Proceedings of *The Riddle of Cooling Flows in Galaxies and Clusters of Galaxies*: E41
May 31 – June 4, 2003, Charlottesville, Virginia, USA
Ed. T. H. Reiprich, J. C. Kempner, & N. Soker

XMM-Newton Observation of the Centaurus Cluster

Isao Takahashi,[1] Madoka Kawaharada,[1] Kazuo Makishima,[1] Yasushi Ikebe,[2] and Takayuki Tamura[3]

[1] *University of Tokyo*
[2] *JCA(Joint Center for Astrophysics) UMBC(University of Maryland, Baltimore County) / GSFC(Goddard Space Flight Center)*
[3] *SRON(Space Research Organization Netherlands) / ISAS(The Institute of Space and Astronautical Science)*

By analyzing the *XMM–Newton* data of the Centaurus cluster, the picture obtained by *ASCA* is examined and refined. The radially sorted EPIC spectra can be reproduced by a two components model with temperatures of 3.8 keV and 1.7 keV, and the derived radial profiles of volume filling factor of the cool phase and the Fe abundance are generally consistent with those measured with *ASCA*. At the very central region ($r < 12\ h_{75}^{-1}$ kpc), another cool emission with a temperature of ~ 0.7 keV is seen, which was not detected by *ASCA*. The isobaric cooling flow model cannot reproduce the data, because cool emission components with temperatures less than 0.5 keV are insignificant.

1. Introduction

The central regions of clusters have particular importance. Concerning its physical condition, we have analyzed the *ASCA* data in detail (e.g., Makishima et al. 2001) and found that something is wrong with the widely believed cooling flow hypothesis (e.g., Fabian 1994). Now it becomes clear that the cooling flow hypothesis contradicts the results of *XMM–Newton* (e.g., Tamura et al. 2001) and *Chandra*. Through *ASCA* analyses, our group has suggested another interpretation (e.g., Makishima et al. 2001), which provide us with a valuable working hypothesis.

The Centaurus cluster ($z = 0.0104$) is one of the most suitable targets for the study of central regions, because it is near, luminous, and has an outstanding central cool component. By using *ASCA*, Fukazawa et al. (1994) have shown that not only cool but also hot emission comes from the 3-dimensional core region ($r < 60\ h_{75}^{-1}$ kpc). Strong metal concentration toward the center has also been detected. Ikebe et al. (1999) have utilized both the *ASCA* and *ROSAT* data and shown that the whole spectral and spatial emission properties are well explained by assuming a two-phase plasma, one is hot (~ 4 keV) and the other is cool (~ 1.5 keV), confined in a double-beta gravitational potential.

Here, we try to confirm and refine the *ASCA* picture with *XMM–Newton*. The observation was carried out in 2002 January (PI=Dr. Y. Ikebe), and yielded Good Time Intervals of about 35 ksec total. We assume $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$.

2. EPIC Results

In Figure 1, we show background subtracted EPIC spectra extracted from seven concentric annular regions. For comparison, the *ASCA* GIS spectra from nearly the same regions, taken from Ikebe et al. (1999), are also shown. Obviously, the *XMM–Newton* spectra reveal low-energy lines much more clearly than *ASCA*, while *ASCA* successfully detected the hard emission from regions much further out owing to its very low and stable background.

The *XMM–Newton* spectra indicate that the sulphur line is almost hydrogenic outside $r \sim 5'$ ($60\ h_{75}^{-1}$ kpc), and hence the plasma temperature is higher than about 4 keV. As we go to inner regions, the representative temperature clearly decreases. Characteristic shapes of the right shoulder of the Fe-L complex show the presence of a plasma component with a temperature of about 2 keV. At the innermost region, Fe-L lines below 1 keV emerge, indicating the presence of a plasma component with a temperature less than 1 keV. Therefore, the *XMM–Newton* spectra reveal at least three typical temperatures; about 4, 2, and little less than 1 keV. Since *ASCA* did not have a sufficient sensitivity to detect the coolest component, there is no contradiction.

First, we excluded the very central region, within $1'$, and applied a conventional single temperature analysis. The obtained radial temperature profile is shown in Figure 2. As is often seen in other clusters, the temperature gradually decreases toward the center to about half the outermost temperature. We also carried out the two-phase analysis after the *ASCA* results, with the two temperatures fixed at 3.8 keV and 1.7 keV. When we consider the systematics, the fit goodness is statistically comparable to those obtained in the single temperature analysis. As representative parameters obtained with the two-phase analysis, Figure 3 shows the volume filling factors of the cool phase and the Fe abundances. The *ASCA* results from Ikebe et al. (1999) are also shown, and they are consistent. Therefore, *XMM–Newton* confirms the *ASCA* results, though model dependent.

In the very central region, the single-temperature model becomes no longer acceptable, because of the coolest component with a temperature less than 1 keV. This component is not taken into account in the *ASCA* picture. To understand properties of the emission from

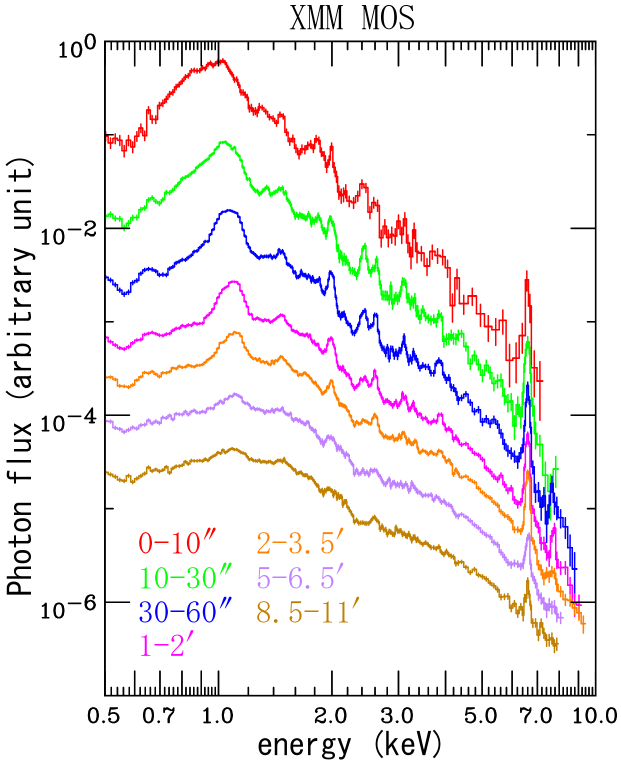

FIG. 1.— The *XMM-Newton* MOS (left) and *ASCA* GIS (right) spectra of the Centaurus cluster, extracted from various concentric annuli. Vertical scale is arbitrary. $1'$ corresponds to 12 h_{75}^{-1} kpc.

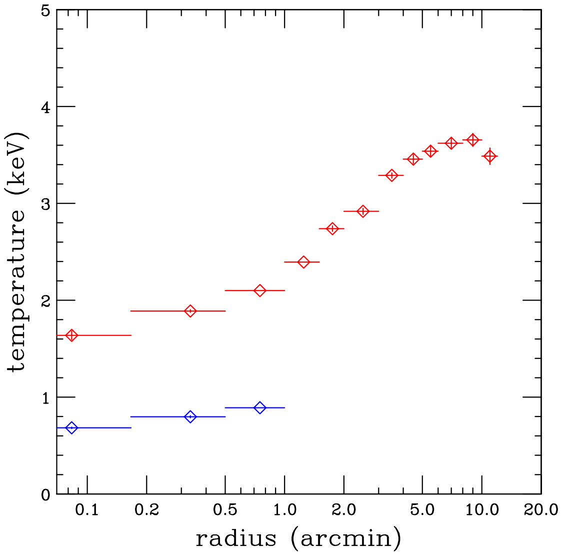

FIG. 2.— Radial profiles of the plasma temperature, derived assuming a single phase for $r > 1'$ and two phases for $r < 1'$.

the central region, we simply applied a two component model with free temperatures, which is unrelated to the *ASCA* two phase model. The whole spectra are generally reproduced successfully, yielding the temperature profiles as shown in Figure 2. Therefore, the coolest plasma component with a temperature of about 0.7 keV exists at the very center. It is localized within $1'$, or 12 h_{75}^{-1} kpc, of the cD galaxy.

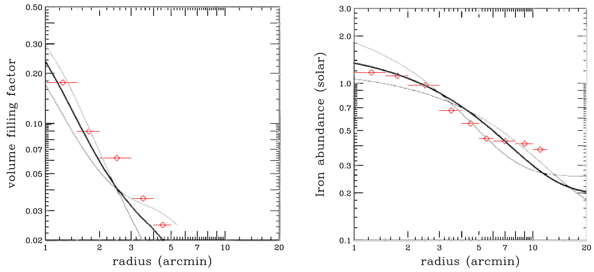

FIG. 3.— Radial profiles of (left) volume filling factor of the cool phase and (right) iron abundance are shown in red, obtained with a two phase model with the temperature fixed at 3.8 keV and 1.7 keV. Thick solid lines show the best-fit model obtained with *ASCA*, while thin lines represent 90 % confidence limits of the model. See Ikebe et al. (1999) for details.

The luminosities of the ~ 4 keV, 1.7 keV, 0.7 keV components turned out to be 5×10^{43} h_{75}^{-2} erg s^{-1}, 5×10^{42} h_{75}^{-2} erg s^{-1}, and 5×10^{41} h_{75}^{-2} erg s^{-1}, respectively. The former two values well coincide with the *ASCA* results. The coolest component, which was not detected with *ASCA*, only contributes about 1 % to the total luminosity.

3. **RGS Results**

We also analyzed the RGS data for the further study of the properties of the central region. The RGS spectrum extracted within $1'$ is shown in Figure 4. Many Fe-L lines from various ionization states are detected; the emission cannot be from a single temperature plasma. If we ap-

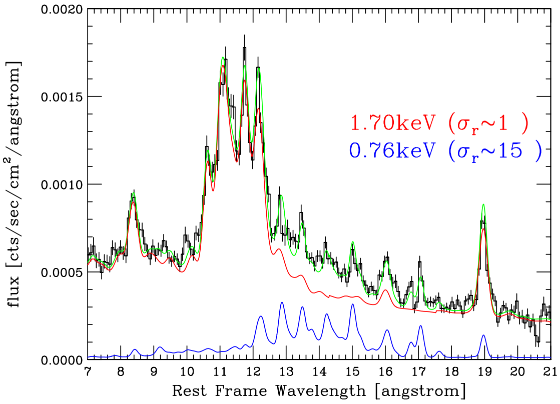

FIG. 4.— The RGS spectrum extracted from the central 60″ is shown in histograms. Rough contributions of the two components and their sum are indicated in solid lines.

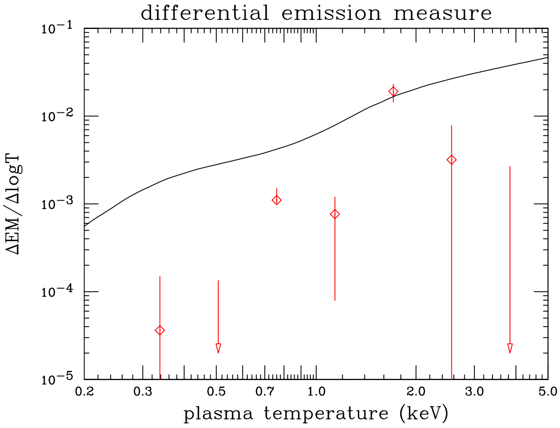

FIG. 5.— Differential emission measure obtained with a 7 component model is shown in red. The solid line, of which the scale is arbitrary, shows the prediction from the isobaric cooling flow model.

ply the two temperature modeling, the whole spectrum is reasonably reproduced with the temperatures of 1.7 keV and 0.76 keV. Rough contributions of the two components are also indicated in Figure 4. This is consistent with the EPIC results. The lines from the lower temperature component seem to be narrower, suggesting that it is localized within a narrower region.

To study whether there are other temperature components or not, we carried out multi component fitting (Tamura et al. 2003). We prepared seven components, whose temperature intervals were fixed at a step of factor 1.5. We left the normalization of each component and the maximum temperature to be free. The result is shown in Figure 5. The 1.7 and 0.7 keV components are still prominent. The RGS results agree with the *ASCA* view (∼ 1.5 and 4 keV), because the hot emission would be weak in such a small central region. We find that the 1.1 keV component is relatively weak when compared with the 1.7 and 0.7 keV components, so the temperature distribution may be discrete, rather than continuous. For reference, the prediction from the isobaric cooling flow model is also shown in Figure 5. It is revealed that the coolest emission below 0.5 keV is very weak, and the isobaric cooling flow model is very unlikely.

4. **Summary**

The *XMM-Newton* results on the Centaurus cluster are generally consistent with those from *ASCA*. There are 3 typical plasma temperatures, roughly 4, 1.7, and 0.7 keV, with a rough luminosity ratio of 100 to 10 to 1. The coolest component, which was not detected with *ASCA*, is localized to a very central region ($r < 12\ h_{75}^{-1}$ kpc). Cool emission with temperature below 0.5 keV is insignificant, implying that the ordinary cooling flow picture does not hold.

References

Fabian, A. C., ARA&A, 32, 277, 1994
Fukazawa, Y., et al., 1994, PASJ, 46, L55
Ikebe, Y., et al., 1999, ApJ, 525, 58
Makishima, K., et al., 2001, PASJ, 53, 401
Tamura, T., et al., 2001, A&A, 365, L87
Tamura, T., et al., 2003, A&A, 399, 497