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Radial Distributions of the Temperature and Metal Abundances in the Ophiuchus Cluster of Galaxies

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Abstract

We report on the first result concerning the Ophiuchus cluster of galaxies observed with ASCA during the performance-verification phase. The obtained image in the energy range of 0.7–10 keV is nearly circular, and the peak of the X-ray surface brightness is coincident with the position of the cD galaxy. We analyzed the ASCA GIS data within a $13'.8$ radius of the cluster center while considering the energy-dependent flux-contaminated effect due to ASCA X-ray telescope. This data can be well explained with the isothermal β model, in which the density profile is expressed with a β profile of $r_{\rm core} = 3'.8$ and $\beta = 0.62$, and the temperature and metal abundances are constant at $kT = 9.8$ keV and $Z = 0.24\ Z_{\odot}$. The central excess density profile obtained with Einstein HRI is also consistent with the ASCA GIS data.

Key words: Galaxies: abundances — Galaxies: clusters of — Galaxies: individual (Ophiuchus cluster) — Galaxies: X-rays — X-rays: sources

1. Introduction

The Ophiuchus cluster of galaxies is a nearby rich cluster lying near to the galactic center ($l = 0^\circ.5,\ b = 9^\circ.4$) with an optical redshift of $z = 0.028 \pm 0.003$ (Johnston et al. 1981) and with a distance of 170 Mpc for $H_0 = 50$ km s^{-1} Mpc^{-1}. There is a cD galaxy at the center of the cluster (Wakamatsu, Malkan 1981). The X-ray observations were performed by HEAO-1 A2 (Johnston et al. 1981), Einstein, EXOSAT (Arnaud et al. 1987), Tenma (Okumura et al. 1988), and Ginga (Kafuku et al. 1992). The Ophiuchus cluster is one of the most luminous clusters with its obtained X-ray luminosity of (1.3–1.9)$\times 10^{45}$ erg s^{-1}. The X-ray surface-brightness profile observed with Einstein HRI was nearly circular (Arnaud et al. 1987). The temperature and metal abundances derived from the previous observations were in the range of $kT = 9.4$–11 keV and $Z = 0.16$–$0.26\ Z_{\odot}$, respectively. No spatial distributions of these parameters have yet been investigated.

In this paper, we report on the radial distributions of the temperature and metal abundances of the Ophiuchus cluster of galaxies obtained with the ASCA satellite (Tanaka et al. 1994). ASCA is the first satellite which enables us to measure an X-ray brightness profile in the high-energy band up to 10 keV, and to investigate the distributions of the temperature and metal abundances with a good energy resolution. ASCA carries four identical X-ray telescopes (XRT) and four focal-plane detectors, two gas imaging spectrometers (GIS) (Ohashi et al. 1996; Makishima et al. 1996) and two solid-state imaging spectrometers (SIS) (Burke et al. 1991). Since the point-spread function (PSF) of the XRT, which is an image of a point source, is broad (Serlemitsos et al. 1995), the detected flux in a region is contaminated by photons from the other regions. Moreover, the XRT PSF depends on the energies and the incident positions of the X-ray photons. These XRT effects are quite serious for an analysis of extended sources, such as clusters of galaxies (Ikebe 1995). Therefore, the conventional analysis method, fitting independently the individual spectra extracted from the different regions, is no longer usable for extended sources. We have to take into account this energy-dependent flux-contaminated effect due to the XRT PSF in order to determine the distributions of the temperture and metal abundances of a cluster (see Ikebe 1995)

We describe the observations in section 2, the surface brightness distribution of all the observations and the spectral fitting results within a $6'$ radius of this cluster center in section 3 and the radial distributions of the temperature and metal abundances in section 4. A discussion is given in section 5.

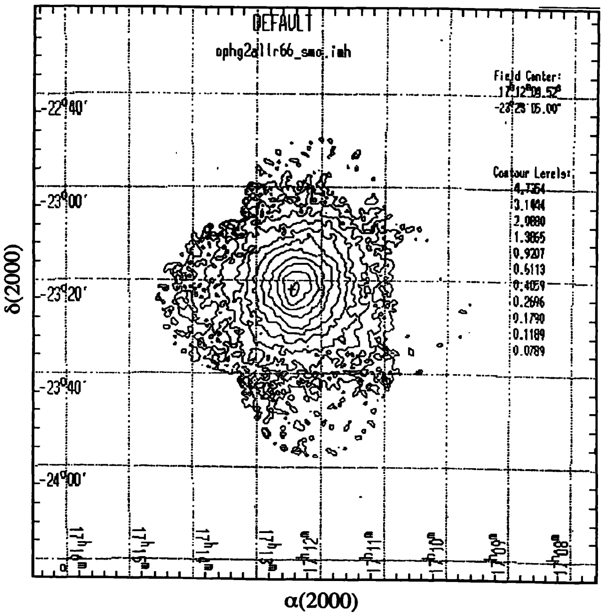

Fig. 1. Surface brightness of the Ophiuchus cluster of galaxies observed with the GIS2 in the 0.7–10 keV energy band. The count rates were corrected based on the efficiency and exposure time. The data were smoothed by convolution with a 2D Gaussian of a standard deviation of 0.′37. The contour levels show the relative counts per 1 pixel. The cross mark shows the position of a cD galaxy (Wakamatsu, Malkan 1981).

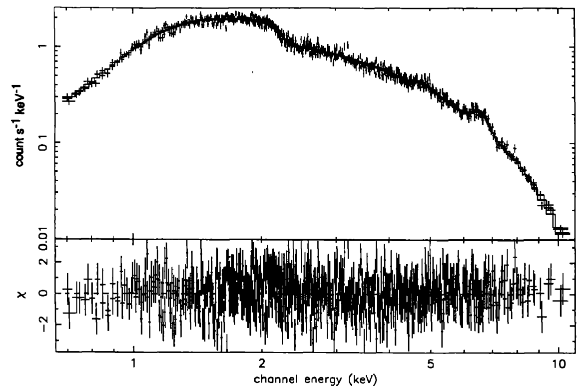

Fig. 2. GIS spectrum (crosses), fitting model (curves) and rediduals in terms of sigmas with error bars of size one (χ)(lower panel) within a 6′ radius of the cluster center. The thermal-plasma model for fitting was the Raymond-Smith model.

2. Observations

ASCA observed the Ophiuchus cluster of galaxies from 1993 August 26 to August 28 during the performance-verification phase. Five pointing observations were performed in total; one pointing was at the cluster center, and four pointings were about 20′ offset from the center. In this paper we present mainly the results from the center pointing observation. The GIS sensors were operated in the PH normal mode. The effective exposure time of the center pointing was $\sim$ 12 ks, and the mean count rate, including the background, was 9.6 count s^{-1} for each GIS sensor.

3. X-Ray Images and Spectra

GIS2/3 images of the Ophiuchus cluster show that the X-ray surface-brightness distribution is nearly circular (figure 1). The peak of the X-ray surface brightness is at $(\alpha, \delta)_{2000} = (17^{\rm h}12^{\rm m}25^{\rm s} \pm 4^{\rm s}, -23°22' \pm 1')$. This peak of the X-ray surface brightness coincides with the position of the cD galaxy determined by Wakamatsu and Malkan (1981) and with that of the X-ray luminosity peak observed by Einstein HRI (Arnaud et al. 1987) within the uncertainty of the ASCA aspect solution.

In figure 2, we show the GIS spectrum within a 6′ radius of the cluster center, which we adopted as a reference spectrum of this cluster. We binned the spectrum so that the minimum count per bin is 110. The background was taken from observations of the blank sky, which has no apparent bright sources, and contains the inctrinsic detector backgournd and cosmic diffuse X-ray background. We fitted the spectrum to two models: a thermal-emission model from an optically-thin hot plasma given by Raymond-Smith model (1977, in XSPEC Ver.8.6.1), and a thermal-bremsstrahlung model plus two narrow lines representing the iron-Kα and Kβ lines. In both models, we included the galactic absorption with the hydrogen column density as a free parameter. We obtained acceptable χ^2 values for both models; the best-fit parameters are summarized in table 1. These results are consistent with the previous results of HEAO-1 A2, Einstein Observatory, EXOSAT, Tenma, and Ginga.

4. Radial Distributions of the Temperature and Metal Abundances

In order to analyze an extended source, especially to determine the distributions of the temperature and metal abundances in a cluster, we need to fit the spectra from the different regions simultaneously with a cluster model which includes the spatial distributions of the gas density and temperature (see Ikebe 1995). Therefore, in this study, we employed the ASCA instrument simulator (Ikebe 1995), in which all of the instrumental re-

Table 1. Best-fit parameters to the GIS spectrum within a 6′ radius.

Raymond-Smith model			
kT(keV)	Redshift	$Z(Z_{\odot})^*$	$N_{\rm H}(10^{21}{\rm cm}^{-2})$
$9.9^{+0.5}_{-0.4}$	$0.031^{+0.004}_{-0.007}$	$0.29^{+0.04}_{-0.04}$	$2.9^{+0.1}_{-0.1}$
χ^2/d.o.f. 780.1/609			

Thermal bremsstrahlung + two lines							
		Fe Kα line			Fe Kβ line		
kT (keV)	$N_{\rm H}$ ($10^{21}{\rm cm}^{-2}$)	E (keV)	Intensity $\left(\frac{10^{-4}{\rm photon}}{{\rm cm}^{-2}\ {\rm s}^{-1}}\right)$	EW (eV)	E (keV)	Intensity $\left(\frac{10^{-4}{\rm photon}}{{\rm cm}^{-2}\ {\rm s}^{-1}}\right)$	EW (eV)
$9.7^{+0.4}_{-0.4}$	$2.9^{+0.1}_{-0.1}$	$6.60^{+0.04}_{-0.04}$	$6.0^{+0.8}_{-0.8}$	231^{+32}_{-32}	$7.8^{+0.1}_{-0.2}$	$1.6^{+0.9}_{-0.9}$	90^{+47}_{-47}
χ^2/d.o.f. 787.2/607							

* The metal abundances are the numbers of nuclei per hydrogen nucleus relative to the cosmic abundances of Anders and Grevesse (1989), e.g., $N({\rm Fe})/N({\rm H}) = 4.68 \times 10^{-5}$.

sponses, including the XRT PSF, GIS RMF (energy redistribution matrix), and their quantam efficiency were fully taken into account, and GIS events, were generated from the given incident X-ray photons using the Monte-Calro method. The XRT PSFs were constructed from the actually observed images of Cyg X-1.

We investigated the radial distributions of the temperature and metal abundances within a 13′.8 radius of the cluster center, where we could obtain a sufficient number of photons for the present analysis. We divided the region within a 13′.8 radius into 8 annular regions, so that the number of GIS events was about 10^4 in each region. Thus, we derived a total of 16 spectra from the two GIS sensors. The outer radii of these 8 annuler regions are 2′.0, 3′.2, 4′.3, 5′.4, 6′.6, 8′.2, 10′.3, and 13′.8. We binned the spectra so that the minimum count per bin was 60. We fitted these 16 spectra simultaneously.

As the model, we employed an isothermal cluster having a constant metal-abundance distribution. We assumed that the X-ray emitting hot intracluster gas is distributed in spherically symmetry, and that its maximum radius is 19′.6 ($\sim$ 1 Mpc). It was assumed that the density distribution of the gas can be expressed with the β model,

$$n(r) = n_0 \left[1 + \left(\frac{r}{r_{\rm c}}\right)^2\right]^{-3\beta/2}, \quad (1)$$

where n_0 is the central density, r is the distance from the cluster center, and $r_{\rm c}$ is the core radius. The galactic hydrogen column density was assumed to have constant distribution within 19′.6. We employed a Raymond-Smith model with a fixed redshift of $z = 0.031$ as a thermal-plasma model.

We generated X-ray photons based on the above cluster model and converted to the simulated GIS events using the ASCA instrument simulator. From the simulated events, we made a set of 16 spectra from the corresponding annular regions. We added the background spectra to the simulated spectra. We then compared them with the actually observed spectra in order to evaluate the goodness of the model cluster. We made the total photons of the simulated spectra about 12-times those of the observed spectra in order to reduce the statistical errors in the simulation. The free parameters were $r_{\rm c}$, β, kT, Z, and $N_{\rm H}$. We added systematic errors of 5% and 4% to the simulated spectra and to the background spectra, respectively (see Ikebe 1995).

The best-fit spectra are shown in figure 3. The best-fit parameters are shown in table 2. The model with the constant temperature and metal abundances within a 13′.8 radius is acceptable. The luminosity of the best-fit model is 1.8×10^{45} erg s^{-1} in the 0.7–10 keV band within a 13′.8 radius, and the estimated central electron density is $n_0 = 9.2 \times 10^{-3}$ cm^{-3}.

5. Discussion

It is known that galactic diffuse X-ray emission exists along the galactic plane (e.g. Koyama et al. 1989). Since the Ophiuchus cluster is near to the galactic center ($l =$ 0°.5, $b =$ 9°.4), we estimated the contamination of the above observed spectra from the galactic diffuse X-ray

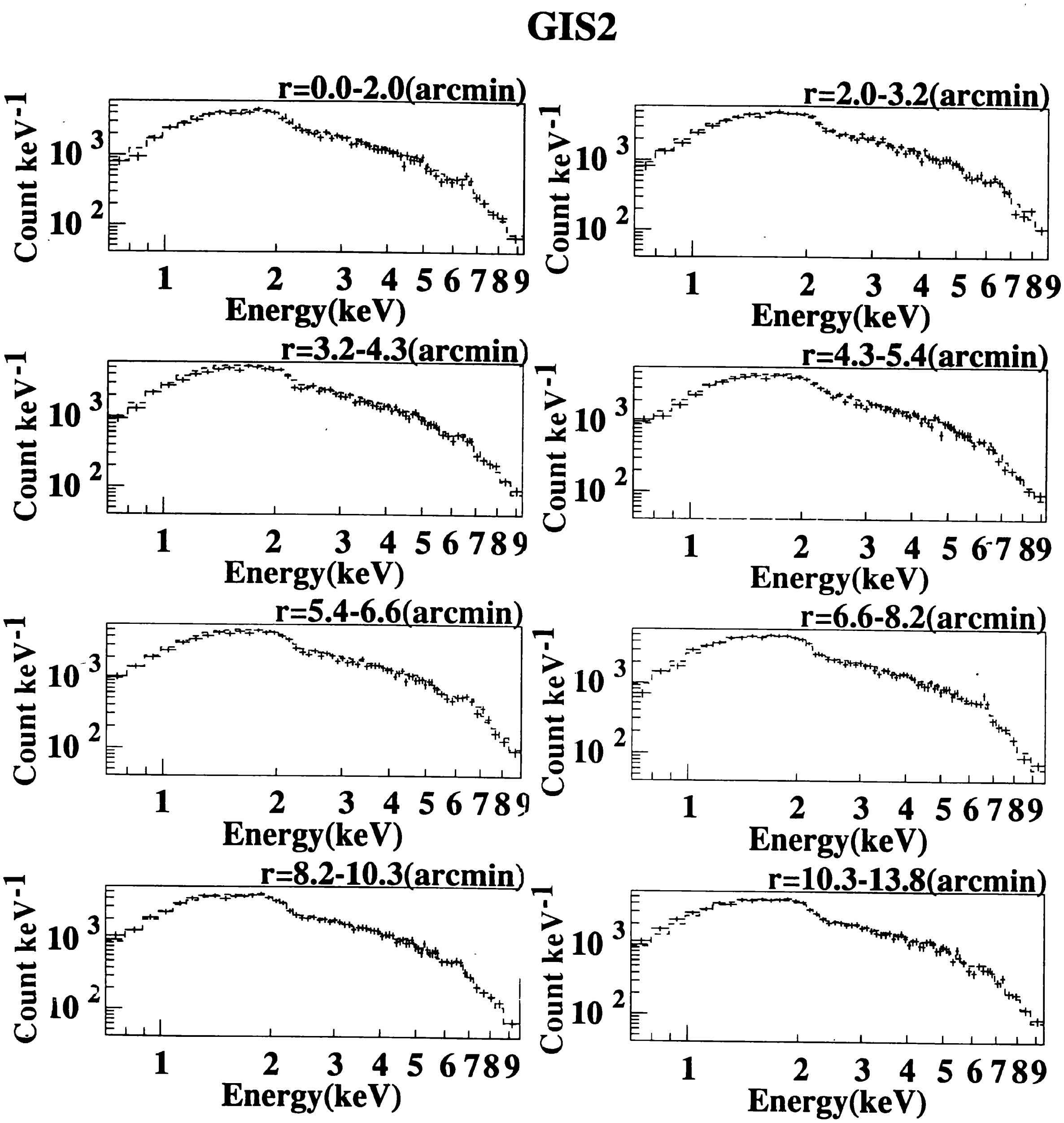

Fig. 3. GIS2 and GIS3 spectra (crosses), the simulated fitting model spectra (dashed lines) in each annular region.

emission. Ginga LAC performed a scanning observation along the galactic plane from $l = -5°$ to $l = 4°$ at $b = 9.^\circ5$ (Yamauchi 1993). The surface brightness of the galactic diffuse component near to the Ophiuchus cluster has been estimated to be $\sim 1 \times 10^{-8}$ erg s^{-1} cm^{-2} sr^{-1} in the 1.1–9.2 keV energy band. On the other hand, the surface brightness in the most outer region at a $10.'3$–$13.'8$ from the cluster center is $\sim 3 \times 10^{-6}$ erg s^{-1} cm^{-2} sr^{-1} in the 1–10 keV band. Thus, the flux contamination from the galactic diffuse component is negligible for the spectra of the Ophiuchus cluster within a $13.'8$ radius.

In figure 4, we compare the electron-density distribution of the ASCA GIS best-fit model with that obtained with Einstein HRI (Arnaud et al. 1987). The ASCA den-

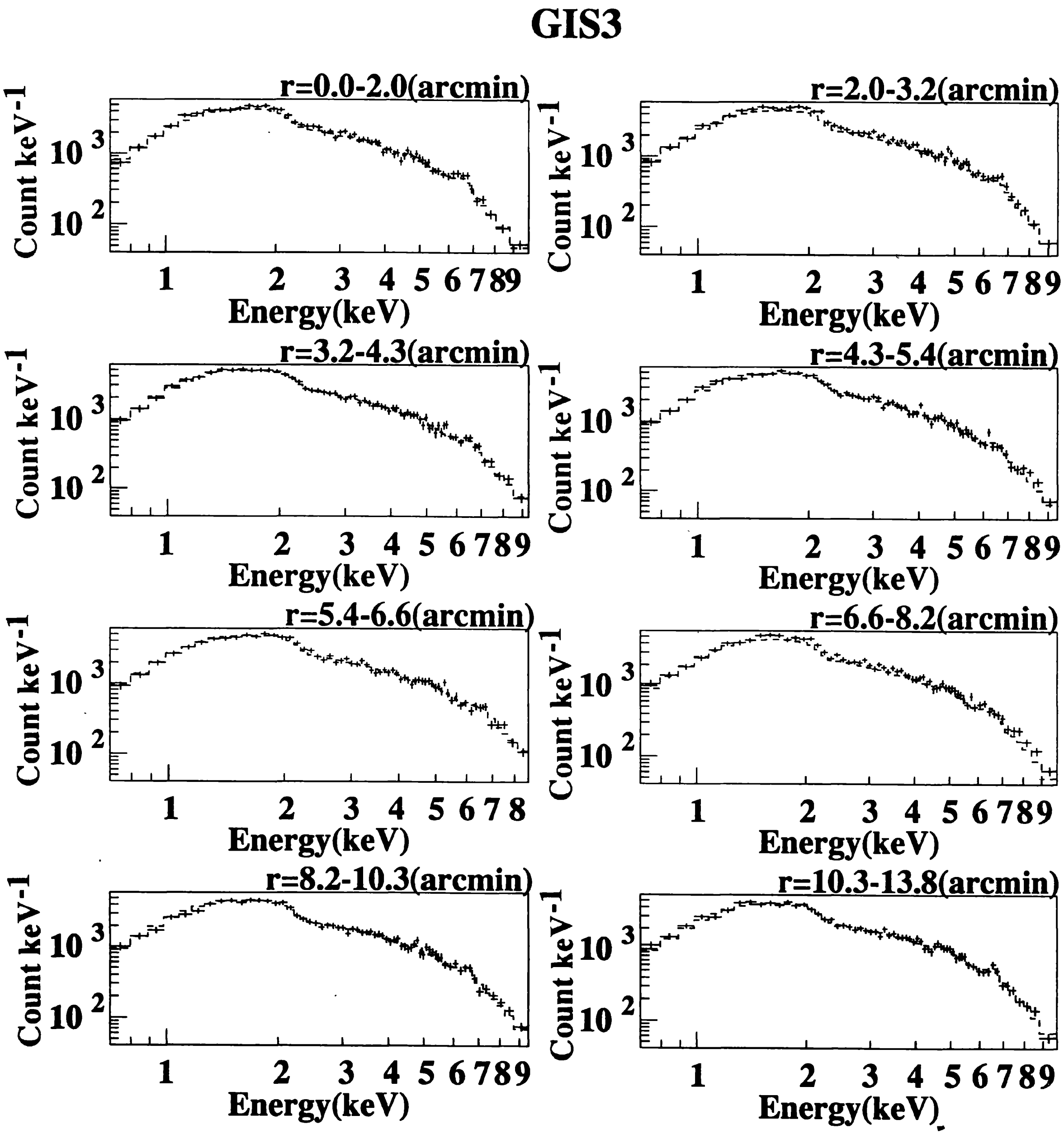

Fig. 3. (continued)

sity distribution agrees quite well with that of Einstein HRI, except within a $1'$ radius, where an excess over the β model is found. Based on this excess, Arnaud et al. (1987) suggested that the Ophiuchus cluster has a cooling flow within a $1'$ radius. However, since ASCA has a much broader spatial resolution than that of Einstein HRI, ASCA may not resolve the excess density profile within a $1'$ radius observed with Einstein HRI. We then examined the consistency of the central excess density profile and the cooling flow with the above ASCA GIS data by the above-mentioned fitting method in section 4.

First, we employed the following density profile $n(r)$ as a fitting model to test the existence of the central excess in density profile:

Table 2. Best-fit parameters to the 16 GIS spectra within a 13.′8 radius.

n_0 (cm^{-3})	r_c (arcmin)	β	kT (keV)	Z ($Z_\odot$)*	N_H ($10^{21} cm^{-2}$)
9.2×10^{-3}	$3.8^{+0.1}_{-0.2}$	$0.62^{+0.01}_{-0.02}$	$9.8^{+0.7}_{-0.3}$	$0.24^{+0.03}_{-0.06}$	$2.8^{+0.3}_{-0.3}$
		χ^2/d.o.f.	1078/1023		

* The metal abundances are the numbers of nuclei per hydrogen nucleus relative to the cosmic abundances of Anders and Grevesse (1989), e.g., $N(\mathrm{Fe})/N(\mathrm{H}) = 4.68 \times 10^{-5}$.

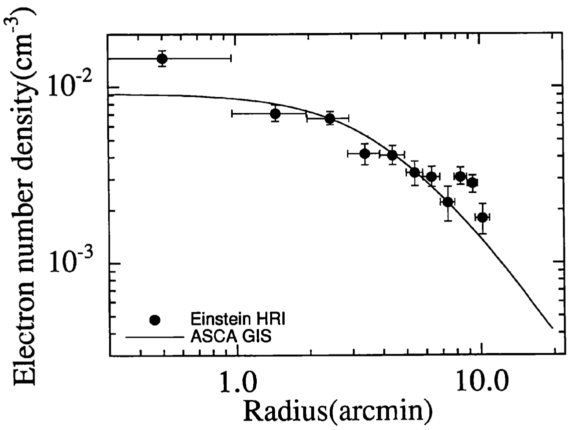

Fig. 4. Density radial distribution of the Einstein HRI data (closed circles) and that of the ASCA best-fit β model with the GIS spectra (solid line).

$$n(r) = n_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta/2} + n',$$
$$n' = \begin{cases} 0.59 \times n_0 & (r \leq 1') \\ 0 & (r > 1') \end{cases}. \quad (2)$$

Here, n' is estimated from the central density ratio of the Einstein HRI data to the ASCA GIS best-fit β model. We again performed simultaneous to fit the above 16 GIS spectra with this density profile, assuming a constant temperature. The minimum χ^2 of the isothermal central excess β model is 1080 for 1023 degrees of freedom, and is not improved compared with the previous result based on the isothermal β model.

We next checked for any deviation from isothermality in the central part of the cluster. When the cooling flow is present, the central temperature is expected to be lower than that of the outer regions. We varied the temperature within a 1′ radius independently from the outer temperature down to 2 keV, and examined how the minimum χ^2 values vary with the central temperature. We fitted the 16 GIS spectra with a model in which the central excess in the density profile is defined in equation (2). The minimum χ^2s are 1079–1081 for 1021 degrees of freedom, and are thus not significantly improved regardless of the central temperature.

Therefore, the ASCA GIS data are consistent with the central excess density profile obtained by the Einstein HRI observation, and gives no constraint on the temperature structure within a 1′ radius, where Arnaud et al. suggested the existence of a cooling flow. On a large scale, we confirmed the isothermality up to ~ 700 kpc from the cluster center with broad band (0.7–10 keV) ASCA spectroscopy.

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