Temperature Map and Iron Abundance of the Ophiuchus Cluster of Galaxies

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Abstract

We present an X-ray surface-brightness distribution and a temperature map of the Ophiuchus cluster of galaxies observed by ASCA. The Ophiuchus cluster is a nearby rich cluster located at $z = 0.028$ having an angular extent of $\sim 1^\circ$. The observations were made by five pointings that cover the whole cluster. After deconvolution with the ASCA complex response function, we obtained the surface-brightness distribution with an angular resolution of 2$'$ and a temperature map with 8$'$ resolution. The X-ray surface-brightness distribution shows a nearly spherically symmetric distribution, except for a 15$\sigma$ image excess at the position of 10$'$ to the north of the cluster center. On the other hand, a hot region with a temperature $> 13$ keV is spread over a region of $20' \times 30'$ at 20$'$ to the west of the cluster center. Because these characteristics are similar to those of the Coma cluster, we conclude this cluster has never relaxed dynamically, and is also recently experienced a merger.

Key words: galaxies: clusters: individual (Ophiuchus) — galaxies: evolution — X-rays: galaxies

1. Introduction

The Ophiuchus cluster is a nearby rich cluster located in the direction near to the galactic center ($l = 0^\circ.5, b = 9^\circ.4$). Optical observations identified 150 member galaxies in a crowded area associated with the Ophiuchus cluster with a core radius of 9.5$'$ (Wakamatsu, Malkan 1981). The redshift was derived from a spectroscopic observation of the cD galaxy at the cluster center to be $0.028 \pm 0.003$, corresponding to a distance of 170 Mpc for $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ (Johnston et al. 1981). A galaxy survey and spectroscopic observations of the galaxies around the Ophiuchus cluster were performed by Hasegawa et al. (2000) for a $12^\circ \times 17^\circ$ area. They identified seven new clumps of galaxies and showed that these clumps and the Ophiuchus cluster formed a large-scale structure of supercluster size. The X-ray image of the central region was observed to be nearly circular using the EINSTEIN HRI (Arnaud et al. 1987). The X-ray spectrum of the whole cluster was obtained 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). These results show a temperature of 9–11 keV, an iron abundance of 0.16–0.49 relative to the cosmic value and the metal abundance in the central region within a radius of 12$'$ using the ASCA data. They didn’t find any significant substructure in their analysis. We analyzed all of the data covering a radius of 30$'$ to derive the temperature and the abundance distribution.

In this paper, we present a temperature map and an X-ray image in the 0.5–10 keV band of this cluster. In section 2, we describe the observation and analysis methods of spectro-imaging and spectral fitting. Special care was taken for background subtraction, since the contribution of the galactic diffuse X-ray emission is significant in this region. The results including the X-ray image, the temperature map, and the spectra are given in section 3, we discuss these results in section 4.

2. Observation and Analysis Method

The Ophiuchus cluster was observed by five pointings with ASCA that cover the angular extent of the whole cluster, as described in Matsuzawa et al. (1996). Ten X-ray images in total were taken with the two GIS detectors (GIS 2 and GIS 3), whereas the SIS detectors partially covered the GIS field of view (FOV) due to the smaller FOV with $22' \times 22'$. These data were screened with ASCA standard processing tools (Arnaud 1993), using the criteria of a minimum Earth elevation angle of $5^\circ$ and a cut-off rigidity of 6 GV. The observed GIS images were combined together, as shown in figure 1, after correcting the exposure time and boresight, and subtracting the background. The SIS data were used for spectral analysis in the central region.

2.1. Background

Diffuse background spectra observed in the direction of the Ophiuchus cluster are somewhat different from the ASCA standard background spectra normally used for the analysis of clusters of galaxies. Since its direction is close to the galactic center, the contribution of the galactic ridge emission is not...
Fig. 1. Five pointed ASCA observations are shown with circles with radius 18′ (GIS field of view) superimposed on a contour map of the observed surface-brightness distribution after a correction for the exposure time and subtraction of the BGD. The image center is RA = 258°02′, DEC = −23°39′.

Fig. 2. GIS spectrum in the source-free region of H 1705−250 (solid marks) and the ASCA standard background spectrum (dotted marks). The count rate in the 0.7–3 keV band is higher by the factor of two, while that in 3–10 keV band is almost the same as the standard background. It is not possible to obtain a useful galactic ridge background spectrum for the case of the SIS due to the smaller FOV. The contribution of the background becomes significant in the outer region of the cluster.

2.2. Spectro-Imaging Analysis

After subtracting the proper background, we constructed X-ray images in three energy bands of 0.5–10 keV (total band), 0.5–3.0 keV (soft band), and 3.0–10.0 keV (hard band) over the whole cluster. The total band image was binned into 2′ × 2′ pixels. The pixel size of the soft and the hard band images was made larger to be 8′ × 8′ for deriving the Hardness Ratio (HR) with good statistics. We excluded pixels whose number of counts was less than 20 for the total band and 200 for the soft and the hard bands from the image analysis because of its large statistical uncertainty.

The ASCA X-ray telescope (XRT) has a complex Point Spread Function (PSF) which depends on the incident energy and off-axis angle from the optical axis of the XRT. Our analysis took into account this effect, as described in Watanabe et al. (1999) (hereafter W99) in detail.

We started to simulate X-ray images of the Ophiuchus cluster in the soft, hard, and total bands with initial conditions of the isothermal temperature of 10 keV and the observed image. We estimated the differences of images and HRs between the observed data and the simulated values, and then adjusted the source image and the temperature distribution. Again, we performed a second simulation with the corrected image and the temperature distribution. The deconvolution process was carried out in such a way to iterate this simulation until the differences between the data and simulated values were smaller than systematic and statistical errors. The HRs were converted to a plasma temperature ($kT$) based on the assumption of a single temperature. The $kT$–HR relation was estimated from ASCA full simulation, and is shown in figure 3 as a function of the off-axis angle. In this relation, we include the effect of the spurious photons, which are coming from the out-of-field of view due to the largely extended ASCA XRT PSF, and includes the effect in the $kT$–HR relation and compensate it. We used the mean value if the noticed region was overlapped by two observations.
2.3. Spectral Fitting

In order to confirm the temperature distribution derived by the method mentioned above, we performed a spectral fitting of a Raymond–Smith model (Raymond, Smith 1977) to the observed spectra of the GIS in six regions divided by referring to the temperature map. We derived the plasma temperatures and the iron abundances relative to the solar value, e.g., \( N(\text{Fe})/N(\text{H}) = 4.68 \times 10^{-5} \) (Anders, Grevesse 1989). The hydrogen column density was fixed at the galactic value, \( 3.0 \times 10^{21} \) atoms cm\(^{-2}\), in this direction. We also fitted the spectra with a thermal bremsstrahlung model of a single temperature and Gaussian lines to derive the ionization temperature, line energies, and intensities of Fe-K\(\alpha\). The SIS detectors made it possible to resolve the He-like and the H-like Fe-K\(\alpha\) lines. The ionization temperature was obtained by the intensity ratio of the He-like and the H-like Fe-K\(\alpha\) lines and compared with the electron temperature derived from the continuum component. The energy band was important for the spectral analysis. For the GIS data we used the galactic ridge background in the 0.7–10 keV region and the ASCA standard background in the 3–10 keV region. An SIS spectral analysis was performed in the 3–10 keV region by subtracting the ASCA standard background, since the galactic ridge one was not available. Subtracting the background was not very significant for the analysis in the central region. We tried to derive the redshift of this cluster by means of the shift of the mean line energies of the Fe-K\(\alpha\) obtained from the GIS and SIS spectra.

3. Results

3.1. Surface-Brightness and Temperature Distribution

The temperature map and the surface-brightness distribution in the total band thus obtained for the Ophiuchus cluster are shown in figure 4. The position center is RA = 258° 02′, DEC = −23° 39′. The typical errors for the temperatures are estimated to be 1.5 keV in the central region and 2–6 keV in the outer region, which are caused by statistics and the sensitivity of the \( HR \) to the temperature. The radial profile of the surface-brightness distribution was fitted with the \( \beta \) model in the radius of 3′–20′. The core radius (\( R_c \)) and \( \beta \) were obtained to be 3′ 2 and 0.64, respectively. These values are roughly consistent with those derived within the radius of 13′ 8 by Matsuzawa et al. (1996). The image excess from the \( \beta \) model is shown in figure 5. A hot region (\( kT > 13 \) keV) spreads out to 20′ off to the west and extends to the north, having a size of 20′ × 30′. The surface-brightness of this region is 4\( \sigma \) lower than the average value derived by the \( \beta \) model, as shown in figure 5. The other hot region is seen at 20′ off to the south from the center. A 15\( \sigma \) image excess region is seen at 10′ off to the north, which coincides to 1RXS J171209.5−231005 reported in the ROSAT All-Sky Survey Bright Source Catalogue (Voges et al. 1999). If this source is excluded in the radial profile fitting, \( R_c \) and \( \beta \) would be changed to be 2′ 5 and 0.62, respectively. The temperature in this region is obtained to be 10 keV and somewhat lower than that in the central region.

3.2. Spectra in Subdivided Regions

The best-fit parameters of the GIS spectra derived by the spectral fitting in the 0.7–10 keV (total band) and the 3–10 keV
These temperatures \(k T\) are summarized in Table 1 for the 6 subdivided regions. The differences in the temperatures are explained by introducing a non-thermal component of which the contribution is estimated to be less than 10%. The mean line energies of Fe-K \(\alpha\) given in Table 2 are systematically smaller than the expected values by 0.028 obtained for cD galaxies (Johnston et al. 1981) and 0.0288 for 18 galaxies in the central region (Hasegawa et al. 2000) by optical observations. This difference is a bit marginal within the accuracy of the energy calibration.

### Discussion

A temperature map of the Ophiuchus cluster derived from the spectro-imaging analysis clearly shows the existence of a hot extended region in the outer envelope. This fact was also confirmed by a spectral fitting from which the plasma temperatures were derived in six subdivided regions. A spectral analysis was also made in the 8 annular regions within a radius of 13.8 by Matsuzawa et al. (1996). Their results are consistent with ours in the central region. This temperature and surface-brightness distribution are similar to those of the Coma cluster of galaxies reported in W99. The patchy temperature distribution obviously indicates that this cluster has not been dynamically well relaxed. This means that the large-scale hot region could be produced by cluster merging, extending more
than 1 Mpc. Roettiger et al. (1997) and Takizawa (1999) numerically simulated the process of cluster merging. They show surface-brightness and temperature distributions as a function of the elapsed time after the epoch of merging in the several cases of model parameters. Referring to their results, it seems that this cluster would be formed by cluster merging within 1 Gyr, as in the case of the Coma cluster.

The image excess shown in figure 5 coincides to a source of 1RXS J171209.5–231005 and also corresponds to the lowest temperature region. This indicates that a small group of galaxies having lower temperature is projected on, or associated with, the Ophiuchus cluster. Identification of the optical counterpart is not available, since optical observations are very difficult in this region close to the galactic center.

The iron abundance was obtained to be 0.33–0.89 in 6 subdivided regions. The Coma cluster does not show any significant variation of the iron abundance over the whole cluster, which is 0.22 in the central region (Watanabe et al. 1997). Okumura et al. (1988) derived the iron abundance of the Ophiuchus and the Coma cluster to be 0.42 and 0.27 averaged over the whole cluster by Tenma observations with a field of view of 3°1 × 2°5, respectively. This fact indicates that the Ophiuchus cluster is chemically more evolved than the Coma cluster. Allen and Fabian (1998) examined the abundance of cooling and non-cooling flow clusters, which are 0.344 ± 0.057 and 0.207 ± 0.054 on average, respectively. The Ophiuchus cluster is more centrally concentrated, like a cooling flow cluster, having a core radius of 3°2 (160 kpc), while the Coma cluster has 9°3 (380 kpc) (W99). However, this cluster has a much higher temperature than do cooling clusters.

We speculate that the Ophiuchus cluster was formed by a merging of two clusters with different abundance. The intra-cluster gas has not yet mixed up well, but has been heated up by shock waves. The abundance distribution is a good indicator for the mixing of intracluster gas caused by the merging process. It seems that the relaxation time of ICM mixing is longer than that of shock propagation. Thus, the relatively high temperature of the Coma and the Ophiuchus clusters is well explained by cluster merging.

5. Summary

We have found some dynamical structure of the Ophiuchus cluster from the X-ray surface-brightness distribution, temperature map, and spectra in the subdivided regions obtained by ASCA:

1. The surface-brightness distribution is nearly spherically symmetric, and is represented by the \( \beta \) model with
$R_c = 3'2$ and $\beta = 0.64$ for a radius of $3' < r < 20'$.

2. A hot region is extended from the west to the north in the outer envelope with an angular size of $20' \times 30'$.

3. The excess emission with $15\sigma$ coincides to 1RXS J171209.5−231005 located in the lowest temperature region.

4. The iron abundance in hot regions is higher than that in other regions by a factor of 2, at most.

This observational evidence could be explained by the cluster merging process.

References

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