TEMPERATURE MAP OF THE PERSEUS CLUSTER OF GALAXIES OBSERVED WITH ASCA

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ABSTRACT

We present a two-dimensional temperature map of the Perseus Cluster based on multipointing observations with the ASCA Gas Imaging Spectrometer, covering a region with a diameter of ~2°. By correcting for the effect of the X-ray telescope response, the temperatures were estimated from hardness ratios, and the complete temperature structure of the cluster with a spatial resolution of about 100 kpc was obtained for the first time. There is an extended cool region with a diameter of ~20' and kT ~ 5 keV about 20' east of the cluster center. This region also shows higher surface brightness and is surrounded by a large ringlike hot region with kT ≥ 7 keV and is likely to be a remnant of a merger with a poor cluster. Another extended cool region is extending outward from the IC 310 subcluster. These features and the presence of several other hot and cool blobs suggest that this rich cluster has been formed as the result of a repetition of many subcluster mergers.

Subject headings: galaxies: clusters: individual (Perseus) — intergalactic medium — X-rays: galaxies

1. INTRODUCTION

Temperature maps of clusters of galaxies give almost direct knowledge about the history of past subcluster mergers. Many clusters are now known to exhibit significant temperature structures in the intracluster medium (ICM) based mainly on ASCA observations, and these results give us a view that clusters of galaxies are still evolving (see, e.g., Markevitch 1996; Markevitch et al. 1998). However, the spatial resolution of ASCA is not capable of resolving 100 h⁻¹ kpc scale structures for objects at z ≥ 0.03. On the other hand, nearby clusters (z < 0.03) are very extended, with 0.5r₅₀₀ > 1°, which requires us to perform multipointing observations. This makes the analysis complicated because of the energy-dependent point-spread function (PSF) of the ASCA X-Ray Telescope (XRT), and only recently have several results been available (Watanabe et al. 1999, 2001; Kikuchi et al. 2000; Shibata et al. 2001; Furusho et al. 2001).

This Letter reports the temperature structure of the Perseus Cluster (A426, z = 0.0183) over a radius of 170 (~2 h⁻¹ Mpc). This is the brightest cluster in the X-ray sky and a very suitable object for the study of various properties of the ICM. The Position Sensitive Proportional Counter (PSPC) image of the Perseus Cluster showed significant substructures east of the cluster center, which has been interpreted as evidence that the cluster is not in a relaxed state but has undergone recent mergers (Schwarz et al. 1992; Ettori, Fabian, & White 1998). Following the initial ASCA study on the temperature variation for the central pointing (Arnaud et al. 1994), Ezawa et al. (2001) showed the large-scale metal abundance gradient and fluctuation of temperature distribution in four sectors based on mapping observations from ASCA. They also reported an extended soft component in the cluster center, characterized by a temperature kT ~ 2 keV. A recent Chandra image showed a complicated X-ray morphology around the central galaxy NGC 1275 (Fabian et al. 2000).

In this Letter, we report on the two-dimensional temperature map with the resolution of 2.5 (78 h⁻¹ kpc) derived from multipointing observations of the Perseus Cluster with ASCA. We use H₀ = 50 h₀ km s⁻¹ Mpc⁻¹ and q₀ = 0.5, which indicate 1' = 31 kpc at the Perseus Cluster. The solar number abundance of Fe relative to H is taken as 4.68 × 10⁻³ (Anders & Grevesse 1989).

2. OBSERVATION AND ANALYSIS

ASCA observations of the Perseus Cluster were performed on four separate occasions between 1993 August and 1997 February. The number of pointings is 13, with an average exposure time of 10–20 ks each, and the total exposure time amounts to 172 ks. The observed regions cover a diameter of about 2°. In this Letter, we deal only with the Gas Imaging Spectrometer data because of its larger field of view than the Solid-State Imaging Spectrometer. The data screening procedure was the same as in our previous analysis for three other clusters (Furusho et al. 2001). The cosmic X-ray background was taken from the archival blank sky data taken during 1993–1994 (Ikebe 1995).

The flow of the data analysis is almost the same as that described in Furusho et al. (2001); i.e., we calculated the hardness ratio in each pixel of the merged image for the 13 pointings after the background subtraction and estimated temperature by comparing it with simulated values for the isothermal ICM. The ray-tracing simulation includes effects from the energy-dependent PSF and stray light (Tsusaka et al. 1995). As for the input X-ray image of the cluster, we employed the observed two-dimensional PSPC image in the energy range 0.5–2.0 keV in the same way as in Furusho et al. (2001). The PSPC observation of the Perseus Cluster consists of five pointings, and the data were analyzed with the Extended Source Analysis Software package (Snowden et al. 1994). The input spectrum was assumed to be a single-temperature MEKAL model with kT = 6 keV with the Galactic absorption (N_H = 1.4 × 10²¹ cm⁻²), and the significant metallicity gradient reported by Ezawa et al. (2001) was included in the model.

The definition of the hardness ratio is HR = H/S, where H and S represent count rates in the energy range 2–10 and 0.7–2 keV, respectively. The ratio of HRs between the data and the isothermal simulation for each pixel gives a deviation factor of the HR from the assumed temperature along with its statis-
Fig. 1.—Color-coded temperature map of the Perseus Cluster obtained from ASCA multipointing observations. The contours indicate the residual PSPC image after subtraction of a $\beta$-model, and $R_{\text{vir}}$ is calculated to be 3.3 $h_0^{1/3}$ Mpc for $kT = 7$ keV, assuming the virial radius given as $R_{\text{vir}} = 1.23 (T_e/1\text{ keV})^{1/2} h_50^{-1/2} h_50^{-1}$ Mpc by Evrard, Metzler, & Navarro (1996).

Fig. 1 shows the color-coded temperature map of the Perseus Cluster compared with a residual PSPC surface brightness after subtracting a smooth $\beta$-model from the observed image. The subtracted $\beta$-model parameters, derived for the smooth western sector, were taken from Ettori et al. (1998). The temperatures were estimated assuming a single temperature, as mentioned earlier. We first note that the temperature structures in the map are generally consistent with the previous coarse-resolution results by Ezawa et al. (2001). There is a large cool region around 20' east of the cluster center, which is clearly extended with a diameter of about 30' ($\sim 900$ $h_50^{-1}$ kpc). This cool region shows a remarkable correspondence to the enhancement in the surface brightness as seen in Figure 1. The correspondence between the cool region and the excess surface brightness suggests that this extended region is either embedded in or lying foreground to the Perseus Cluster. This substructure in the surface brightness was already noted by Schwarz et al. (1992) and Ettori et al. (1998), but this is the first case that reveals that this feature accompanies a clear temperature drop.

The other interesting feature in the temperature map is the ringlike hot region that almost encircles both the cool region and the cluster center. The eastern ridge, at $r \sim 40'$ from the center running north to south, seems particularly hot, with $kT \gtrsim 10$ keV in a number of connected pixels. The rest of the ringlike feature indicates approximately the same temperature, with $kT \sim 7$ keV. There are other soft regions: one small region in the south-southwest direction at $r \gtrsim 30'$ and an elongated
region at the northeast edge. Neither of the regions show structures in the surface brightness distribution, suggesting that the low ICM temperatures in these regions do not accompany significant density contrast.

The central region within a diameter of 10' shows a marked softening of the spectrum, as studied by Ezawa et al. (2001). They showed that two spectral components were needed to fit the spectra in the central region with $r = 20'$, but the hotter component itself also indicated a marked softening down to $kT = 5.7$ keV. We also carried out spectral analysis assuming the two-temperature model and produced a temperature map only for the hot component. As a result, the color pattern turned out to be similar to Figure 1 in that the temperature in the central region within $r = 7'$ became low with $kT < 5$ keV. See Ezawa et al. (2001) for more information about the spectral softening in the central region.

Apart from the central concentration of the soft component, the two bright point sources, IC 310 and 1RXS J031525.1+410620, in the southwest region are clearly recognized in the temperature map. These sources are characterized by low ($\sim$4 keV) and high ($\sim$11 keV) temperatures, respectively, showing that the temperature map can effectively separate contributions from discrete sources.

One-dimensional cutouts of the temperature distribution are shown in Figure 2a along east-to-west and south-to-north paths running through the center with a width of 10', as indicated in Figure 2b. The errors in the plot denote 90% statistical errors for single parameters. These plots clearly demonstrate that the observed temperature variation is statistically significant. The extended cool region is recognized as a flat region between $-20'$ and $-10'$ along path A in Figure 2a, which corresponds to the residual component as shown by the contours in Figure 1. The very high temperature at the eastern edge ($-40'$ in path A), the hot region in the south ($-30'$ in path B), and the northern cool region (+35' in path B) can also be identified clearly. These one-dimensional plots suggest that a significant change of the temperature occurs on a scale of $\sim 10'$ (300 kpc) even though the finer scale structure may be suppressed by the bin width of 5'.

To look into the spectral variation in correlation with the temperature variation in some detail, we have accumulated the energy spectra for selected regions and carried out spectral fits. We have chosen three representative regions as shown in Figure 2b, which indicate medium (region 1), low (region 2), and hot (region 3) temperatures. The strong cool component around the central region causes the fit with single-temperature models to be unacceptable and complicates the temperature estimation. To avoid this problem, we limited the energy range to 2–10 keV and carried out single-temperature fits. Since the temperature of the cool component is about 2.0 keV (Ezawa et al. 2001), about 80% of the photon flux in the cool component can be suppressed. Free parameters were normalization, temperature, and metal abundance, and $N_H$ was fixed to the Galactic value. The results are summarized in Table 1 along with 90% errors for single parameters. Since the data need to be accumulated in a few hundred square arcminutes, the amplitude of temperature variations is suppressed if small-scale variations exist. The temperatures in the hot and medium regions overlap in the 90% error, but the value in the cool region (region 2) is significantly lower than the other two. It is notable that the accumulated spectrum in the east hot region does not show the

| Region         | $kT$ (keV) | $Z$ (solar) | $\chi^2$/dof |
|----------------|------------|-------------|---------------|
| 1 (west hot)   | 7.78$^{+0.20}_{-0.23}$ | 0.26$^{+0.04}_{-0.00}$ | 90.1/68       |
| 2 (east cool)  | 5.77$^{+0.17}_{-0.19}$ | 0.34$^{+0.04}_{-0.04}$ | 88.8/68       |
| 3 (east hot)   | 8.27$^{+0.20}_{-0.19}$ | 0.38$^{+0.16}_{-0.19}$ | 39.7/32       |

Note.—For the single-temperature MEKAL model ($N_H$ fixed, 2–10 keV).
The ringlike temperature structure. With a small-size cluster (such as A1060) may have created colliding system is then at least is estimated to be ergs. The necessary mass of the ring is as large as about 1 M

Figure 1. Previous studies from ASCA (Arnaud et al. 1994; Ezawa et al. 2001) based on spatially accumulated spectra indicated that the ICM temperature significantly varied in several regions. However, this is the first case in which the temperature map of the whole cluster is derived with a spatial resolution \(\sim 10\) arcmin. The Perseus Cluster has several extended cool (\(kT \sim 5\) keV) regions that seem to be surrounded by a filamentary structure with medium (\(\sim 7\) keV) to hot (\(\sim 10\) keV) temperatures. This feature looks quite different from, e.g., the Centaurus Cluster, in which a hot region exists near the cluster center (Churazov et al. 1999; Furusho et al. 2001).

The remarkable finding is the extended cool region with a low temperature of about 5 keV 10–20' east of the cluster center. As seen in Figure 1, this region has a diameter of about 20' (600 kpc). The same region was recognized in the ROSAT observations (Schwarz et al. 1992; Ettori et al. 1998) based on the substructure in the surface brightness. The residual image after subtraction of a \(\beta\)-model (contours in Fig. 1; see also Schwarz et al. 1992) is very similar to the structure of the extended cool region. Ettori et al. (1998) discuss that there is possibly a group of galaxies merging into the main body of the cluster. Considering the size and temperature of the cool region, the merged body may well be an established poor cluster. No significant variation of metal abundance in this cool region suggests that the merged cluster was already enriched with metals to around 0.3 solar. Since the density contrast should be smoothed out in the sound crossing time (\(< 1 \times 10^{10}\) yr), this extended cool region would have been created within the past \(10^{9}\) yr.

Figure 1 also shows that a chain of hot regions seem to be surrounding the cool region discussed above. It could be that the collision of the poor cluster, whose direction may be nearly in parallel to the line of sight, has caused shock heatings and created a large ringlike hot region. The diameter of the “hot ring” is as large as about 1' (~2 Mpc). Assuming that the hot region has a spherical shell structure with inner and outer radii of 500 kpc and 1 Mpc, respectively, its excess thermal energy is estimated to be \(2 \times 10^{52}\) ergs. The necessary mass of the colliding system is then at least \(2 \times 10^{13}\) \(M_\odot\) if the relative velocity is about 1000 km s\(^{-1}\). This suggests that a major merger with a small-size cluster (such as A1060) may have created the ringlike temperature structure.

Let us look into relevant timescales here. The thickness of the hot ring is less than about 500 kpc; therefore, if the heat front propagates at \(\sim 1000\) km s\(^{-1}\), the time required to heat up the ring is less than \(5 \times 10^8\) yr, which is comparable to the ion-electron relaxation time (Takizawa 1999). On the other hand, the conduction time for this hot ring structure to be smoothed out is roughly estimated as \(2 \times 10^9\) yr, assuming a standard thermal conductivity. This means that the hot structure would dissipate away before the whole region is sufficiently heated up. The presence of the hot ring suggests that the thermal conductivity in the ICM may be lower by an order of magnitude than the standard value, as recently pointed out by Ettori & Fabian (2000). In such an outer region of the cluster with low gas density, however, suppression of the conduction in terms of a strong magnetic field may not be effective.

Other structures in the temperature map are smaller and seemingly consist of many blobs with a rough size of 10' (300 kpc). We note that in the Virgo Cluster, Shibata et al. (2001) reported that the spatial scale of hot and cool regions are about 300 kpc, which is more or less the typical size of groups of galaxies. The Perseus Cluster shows hot regions with \(kT \geq 8\) keV toward the southern and northeastern edges of the cluster. Low temperatures (\(kT \sim 5\) keV) are seen at northwestern and southwestern edges, with the latter around IC 310. These asymmetric temperature structures do not accompany significant surface brightness contrast except for the IC 310 subcluster. This indicates that the pressure distribution is not smooth and that a considerable bulk flow of the gas may be present. Numerical simulations indicate that the temperature structure remains several \(\times 10^9\) yr after a subcluster collision (see, e.g., Schindler & Müller 1993) and that the slow relaxation process between ions and electrons would also cause complex distribution of the electron temperature (Takizawa 1999). The observed temperature structure in the Perseus Cluster suggests that this cluster has experienced many subcluster mergers. These mergers may well have been the main building processes that have made the Perseus Cluster into such a massive system, as suggested from numerical simulations of the cluster growth (Navarro, Frenk, & White 1995).

Finally, the distribution of the cool gas in the southwest near IC 310 looks as if the subcluster gas is blown away from the center of the Perseus Cluster. This suggests that the IC 310 subcluster is now falling into the main cluster and that the cool gas associated with the subcluster may be slowed down because of the ram pressure. We hope that observations with high angular resolution may lead to direct detection of shock features, such as sharp edges (Markevitch et al. 2000) observed with \(Chandra\), and bring us a closed-up view of the dynamical processes in the cluster system.

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