed on 1989 November 19 to evaluate the field background for the NGC 1399 pointing. Figure 1 shows the scan path and the positions of the LAC field of view (1°.1 × 2°.0 FWHM), for the source and background pointings.

2.1. *Source Extent and X-Ray Flux*

Figure 2 shows the profile resulting from the superposition of 1–8 keV data from 16 scans taken in the low background region of the *Ginga* orbit. Since the observations were carried out when the background was low and stable, the background level is well approximated by a straight line connecting the off-source regions of the profile. This background level is consistent with that independently estimated from the monitor count rates (see Hayashida et al. 1989).

We have estimated the contributions of IPC sources (Harris et al. 1989; see Fig. 1) to the scan profile of Figure 2 using the IPC flux of Gioia et al. (1990) and those of sources in the slew survey (Elvis et al. 1992) assuming suitable energy spectra for each source. We find that these contributions within 2° from NGC 1399 are ~9% of the total count rate, which is therefore dominated by the emission from the Fornax cluster. A nearby elliptical galaxy NGC 1404 has a 0.2–4 keV flux around 15% of the NGC 1399 flux according to FKT. However, the two galaxies lie very close in scan direction, different by 0°.11 and the IPC image by KB suggests that their X-ray halos are almost connected. Therefore, we treat NGC 1399 and NGC 1404 together in the present analysis.

Comparison with the *Ginga* spatial response suggests that the scan profile is extended. Our data, however, do not allow us to discriminate between different functional dependences of the X-ray surface brightness. For comparison with the *Einstein* results (KB) we have fitted the scan profile with a surface

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[1] Department of Physics, University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113, Japan.

[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

[3] Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I50125, Firenze, Italy.

[4] Department of Electronic Engineering, Miyazaki University, 1-1 Gakuen Kibanadai Nishi, Miyazaki 889-21, Japan.

[5] Institute of Space and Astronautical Science, 3-1-1, Yoshinodai, Sagamihara, Kanagaw 229, Japan.

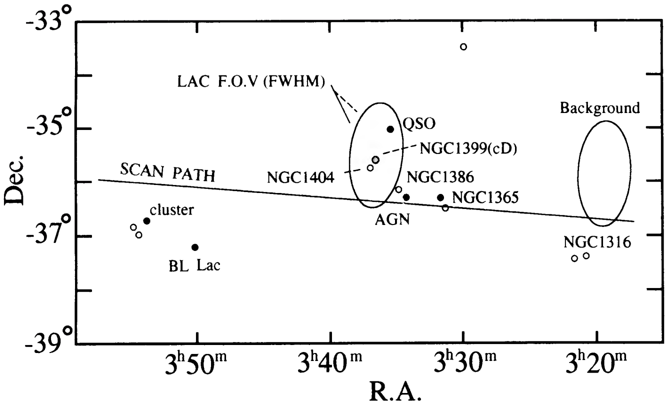

FIG. 1.—The observed sky region. The scan path of the LAC is shown with a solid line, and two ovals indicate the field-of-view directions for the on-source and the background observations for NGC 1399. Circles indicate IPC sources; open circles are stars and galaxies, and filled circles are AGNs and clusters of galaxies.

brightness of the form

$$\Sigma(x) = \Sigma_0\left[1+\left(\frac{x}{a}\right)^2\right]^{-3\beta+0.5}, \qquad (1)$$

where x is the projected radius, a is the core radius, $\beta = (\mu m_p \sigma^2)/(3kT)$, and σ is the three-dimensional velocity dispersion of galaxies (see Cavaliere & Fusco-Femiano 1976). A cutoff radius $R_{\max}$ is also introduced in the profile to avoid divergence. Since the present data is a one-dimensional profile obtained with a large field of view, the surface brightness given by equation (1) is integrated with the collimator response for each scan angle and then compared with the data. The core radius is fixed at $3'\!.8$, the best-fit IPC value by KB, and Σ_0, β, $R_{\max}$, and one-dimensional center position are varied as free parameters.

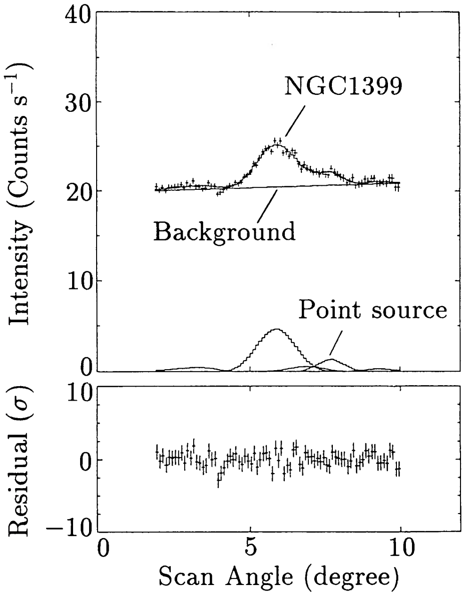

FIG. 2.—Scan profile of NGC 1399/Fornax cluster in the energy 1–8 keV range. The data are fitted with the isothermal "beta" model and an additional point source. The bottom panel shows the residuals of the fit. The parameters are given in Table 1.

TABLE 1

PARAMETERS OF EMPIRICAL ISOTHERMAL MODEL AND CLUSTER PROPERTIES

Parameter	Value
β	$0.23^{+0.16}_{-0.23}$
$R_{\max}$	420^{+210}_{-60} kpc ($0^\circ\!.90^{+0.44}_{-0.13}$)
F_X (2–10 keV)	2.3×10^{-11} ergs cm^{-2} s^{-1}
L_X (2–10 keV)[a]	2.1×10^{42} ergs s^{-1}
$n_{e,0}$[b]	<0.6
$M_{\rm gas}$[c]	$(2.4\text{–}3.5) \times 10^{12}\ M_\odot$
$M_{\rm grav}$[c]	$(1.3\text{–}2.9) \times 10^{13}\ M_\odot$
$M_{\rm stellar}$[c,d]	$\sim 3 \times 10^{12}\ M_\odot$

[a] Distance assumed to be 27 Mpc.

[b] Number density of electrons at the center.

[c] Estimated within 1° from NGC 1399.

[d] L_B of galaxies from Jones & Jones 1980, and $M_{\rm stellar}/L_B = 6$ is assumed.

Figure 2 shows that there is a second fainter source to the right of the NGC 1399 profile. By adding a point source to the model, we obtained an acceptable fit. Because of the large field of view the detailed profile of the X-ray surface brightness is not constrained in the present data, and even $\beta = 0.17$ (a square profile) is acceptable with the corresponding $R_{\max} = 0^\circ\!.85 \pm 0^\circ\!.08$. A $\chi^2_{\min} = 70.2$ ($\nu = 75$) is obtained at $\beta = 0.23$ and $R_{\max} = 0^\circ\!.9$, and the 90% two-parameter confidence limits are $\beta < 0.39$ and $R_{\max} = 0^\circ\!.9(+0^\circ\!.5, -0^\circ\!.2)$, respectively. The centroid of the X-ray emission agrees with the position of NGC 1399 within $0^\circ\!.1$. The β value derived from the *Ginga* data is consistent with the IPC result, $\beta = 0.39$–0.44 (KB). The overall flux, F_X, integrated for the whole emitting region in 2–10 keV assuming a thermal model by Masai (1984) with $kT = 1.4$ keV (see below) is 2.3×10^{-11} ergs cm^{-2} s^{-1}, implying a 0.5–4.5 keV flux consistent with the *Einstein* results (KB; FKT). The corresponding L_X in the 2–10 keV range is 2.1×10^{42} ergs s^{-1} for a distance of 27 Mpc. These results are summarized in Table 1.

2.2. *Spectral Analysis*

The background-subtracted observed energy spectrum of the NGC 1399 region obtained with the pointing observation is shown in Figure 3*a*. We have first fitted these data with a simple thermal bremsstrahlung model, obtaining a minimum $\chi^2 = 28.5$ for $\nu = 11$. The model is unacceptable at more than 99.5% confidence. We notice that the residuals relative to the best-fit model (Fig. 3*b*) show an excess of counts at $\sim$6.7 keV, suggesting the presence of an Fe line. Including a narrow emission line in the model, we obtained an acceptable fit with minimum $\chi^2 = 9.6$ with $\nu = 9$. The line-center energy is 6.57 ± 0.10 keV, and the equivalent width is $3.1^{+1.7}_{-1.3}$ keV. This result indicates that there is a significant iron line in the energy spectrum of NGC 1399.

The data were then compared with the thermal model by Masai (1984), which takes into account the contribution of line emission. By varying intensity, temperature, iron abundance, and $N_{\rm H}$, we obtained a good fit with minimum $\chi^2 = 14.5$ for $\nu = 11$. In this fit, abundances of lighter elements have been fixed at solar values. The residuals for this fit are indicated in Figure 3*c*. The parameter values are listed in Table 2. The 90% constraints on the iron emission line indicate an iron abundance of 0.6–2.4 times solar if the abundance is uniform in space.

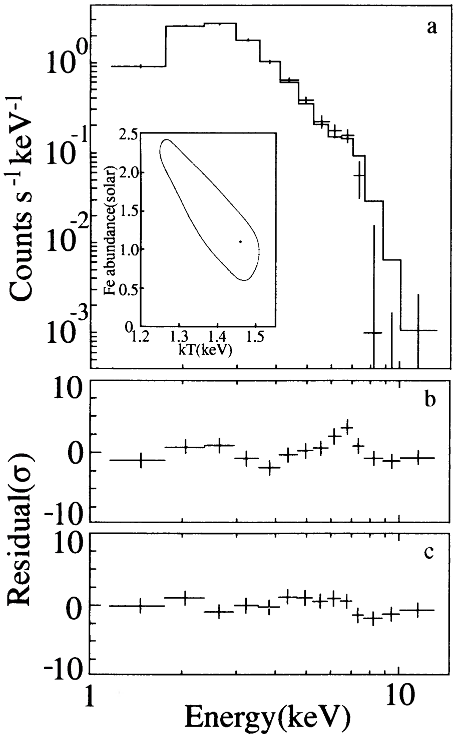

FIG. 3.—(*a*) Pulse-height spectrum of NGC 1399 obtained with the pointed observation, fitted with Masai's thermal model. Confidence contour at 90% limit for two interesting parameters shows the iron abundance against temperature. (*b*) Residuals for a thermal bremsstrahlung model with no emission line. The model is unacceptable at more than 99.5% confidence, and the hump near 6.7 keV indicates the need for an iron K emission line. (*c*) Residuals of the best-fit thermal model ($kT = 1.46$ keV, iron abundance equals 1.1 solar).

3. DISCUSSION

The *Ginga* observations of the Fornax cluster and NGC 1399 have revealed very extended X-ray emission centered at NGC 1399, which is most likely due to thermal emission from hot gas. The cutoff radius obtained for an isothermal model is ~400 kpc assuming $H_0 = 50$ km s^{-1} Mpc^{-1}, 3 times larger than that derived from the IPC observation (KB). Such an extended halo is unusual for elliptical galaxies whose halos generally indicate $R_{\max} < 100$ kpc (Forman, Jones, & Tucker 1985; Trinchieri, Fabbiano, & Canizares 1986), in part due to a limited detector background. This suggests that the hot gas responsible for the extended X-ray emission is bounded by the Fornax cluster, although our data cannot tell the difference in the shape of the hot gas distribution from that observed with IPC around NGC 1399. A similar extended feature has been observed, for example, around M87 in the Virgo cluster (Fabricant & Gorenstein 1983; Takano et al. 1989). The distribution of the hot gas does not apparently follow that of the galaxies, since NGC 1399 lies in the eastern side of the Fornax cluster. If the gas is in the hydrostatic equilibrium, the spatial distribution of the dark matter, responsible for the cluster gravitational potential, might be somewhat different from that of the luminous matter. However, we also note that the X-ray emissivity, scaling with the square of the density, tends to exaggerate the nonuniformity of the gas distribution.

TABLE 2

SPECTRAL FITS

Model	Parameter	Value
Thermal bremsstrahlung	kT	$1.20^{+0.10}_{-0.08}$ keV
	N_H	$<3 \times 10^{21}$ cm^{-2}
	EW	$3.1^{+1.7}_{-1.3}$ keV
Masai 1984	kT	$1.46^{+0.05}_{-0.21}$ keV
	N_H	$<3 \times 10^{21}$ cm^{-2}
	Fe abundance	$1.1^{+1.3}_{-0.5}$ solar

The binding mass, assuming hydrostatic equilibrium, and isothermality, is calculated using the formula by Fabricant & Gorenstein and shown in Table 1. The result suggests that the binding mass is larger than the mass of the hot gas or visible matter by a factor of 5–10. However, a clear answer for the need of a massive dark halo would require precise measurement of the brightness profile as well as the temperature gradient with radius (see Trinchieri, Fabbiano, & Canizares 1986).

The temperature of the hot gas is ~1.4 keV, close to the values obtained for elliptical galaxies (Forman, Jones, & Tucker 1985; Trinchieri, Fabbiano, & Canizares 1986; Awaki et al. 1991; Kim, Fabbiano, & Trinchieri 1992) and for poor clusters of galaxies (Kriss, Cioffi, & Canizares 1983). The 90% confidence limits on the iron abundance, assuming no abundance gradient, is 0.6–2.4 times the solar value. This is significantly higher than the observed iron abundance in rich clusters and marginally consistent with that in poor clusters. In fact, as shown in Figure 4 the result of the Fornax cluster agrees with the trend of inverse correlation between the iron abundance and the cluster temperature, first pointed out by Hatsukade (1989). The relation is now confirmed for a very poor cluster.

The observed iron abundance at ~1 solar in the Fornax cluster suggests that a major fraction of the hot intracluster gas may have been deposited through ejection from galaxies. Before concluding this, we need to examine the possibilities which would make the situation somewhat complex. First, strong central concentration of iron, as suggested for the Perseus and Virgo clusters (Ponman et al. 1990; Koyama, Takano, & Tawara 1991), would cause an apparent abundance

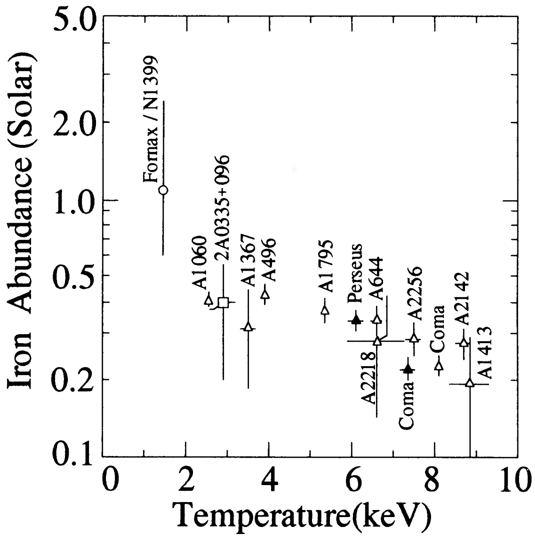

FIG. 4.—Correlation between iron abundance and temperature for various clusters of galaxies including the present result on Fornax cluster. Data shown with triangles originally appeared in Hatsukade (1989): open ones observed with *Ginga* and filled ones with *Tenma*, respectively. Open square (2A0335+096) is the result by Singh, Wastergaard, & Schnopper (1986).

higher by a factor of less than ~10 from the "real" value. Since we cannot spatially resolve the iron line strength, we cannot rule out this possibility. Recent BBXRT results (Serlemitsos et al. 1991) suggest similar values of abundance to our measurement in two fields of a few arcminutes radii centered on NGC 1399. The uncertainties on these measurements are such that the existence of a gradient cannot be firmly established. Second, if the hot gas ejected from galaxies is extremely iron rich (> 10 times solar), a small amount of ejected gas can explain the observed abundance. However, the recent *Ginga* observation of an elliptical galaxy NGC 4472 has shown an upper limit for the equivalent width of iron K-line to be 1.5 keV (see Table 4 in Awaki et al. 1991), corresponding to the iron abundance less than the solar value. This suggests that the gas ejected from elliptical galaxies would have rather low iron abundance. Therefore, if the iron line emission is not centrally concentrated and the hot gas ejected from the Fornax galaxies contains only about one solar abundance of iron, then the hot intracluster medium (showing an iron abundance approximately solar) would almost entirely consist of the gas ejected from galaxies rather than the primordial gas.

As shown in Table 1, the $M_{\rm gas}$ derived here is comparable to the luminous mass, $M_{\rm stellar}$, in the Fornax cluster, both estimated within 1°0 from NGC 1399. Galaxies may lose comparable mass to their luminous matter in the gas ejection process. Recent simulations of the evolution of the interstellar medium in elliptical galaxies (David, Forman, & Jones 1990; D'Ercole et al. 1989; Ciotti et al. 1991) suggests that up to 40% of the initial luminous mass can be ejected from galaxies in the form of galactic winds.

To conclude, we stress that spectroscopic imaging observations, covering the iron K energy band, will be essential in furthering our understanding of the origin of the hot intracluster medium and of the evolution of the interstellar medium of elliptical galaxies. ASTRO-D will allow us to make a big step forward towards the solution of these issues.

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