DETECTION OF AN X-RAY HOT REGION IN THE VIRGO CLUSTER OF GALAXIES WITH ASCA

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ABSTRACT

Based on mapping observations with ASCA, an unusual hot region with a spatial extent of 1 deg² was discovered between M87 and M49 at a center coordinate of R.A. = 12h 27m 36.6s and decl. = 9° 18′ (J2000). The X-ray emission from the region has a 2–10 keV flux of $1 \times 10^{-11}$ ergs cm⁻² s⁻¹ and a temperature of $kT \approx 4$ keV, which is significantly higher than that in the surrounding medium of ~2 keV. The internal thermal energy in the hot region is estimated to be $3.5 \times 10^{40}$ ergs with a gas density of $\sim 10^{-4}$ cm⁻³. A power-law spectrum with a photon index of 1.7–2.3 is also allowed by the data. The hot region suggests there is an energy input due to a shock that is probably caused by the motion of the gas associated with M49, infalling toward the M87 cluster with a velocity $\geq 1000$ km s⁻¹.

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

1. INTRODUCTION

Recent X-ray observations are revealing significant large-scale variations of temperature and surface brightness in many clusters, providing evidence that clusters are evolving. Hydrodynamic simulations show that clusters recently formed through mergers should indicate a complex temperature structure and should become more regular with time (e.g., Roettiger, Burns, & Loken 1993; Takizawa 1999). Thus, spatial distributions of the temperature of the intracluster medium (ICM) should provide important clues about the dynamical evolution and the present state of the cluster.

In this Letter, we perform a detailed investigation on the temperature structure of the ICM in the Virgo Cluster, based on extensive mapping observations with ASCA (Tanaka, Inoue, & Holt 1994). This nearest rich cluster enables ASCA to perform spatially resolved spectroscopy with moderate spatial resolution, and hot-gas properties can be studied in both galaxy scales (<100 kpc) and in the whole cluster scale (>1 Mpc). The Virgo Cluster is thought to be a dynamically young system, as recognized from its irregular structure in the optical and X-ray bands. Thus, the present mapping study of the cluster should provide us with valuable information to investigate the ongoing heating process in the ICM.

We assume the distance to the Virgo Cluster to be 20 Mpc (e.g., Federspiel, Tamman, & Sandage 1998); hence, 1° angular separation at the cluster corresponds to 5.8 kpc. The solar number abundance of Fe relative to H is taken as $4.68 \times 10^{-5}$ (Anders & Grevesse 1989) throughout this Letter.

2. OBSERVATION AND ANALYSIS

2.1. Observation

The mapping observations of the Virgo Cluster have been carried out from 1996 December to 1998 December, with 28 pointings and a total exposure time of ~500 ks (Matsumoto et al. 2000; Ohashi et al. 2000; Yamasaki et al. 1999). Together with the data in the archive, the area covered with ASCA in the Virgo Cluster is ~10 deg². Figure 1 shows the ASCA-observed regions overlaid on the X-ray contours with ROSAT (Böhringer et al. 1994). The radius of the circles is 22′, corresponding to a Gas Imaging Spectrometer (GIS) field of view (Makishima et al. 1996; Ohashi et al. 1996).

We selected the GIS data observed with the telescope elevation angle from the Earth rim greater than 5°, and the data taken with an unstable attitude after maneuvers were discarded. Flare-like events due to the background fluctuation were also excluded (Ishisaki 1996). The cosmic X-ray background (CXB) was estimated from the archival data taken during 1993–1994 (Ikebe 1995), and the long-term variability of the non-X-ray background of the GIS (Ishisaki 1996) was corrected for.

2.2. Image Analysis

To derive the pure ICM component, contaminating X-ray sources have to be excluded. We carried out a source detection analysis developed for the CXB study by Ueda et al. (1999), who dealt with the complicated detector response in a systematic way, including the position and energy dependence of the point-spread function (PSF) of the ASCA X-ray telescope. Pointings containing bright sources such as M87, M49, A1553, and A1541 were excluded from the analysis, leaving 29 pointings to be analyzed (indicated by blue circles in Fig. 1). We adopt a rather low flux level in detecting the source candidates, 3σ above the background in the 0.7–7 keV band, since our interest is in the remaining diffuse component. The analysis detected 231 source candidates with X-ray fluxes $\geq 1 \times 10^{-13}$ ergs cm⁻² s⁻¹ in the 2–10 keV band, and all of them have been masked out from the mapping data (see Fig. 1). The mask regions centered on the candidate positions have radii that depend on the source flux since brighter sources affect wider regions because of the image spread by the PSF effect. The mask radius is determined where the surface brightness due to the source drops to less than 5% of the ICM level.

To examine spatially resolved spectral features, we need to know the surface brightness distribution in the whole cluster in order to estimate the amount of the stray light, which consists of photons generated outside the field of view (e.g., Honda et al. 1996). Fortunately, the ROSAT All-Sky Survey (RASS;
Böhringer et al. (1994; Voges et al. 1996) data are available for this purpose, and we can produce the template of the brightness profile. In the RASS image, diffuse soft X-ray emission, which possibly comes from the rim of Loop I (e.g., Raymond 1984; Egger & Aschenbach 1995), is present in the direction of the Virgo Cluster (Snowden et al. 1995). Therefore, we use the PSPC data only above 0.9 keV to exclude possible soft X-ray contamination. A spatially uniform background, obtained from a blank sky region, was subtracted from the Virgo RASS data. Based on this template image, a ray-tracing simulation (Tsusaka et al. 1995) for the GIS observation was carried out by assuming a uniform temperature of 2.0 keV and a metallicity of 0.2 solar, which are the typical parameters in the Virgo field (e.g., Koyama, Takano, & Tawara 1991; Matsumoto et al. 2000).

As a result, we found that the intermediate region between M87 and M49 was almost free from stray light from M87 and M49. The contaminating flux from these two galaxies is less than a few percent. Considering the complex spectral structures (such as temperature and abundance gradients) in these galaxies, this makes the data analysis for the intermediate region much easier.

### 2.3. Spectral Analysis

To derive spectral parameters (such as temperature and surface brightness) in a region, we have to know the parameters in the surrounding regions in order to evaluate the contamination of stray light. We carried out a first-order estimation of the spectral parameters, adopting an analysis method developed by Honda et al. (1996). This is performed by fitting individual spectra with a modified response function that partly compensates the effect of the stray light. The RASS image obtained in the previous section is used to estimate the amount of the stray light.

A spectral analysis has been performed for each pointed region in the 0.7–8 keV band with a Raymond-Smith model (hereafter the R-S model; Raymond & Smith 1977). The interstellar absorption $N_{HI}$ is fixed to the Galactic value $(1.7–2.5) \times 10^{20} \text{ cm}^{-2}$. The temperature distribution derived from the GIS spectral fits is shown in Figure 2, with a color-coded plot of the temperature in the left panel and a plot as a function of distance from M87 in the right panel.

As shown in Figure 2, the temperature around M87 is $\sim 2.5$ keV and slightly decreases to $\sim 2.0$ keV at $\sim 1^\circ$ away from M87 in the northwest region. In the south region, the average temperature at a distance of $2^\circ$ from M87 is still $\sim 2.5$ keV, with a large scatter from 1.8 to 3.4 keV. The metal abundance is poorly constrained in most of the regions because of low-photon statistics. We only mention that the best-fit values suggest that the metal abundance in the general cluster regions is around 0.2 solar, with a scatter of about $\pm 0.2$ solar from position to position. If we fitted the spectra with free absorption, the data generally require that no absorption (even the Galactic $N_{HI}$) be present. This suggests the existence of an additional soft component below $\sim 1$ keV, which may be the foreground emission of the Galactic soft X-rays.

### 3. THE HOT REGION

As shown in Figure 2, three regions (W1, W2, and W3) along the “emission bridge” between M87 and M49 show the ICM temperatures rising to $\sim 3$ keV. To improve the statistics, the three spectra are combined (hereafter called W123) because individual fits indicate statistically the same temperature. For comparison, the spectra for regions E1, E2, and E3 (hereafter E123), just to the east of W123, are also combined. Both W123 and E123 regions are elongated parallel to the emission bridge, and the distance from M87 and M49 is almost the same. Errors in the contaminating spectra from nearby bright sources (i.e., A1553, NGC 4325, A1541, and QSO 1225+089) and those in the remaining fluxes of masked-out sources are the major origin of the systematic error for temperatures in W123 and E123. This error is found to be less than 0.2 keV, and its effect...
The single-component $g$ model gives a poor fit in the energy range of 0.7–8.0 keV for the two spectra W123 and E123. As shown in Table 1, the best-fit results are $\chi^2/\nu = 45.2/21$ and $\chi^2/\nu = 31.1/21$ for W123 and E123, respectively. This is mainly due to excess emission below 1 keV in both spectra. A two-component (R-S model and a soft thermal bremsstrahlung) model improves the fit to $\chi^2/\nu = 21.8/20$ and $\chi^2/\nu = 27.2/20$ for W123 and E123, respectively (see Fig. 3). The additional thermal bremsstrahlung component yields the best-fit temperature $kT = 0.2–0.3$ keV with $F_X \sim 0.8 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ arcm$^{-2}$ for 0.5–2 keV for both W123 and E123 spectra. These values are close to the ROSAT result ($kT = 0.15$ keV and $F_X = 0.6 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ arcm$^{-2}$) in the 0.5–2 keV band; Irwin & Sarazin (1996), supporting the view that the soft emission is due to the Galactic hot interstellar medium. These results indicate that the region W123 has a significantly high temperature of $\sim 4$ keV, while E123, just to the east of W123, shows a temperature of $\sim 2$ keV, which is the typical temperature of the Virgo Cluster.

Based on these results, we neglect the energy range below 2 keV and look into the pure ICM component in the region of W123. We also subtracted contaminating photons, which come from the surrounding region of W123, assuming the temperature and metallicity of the surrounding ICM are 2 keV and 0.2 solar, respectively. Fixing the abundance to 0.2 solar, acceptable fits with the R-S model are obtained with $\chi^2/\nu = 10.5/11$ (Table 1). The ray-tracing simulation gives a systematic error for the stray-light intensity of $-30\%$ to $10\%$, as estimated from offset observations of the Crab Nebula (Ishisaki 1996). The systematic error due to a fluctuation of the CXB flux is $\sim 10\%$ for the GIS field of view, and the uncertainty in the estimation of the non-X-ray background level is 6%. Including all these errors, we can conclude that the temperature in W123 is still higher than that in E123 with more than 90% confidence. The total flux of the hot region in the 2–10 keV band is $(9.2–10.3) \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ at the 90% confidence limit, and the emission measure $\int n^2 dl$ is estimated to be $(3.4–5.0) \times 10^{51}$ cm$^{-3}$, assuming that an extent of the hot region is $4 \times 10^3$ arcmin$^2$.

So far, the “hot” emission has been assumed to have a thermal spectrum. However, the data also allow nonthermal (power-law) models. The spectral fit for the 2–8 keV hot region data (W123) with a power-law model gives an acceptable result of $\chi^2/\nu = 9.9/11$ with a photon index between 1.7 and 2.3 at the 90% confidence limit (see Table 1). Since no significant Fe K line is seen in the W123 spectrum with EW $\leq 821$ eV for a 6.7 keV line at the 90% confidence limit, the diffuse nonthermal emission remains a possibility from the ASCA observations.

### 4. DISCUSSION

The previous Ginga observations have suggested a temperature rise in the ICM from M87 to M49 (Takano 1990; Koyama et al. 1991). However, the ROSAT data showed no such evidence (Böhringer et al. 1994) and implied the possibility that the nonimaging Ginga data were contaminated by background sources. The extensive mapping observations from ASCA have shown the correct temperature structure in the Virgo Cluster for the first time and unambiguously detected an unusual hot region in the ICM. This detection provides clear evidence that the Virgo Cluster is a young system in which local gas heating is taking place now in the cluster outskirts.

The emission measure of the hot region W123 that was obtained in the previous section gives a rough estimate of the gas density $n$ that is on the order of $1 \times 10^{-4}$ cm$^{-3}$. Here we assume that the line-of-sight depth of the hot component is $\sim 300$ kpc, which is the same order as the projected length of the region. The internal thermal energy of the hot component, $E_{th} = \frac{1}{2} n kT$, where $V$ and $T$ are the volume and temperature, is calculated as $\sim 10^{50}$ ergs. This level of energy is orders of magnitude higher than the kinetic energy of galaxies in the Virgo Cluster.
Hard X-ray ($kT \geq 10$ keV) emission from clusters of galaxies was reported in previous observations (see, e.g., Fusco-Femiano et al. 1999 for the Coma Cluster), and the existence of nonthermal emission has been suggested. For the hot region detected here, we cannot confirm whether the origin of the hard emission is thermal or nonthermal because of the lack of observational evidence. If we assume that relativistic electrons are produced by first-order Fermi acceleration, the momentum spectrum of the electrons is described as $N(p) \propto p^{-\alpha}$. Here $\alpha = (r + 2)/(r - 1)$, where $r$ is a ratio of the shock compression. For the shock with a Mach number of ~2, the exponent is implied as $\alpha \approx 3.3$. In such a steep spectra, an energy loss that is due to nonthermal bremsstrahlung dominates the inverse Compton loss (Sarazin & Kempner 2000). The electrons lose their energy through Coulomb loss, whose timescale is estimated to be $\tau_{\text{cond}} \approx 3 \times 10^8 \text{yr}$. This is similar to the $\tau_{\text{cond}}$ estimated above.

The above considerations suggest that in both thermal and nonthermal cases, the extra energy built up in the hot region would dissipate away within about 1 Gyr because of thermal conduction or Coulomb loss. Therefore, it seems likely that the energy supply to the hot region has started only within the past 1 Gyr or, alternatively, that a long continuous supply of energy has been occurring here over a cosmological timescale. The infall of the M49 subcluster can supply energy to the ICM for a very long time and is probably connected with the local gas heating as detected in the Virgo Cluster.

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