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Metal Concentration and X-Ray Cool Spectral Component in the Central Region of the Centaurus Cluster of Galaxies

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Abstract

Spatially resolved energy spectra in the energy range 0.5–10 keV have been measured for the Centaurus cluster of galaxies with ASCA. Within $10'$ (200 kpc) from the cluster center, the helium-like iron K emission line exhibits a dramatic increase toward the center rising from an equivalent width $\sim$ 500 eV to $\sim$ 1500 eV corresponding to an abundance change from 0.3 to 1.0 solar. The presence of strong iron L lines indicates an additional cool component ($kT \sim 1$ keV) within $10'$ from the center. The cool component requires absorption in excess of the galactic value and this excess absorption increases towards the central region of the cluster. In the surrounding region with radius greater than $10'$, the spectra are well described by a single temperature thermal model with $kT \sim 4$ keV and spatially uniform abundances at about 0.3–0.4 times solar. The detection of metal-rich hot and cool gas in the cluster center implies a complex nature of the central cluster gas which is likely to be related to the presence of the central cD galaxy NGC 4696.

Key words: Galaxies: abundances — Galaxies: clustering — Galaxies: clusters: individual: (Centaurus) — X-rays: galaxies

1. Introduction

Detailed measurements of the properties of hot intracluster medium (ICM), such as its temperature structure and metal distribution, are now essential for our correct understanding of the evolution of ICM and its connection to galaxies in a cluster. Previous observations suggested that outside the central region of the cluster the ICM is roughly isothermal (Hughes et al. 1993; Allen et al. 1992), however many objects exhibit excess X-ray emission in the central region which may be interpreted due to a cooling flow (e.g., Fabian et al. 1984). Iron K line measurements show that abundance of the ICM is 0.2–0.6 solar, therefore part of the ICM must have been ejected from member galaxies. Metal concentration within clusters have been reported for Virgo (Koyama et al. 1991) and Fornax (Serlemitsos et al. 1993) clusters. For Perseus cluster Ponman et al. (1990) and Kowalski et al. (1993) reported a significant iron concentration, which was, however, not confirmed with BBXRT measurement (Arnaud et al. 1991). None of these observations to date are based on spatially resolved energy spectra in its exact sense. ASCA (Tanaka et al. 1994) has now opened the opportunity for high quality X-ray imaging spectroscopy.

The Centaurus cluster of galaxies is one of the nearest and the X-ray brightest Abell clusters (A3526) at a distance of 64 Mpc ($H_0 = 50$ km s^{-1} Mpc^{-1} and $z = 0.0107$). Measurements from non-imaging satellites indicate a temperature between 3 and 4 keV with an iron abundance of about 0.44 times solar. Imaging observations from Einstein Observatory and ROSAT indicate a cooling flow with 20–90$M_{\odot}$ yr^{-1} (Matilsky et al. 1985, Thomas et al. 1987, Canizares et al. 1988, Allen, Fabian 1994) within 100–150 kpc from the center. The spectral observations from HEAO-1 A2 (Mitchell, Mushotzky 1980) and from Ginga (M. Yamanaka, Y. Fukazawa, private communication) suggest a complex spectrum that is not well described by a single temperature model. Here, we report the first results with ASCA, revealing the spatially resolved energy spectra of the Centaurus cluster.

2. Observations and Results

The pointing observations centered on the cD galaxy NGC 4696 were performed on 1993 June 30. Two additional pointings near the edge of the cluster were made, which will be reported elsewhere. The present data have total exposure time of about 23000 s with the GIS (Ohashi et al. 1991) operated in PH normal mode and the SIS (Burke et al. 1991) in 4CCD faint or bright mode. Only faint-mode data from the SIS (12000 s) are used in the present analysis. Since the detector response for extended emission are not yet available, the response matrix employed here is the one for a point source on the optical axis. Correction have been made for vignetting. Data from different sensors or chips are combined after correcting for the gain, for the GIS and the SIS, respectively. In view of these situations, results presented here do not depend on the response matrix details.

Since the emission of the Centaurus cluster covers the full field of view of the GIS (diameter $\sim 50'$), the data are divided according to the angular distance r from the cluster center. In this way, the variation of the energy spectrum in the radial direction of the cluster can be seen directly. Figure 1 shows three pulse-height spectra for each of the GIS and the SIS. Background, for both diffuse X-rays and non X-rays, is subtracted using observations in several blank sky fields. As is evident (figure 1) the emission-line features change dramatically with the radius. The emission lines are the strongest in the center ($r < 5'$ or about 100 kpc), and weaker in the outer region ($r > 10'$). The continuum slope shows no large change with radius. The change in the equivalent width of the Fe K line combined with the relative constancy of the temperature of the high energy continuum implies that the abundance is changing with radius. A close look at the SIS spectra indicates that the K-lines from O (0.65 keV), Si (1.84, 2.0 keV), S (2.4, 2.6 keV), Ar (3.1 keV), and Ca (3.9 keV), as well as the Fe-L line complex (0.8–1.5 keV) are also stronger in the central region.

The spectra in the outer region ($r > 10'$) can be well described by a single temperature thin thermal plasma model (Raymond, Smith 1977) with the galactic column density. The temperature is about 3–4 keV with a metal abundance of 0.3–0.4 times solar. We use XSPEC ver. 8.3 in the analysis. Typical best-fit χ^2 values are 205 for 154 degrees of freedom for the GIS. (This is not formally acceptable, but inclusion of a 1 keV component with about 5% of the total flux gives a reduced χ^2 of 1.1.) We have fixed abundance ratios amongst the different elements to be solar. These temperatures are consistent with Ginga results. In contrast to this, the spectra in the center region are inconsistent with a 1-temperature model showing a χ^2 value of 411 for 154 degrees of freedom for the GIS. To look at the line features closely,

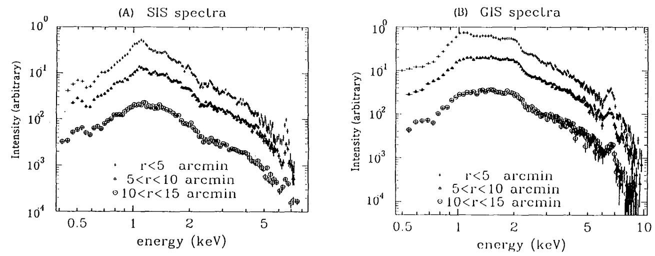

Fig. 1. Pulse-height spectra of the Centaurus Cluster for three different regions sliced by the distance r from the cluster center, i.e. $r < 5', 5' < r < 10'$, and $10' < r < 15'$ with $1'$ corresponding to about 20 kpc in the cluster. Two panels show results for (a) the SIS and (b) the GIS.

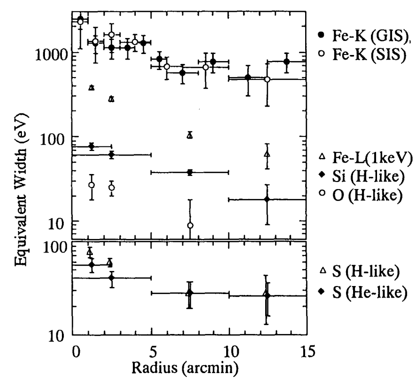

Fig. 2. Equivalent width of emission lines plotted as a function of radius from the cluster center. Single-temperature thermal bremsstrahlung model with narrow gaussian lines at fixed energies is assumed in the fit. Results for Fe-L, Si, O, and S lines are obtained with the SIS.

we fit the spectra using a single temperature thermal bremsstrahlung spectrum as a continuum model and add several gaussian lines. The equivalent width of each line is plotted in figure 2 as a function of r. The equivalent width of the iron K line becomes larger, by a factor of ~ 3, from the outer region to the center, which is much larger than the change of equivalent width with temperature. This clearly indicates that the iron abundance increases toward the center. The iron L lines, whose presence requires an additional cool component, show a similar trend as a function of radius. The lines from O, Si, and S indicate abundance around one solar in the center ($r < 5'$), but are statistically unconstrained in the outer region.

Based on the above results, we fitted the spectra with 2-temperature Raymond-Smith models. The metal abundances for the cool component are assumed to be same as for the hot component, since the data do not allow an independent determination of the abundance and the normalization of cool component. We note that the flux of the hot component dominates the cool component by a factor of > 2 at all radii. In figure 3 we show the radial

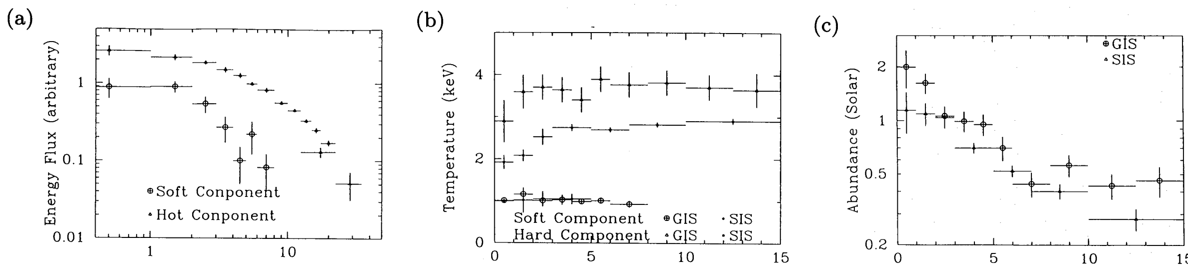

Fig. 3. Profiles of (a) surface brightness, (b) temperatures, and (c) abundances vs. radius (arcmin). Two-temperature Raymond-Smith model is assumed. Abundances for the hot and the cool components are assumed to be the same.

profiles of the respective temperatures, the metal abundances, and the surface brightness. There is a discrepancy in temperature for the GIS and the SIS due to the uncertainty in their response functions. The abundance values for the two instruments shown in figure 3 should therefore be regarded as an uncertainty range of the absolute values. The cool component is required within 10′ from the cluster center. The surface brightness of the cool component shows a steep rise toward the center. While the metal abundance seems constant at $r > 10'$, it starts to increase at $r < 5'$ and becomes about 1 solar or larger at the center. $N_{\rm H}$ shows a significant excess over the galactic $N_{\rm H}$ of 5×10^{20} cm^{-2} within $r < 5'$ and increases to about 1×10^{21} cm^{-2} towards the center.

Two sulfur lines, due to He-like and H-like ions, are resolved. The electron temperature expected from the observed ratio of the two lines is 2.2 ± 0.2 keV, significantly lower than that of the hot component. This supports the presence of the cool component. The equivalent width of the lines are consistent within 15% for a plasma with a solar sulfur abundance.

The radial profile of the surface brightness is similar to the Einstein results. Assuming a core radius of 5′ (Matilsky et al. 1985) similar to the scale of the cD galaxy, we obtain a value for the β-model parameter for the hot component alone of, $\beta = 0.49 \pm 0.05$, which is consistent with the Einstein result, 0.45 ± 0.03 (Matilsky et al. 1985). The cool component produces an excess emission in the central region.

It should be pointed out that the radial extension of the cool component and the region of enhanced abundance cannot be due to a point-like source in the center. Data for point-source observations indicate that the intensity should drop to half at an offset position of $\sim 1'.3$, however the cool component, for example, extends to about 3′ before it drops to half of the central intensity.

3. Discussion

ASCA observations have provided clear evidence of a cool spectral component, a strong concentration of iron within 10′ in the central region of the Centaurus cluster and of excess absorption in the central region. The cool component in the center region may be interpreted in terms of cooling flow models. A multi-temperature cooling flow spectrum does not disagree with the abundance gradient. However, we have shown that the measured spectra in the center region is still dominated by the hot component. In order to investigate projection effects, we estimate the relative flux from the core region and outer region respectively in the same line of sight. The parameters of $\beta = 0.4$–0.6 and core radius of 5′ are employed. The result is that the flux from the core region ($r < 5'$) in the hot component is 60–80% of that expected from the projected spectrum. Therefore most of the continuum flux of hot component seen in the central 5′ region comes from the core region, and this implies that a large amount of the hot component should exist within the core. This is a new finding, and it indicates that the gas does not cool uniformly and that we must consider alternate models such as inhomogeneous cooling-flow models (see Fabian et al. 1984, Thomas et al. 1987, Sarazin 1992).

Based on the emission measure of the hot and cool components with the 2-temperature model fitting, we calculate the ratio of density and volume assuming pressure equilibrium to be $n_{\rm cool}/n_{\rm hot} \sim 3.5$ and $V_{\rm cool}/V_{\rm hot} \sim 0.05$, respectively. This suggests that the cool component is either confined within 30 kpc or occurs in relatively dense filaments. Confinement within 30 kpc is, however, not consistent with the spatial extent of the cool component. The mass of the hot and the cool components are 3–$6 \times 10^{11} M_{\odot}$ and 1–$2 \times 10^{11} M_{\odot}$ within 100 kpc, respectively.

Spatial variation of the iron abundance has been unambiguously detected. The observed equivalent width of iron K line in the GIS data shows a dramatic increase from 500 ± 100 eV at $r > 10'$ to 1500 ± 300 eV in the center. The change of equivalent width by a factor of ~ 3 is much more than can be attributed to observed variation of plasma temperature with radius. Also, the flux of iron K lines associated with the hot component is much higher than that of the cool component whose temperature is less than about 1.5 keV. Therefore, the presence of abundance gradient in the Centaurus cluster is detected in a model independent manner. Based on the two temperature thermal fit, the metal abundances in the center is 1.0 ± 0.1 times solar compared with 0.35 ± 0.05 solar in the outer region. These results further suggest that possibly other metals are showing the similar abundance gradient.

The central spherical region within $5'$ emits roughly 20% of the continuum flux of the entire cluster integrated over $\sim 20'$. A simplified assumption that the iron abundance is 1.0 solar within $5'$ and 0.35 solar for the rest leads to an average abundance (measured with non-imaging instruments) of 0.48 solar. This is very close to the value (0.46 ± 0.05) obtained from the Ginga measurement (M. Yamanaka, Y. Fukazawa, private communication).

Clear evidence of metal concentration has been found for two rather cool clusters, the Virgo (Koyama et al. 1991) and the Centaurus clusters. It may be related to the mass ratio of the gas supplied from the member galaxies to the ambient ICM. The 2–10 keV luminosity of the Centaurus cluster is determined to be 7×10^{43} erg s^{-1} with Ginga (M. Yamanaka, Y. Fukazawa, private communication), which is about half of the expected L_X based on the L_X versus T relation (Edge, Stewart 1991). Therefore, the density of ICM in the Centaurus cluster is factor of $\sim \sqrt{2}$ lower than the average, suggesting that the contribution of the metal rich gas injected from the cD galaxy in central regions of the cluster is relatively high. The Virgo cluster has very similar properties (see Edge, Stewart 1991). If this interpretation is correct, gas-poor clusters may tend to show a strong metal concentration towards the center.

The mass of iron within $5'$ from the cD galaxy NGC 4696 is estimated to be $(5\text{–}10) \times 10^8 M_\odot$, using the gas mass and the β-model parameters. This amount corresponds to 0.06–0.12% of the stellar mass of NGC 4696 assuming $M/L \sim 8(M/L)_\odot$ and $L_B = 10^{11} L_\odot$ (Tully 1988). Injection of iron at a level of order 0.1% of stellar mass through the life of a cD galaxy is just about possible, based on the galactic-wind scenario (Arimoto, Yoshii 1987). However, the temperature of the hot component responsible for iron K lines indicates that the plasma is bound by the large-scale potential of the whole cluster, not by the cD galaxy only. This suggests that much of the iron-rich hot gas would eventually escape away from the potential of NGC 4696. Then, it would be necessary that much more iron than presently observed has been produced by the cD galaxy.

The origin of the metal concentration clearly needs extensive study. If the presence of a cD galaxy implies mergers during the cluster formation, metal concentration may have resulted from the mass ejection from member galaxies in this process. On the other hand, merger process would disturb and efficiently mix the central region and would rather suppress the metal concentration. Ram pressure stripping, in which many galaxies are involved, must be enhanced in the core where the gas is densest. It is, however, not clear which are the key factors in creating the observed metal concentration.

ASCA observation of the Centaurus cluster has revealed three new features: a rise in the abundance of Fe in the central regions, the co-existence of hot ($\sim$ 4 keV) and cool ($\sim$ 1 keV) components in the central 100 kpc ($r < 5'$) region, and the mapping of extra absorption in the central regions. The structure of the ICM in this region is likely to be complex, and further comparison of the properties for various clusters based on ASCA observations would bring us the correct view of the cluster center.

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