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Tenma Observations of the X-Ray Spectra of the Coma, Ophiuchus, and Perseus Clusters of Galaxies

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Abstract

The X-ray spectra of the Coma, Ophiuchus, and Perseus clusters of galaxies were observed with the gas scintillation proportional counters on board Tenma. Redshifted emission lines of iron Kα and Kβ were unambiguously detected at energies of 6.58 ± 0.05 keV and 7.82 ± 0.16 keV for Coma, 6.56 ± 0.06 keV and 7.94 ± 0.11 keV for Ophiuchus, and 6.55 ± 0.03 keV and 7.76 ± 0.26 keV for Perseus. Each of the continuum components is well represented by a thermal bremsstrahlung spectrum of a single temperature. However, the plasma temperature derived from the mean iron Kα line energies is somewhat lower than the continuum tem-

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perature, especially for Perseus, which possibly indicates the existence of nonisothermal temperature distributions in these clusters. The intensity ratios of iron Kα line to iron Kβ line are found to be 3.9 ± 1.5, 2.7 ± 0.9, and 7.8 ± 5.3 for Coma, Ophiuchus, and Perseus, respectively. On the assumption of an isothermal plasma in collisional ionization equilibrium, the iron abundances of the Coma, Ophiuchus, and Perseus clusters are derived from the equivalent widths of iron Kα to be 0.32 ± 0.05, 0.49 ± 0.08, and 0.42 ± 0.05 times the cosmic value.

Key words: Clusters of galaxies; Intracluster gas; X-ray emission lines; X-ray spectra.

1. Introduction

Clusters of galaxies are the largest gravitationally bound ensemble in the universe, which consist of hundreds of galaxies and thin hot intracluster gas and are identified as luminous extended X-ray sources. The X-ray emission in the energy range 2–10 keV from clusters of galaxies is generally believed to arise from optically thin hot intracluster gas, as indicated by the strong emission lines of highly ionized iron. The heavy elements in the intracluster gas are presumably ejected from the galaxies by supernova explosions or ram pressure stripping due to the motion of galaxies in the intracluster space and mixed with the primordial gas. The high energy-resolution observations of their X-ray spectra are very important to investigate the origin and the physical state of the intracluster gas in relation to the formation and evolution of clusters of galaxies.

The X-ray spectra of the Coma and Perseus clusters of galaxies have been observed in the energy range 1–20 keV with conventional proportional counters aboard Uhuru, Ariel V, OSO-8, and HEAO-1 (Serlemitsos et al. 1977; Jones and Forman 1978; McHardy 1978; Mushotzky et al. 1978; Mitchell et al. 1979; Mushotzky 1984; Henriksen 1985; Henriksen and Mushotzky 1986). A high-resolution X-ray spectrum in the 0.5–4-keV band of the Perseus cluster was obtained with the solid-state spectrometer (SSS) on board the Einstein Observatory (Mushotzky et al. 1981), which indicated the presence of iron-L, silicon-K, and sulfur-K emission lines presumably from the low-temperature component in the central core region. The contribution of the cooling component to the observed flux in the 2–15-keV band is insignificant. The X-ray spectrum of the Ophiuchus cluster, listed as 4U 1708−23 in the 4U catalog (Forman et al. 1978), was first observed by HEAO-1 (Johnston et al. 1981), while Wakamatsu and Malkan (1981) established its optical identification in a crowded low galactic latitude region. The Ophiuchus cluster has also been observed recently by the medium-energy detectors and gas scintillation proportional counter on board EXOSAT (Arnaud et al. 1987).

Imaging X-ray observations of the Perseus cluster with the imaging proportional counter (IPC) and the high-resolution imager (HRI) on board the Einstein Observatory have revealed a temperature gradient as well as a central peak in the surface brightness distribution arising from a cooling flow in the core region (Branduardi-Raymont et al. 1981; Fabian et al. 1981). This is confirmed by the X-ray observation in the 1–10-keV band made by Spartan 1 (Ulmer et al. 1987).

Henriksen and Mushotzky (1986) have analyzed the HEAO-1 A-2 spectrum of the Coma cluster using polytropic models. Recently Hughes et al. (1988b) have carried out a detailed nonisothermal analysis for Coma using the Tenma spectrum presented in this paper and the spatial data from the Einstein Observatory. A simlar analysis of the EXOSAT X-ray spectra of Coma has been done by Hughes et al. (1988a).

Most clusters show iron emission lines at 6.7 keV. The iron abundance is derived to be about one half of the solar abundance under the assumption of an isothermal model in collisional ionization equilibrium (Mushotzky 1984).

Here we present the X-ray spectra of the Coma, Ophiuchus, and Perseus clusters of galaxies observed with the gas scintillation proportional counters (GSPC) on board the X-ray astronomy satellite Tenma. The results of a detailed spectral analysis of the iron emission lines are discussed.

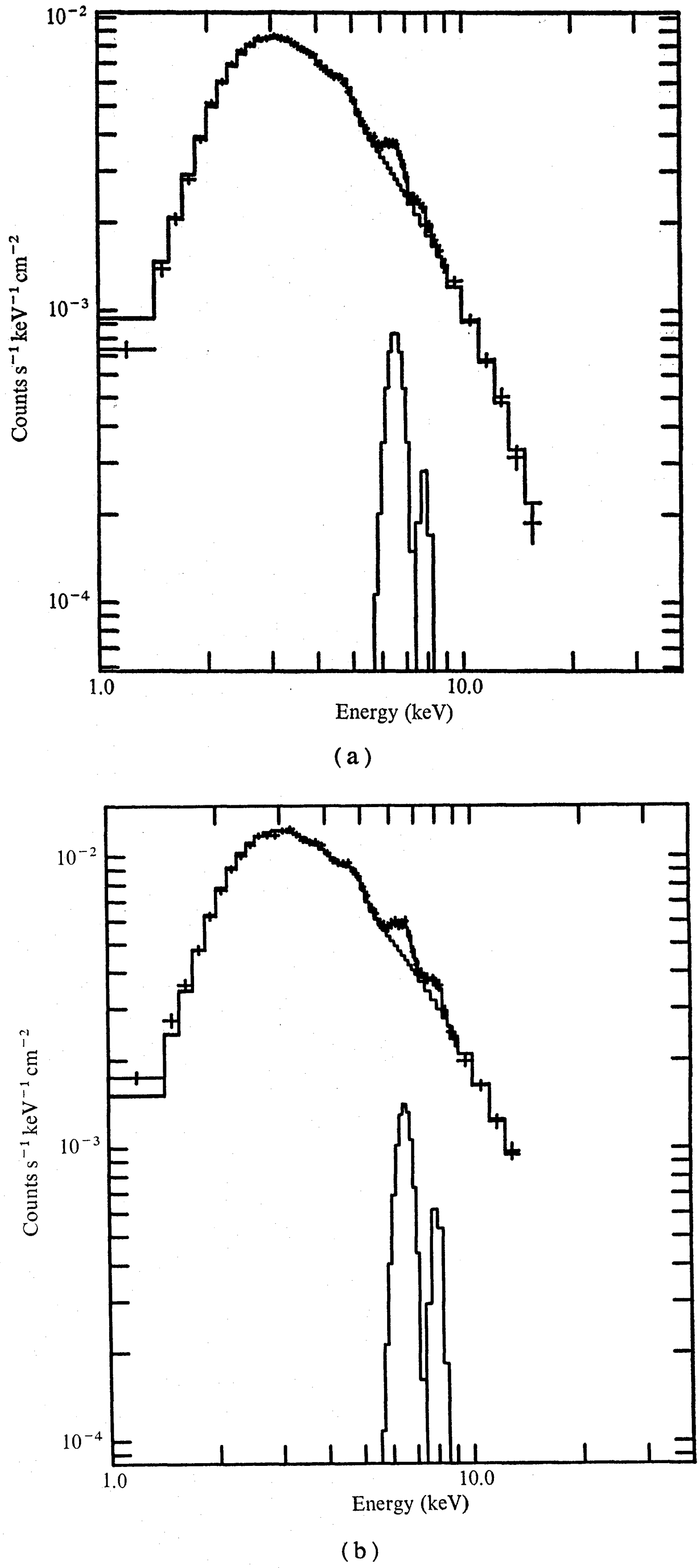
2. Observations and Data Analysis

The observations of the Coma, Ophiuchus, and Perseus clusters of galaxies were made on March 25–31, August 9–10, and October 27–28, 1983, respectively. The net observation times were 3×10^4 s for Coma, 1.6×10^4 s for Ophiuchus, and 7×10^3 s for Perseus. Source-free background data were accumulated in the vicinity of the Coma and Perseus clusters.

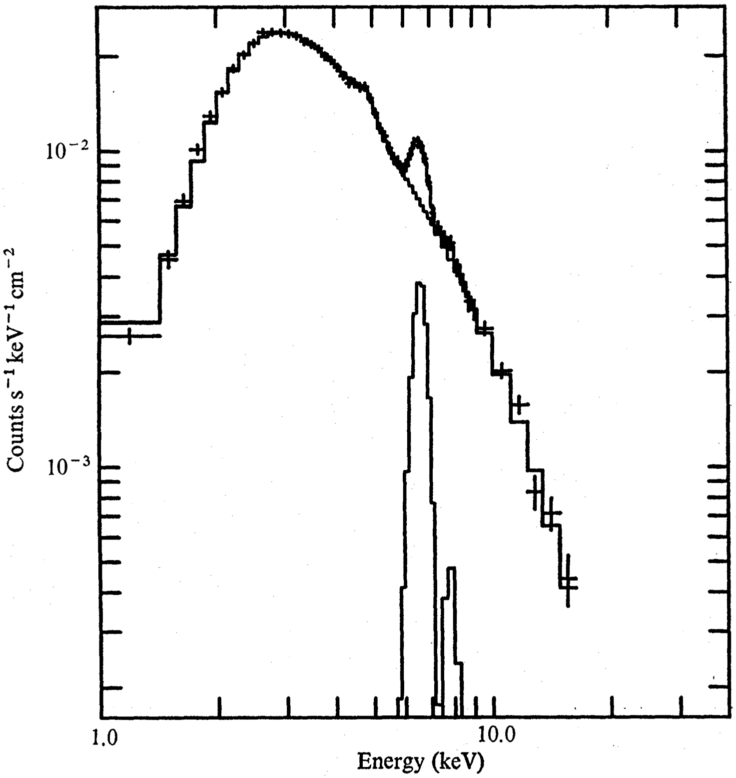
The detector consists of eight individual GSPCs each with effective area 80 cm^2 and with a field of view of $3\overset{\circ}{.}1$ and $2\overset{\circ}{.}5$ (FWHM) for respective sets, consisting of four counters designated as SPC-A and SPC-B (Tanaka et al. 1984). The energy resolution of the GSPCs is 9.5% at 6 keV (Koyama et al. 1984).

The data were carefully selected to avoid periods of serious particle contamination by taking into account the counting rates of the GSPCs above 30 keV and the radiation belt monitor, which were affected by the cosmic-ray cut-off rigidity, the viewing direction of the counters relative to the local earth frame, and the geomagnetic reference frame at the location of the satellite (Koyama et al. 1984). The intensity of tin Kα (25.2 keV), produced in the shielding material by charged particles in ambient space and/or hard X-rays, was a good indicator of the intrinsic counter background level.

The pulse-height spectra for these clusters, shown in figures 1a–c, were obtained by subtracting the off-source background and applying aspect correction. Since no off-source data were available in the vicinity of the Ophiuchus cluster, we used the background spectrum obtained in the vicinity of Coma, adjusting the intensity by reference to the tin Kα line intensity. The contribution of the galactic ridge component observed by Koyama et al. (1986) was negligible at the galactic latitude of this cluster ($b=+9°$). We fit the spectrum observed for each source in the 1–15-keV range with a thermal bremsstrahlung spectrum of a single temperature plus two emission lines which correspond to iron Kα and Kβ, taking into account the hydrogen column density for absorption in the line of sight. The continuum was simulated by a free-free emission with the Gaunt factor given by Matteson (1971) with corrections (nonrelativistic) for electron-electron bremsstrahlung (Maxon and Corman 1967). A finite line width (FWHM) of the Gaussian distribution was introduced only for iron



Figs. 1a and b. See the legend on the next page.



(c)

Fig. 1. The pulse-height spectra for (a) Coma, (b) Ophiuchus, and (c) Perseus clusters of galaxies. Data points are shown as crosses, for which the vertical bar represents the $\pm 1\sigma$ statistical error. The best-fit model spectra folded through the counter response function are superposed upon the data points. The iron lines and the continuum component are separately shown by the solid histograms.

Kα to see the effect of line blend and possible broadening within the resolution of the GSPC. We thus derived the intensity and temperature of the continuum, the intensities and mean line energies of iron Kα and Kβ, the line width of iron Kα, and the hydrogen column density (N_{H}) in the direction of each cluster. The best-fit parameters so obtained are summarized in table 1. The fitting of the spectra is acceptable for all three clusters. We do not need any additional nonthermal components for our fits in the 1–15-keV range, although a power-law component is found for the Perseus cluster by Ulmer et al. (1987). The larger χ^2 for the Coma cluster is due to the better statistics for this observation and the poor fit of the isothermal model in the low-energy part of the spectrum. The residuals of the best-fit spectrum of Perseus show extra counts near the silicon Kα and sulfur Kα lines. Further fitting including these emission lines, slightly reduces the χ^2 value in the 1–15-keV range to 24.4 with 42 degrees of freedom. We obtain the line intensity and energy of silicon Kα of $4.0\pm3.8\times10^{-3}$ photons cm^{-2} s^{-1} and 1.82 ± 0.08 keV; those of sulfur Kα are $1.7\pm2.0\times10^{-3}$ photons cm^{-2} s^{-1} and 2.60 ± 0.13 keV. The other parameters are the same as shown in table 1.

The mean line energies of iron Kα are obtained to be 6.58 ± 0.05 keV for Coma, 6.56 ± 0.06 keV for Ophiuchus, and 6.55 ± 0.03 keV for Perseus. The accurate de-

Table 1. The best-fit parameters.

Parameter	Cluster of galaxies		
	Coma	Ophiuchus	Perseus
Normalization factor (10^{-2} photons cm^{-2} s^{-1} keV^{-1})	5.4 ±0.2*	5.2 ±0.3	16.6 ±0.8
Continuum temperature (keV)	8.2 ±0.3	11.6 ±0.6	6.9 ±0.3
Line intensity of iron Kα (10^{-4} photons cm^{-2} s^{-1})	9.1 ±1.3	14.5 ±2.4	30.9 ±3.5
Line energy of iron Kα (keV)	6.58±0.05	6.56±0.06	6.55±0.03
Line width of iron Kα (keV)	0.62±0.19	0.59±0.20	0.26±0.20
Line intensity of iron Kβ (10^{-4} photons cm^{-2} s^{-1})	2.3 ±0.9	5.3 ±1.5	4.0 ±2.7
Line energy of iron Kβ (keV)	7.82±0.16	7.94±0.11	7.76±0.26
log N_H (H atoms cm^{-2})	22.22±0.02	21.88±0.05	22.00±0.06
χ^2	60.5	49.2	33.4
d.o.f.	46	44	46

* Errors shown here are statistical at the 90% confidence level.

termination of the iron Kα line energy is of great importance in order to confirm the redshift of the cluster with the X-ray emission line. The energy scale of each GSPC was carefully calibrated in flight and adjusted to each other within an accuracy to 30 eV, using the characteristic lines of copper Kα (8.04 keV), thorium Lα (12.97 keV), silver Kα (22.10 keV), and tin Kα (25.20 keV) (Tsunemi et al. 1986). We also detected silver Lα (2.98 keV) above the background level when the counters were viewing the earth. Silver Kβ (24.95 keV) overlapped with tin Kα. Silver lines (Lα, Kα, and Kβ) are generated by the continuous irradiation of the radio isotope ^{109}Cd. Thorium Lα is produced from the contamination in the beryllium window, whereas copper Kα is generated from the collimator material with the same process as tin Kα.

The line width of iron Kα for the Perseus cluster is found to be consistent with that of a single line, whereas finite widths are required for Coma and Ophiuchus, favoring a composite line structure. This is due to the separation of the iron Kα line into the lines arising from the He-like and H-like ions, since they differ by 0.27 keV.

We did not observe any significant time variability for these clusters during the observation periods.

3. X-Ray Emission and Radiative Transfer in an Intracluster Gas

The line energies and the line intensities of iron Kα and Kβ for these three clusters were well determined as a result of the good energy resolution of GSPC. The emission integral (EI), the line energies corrected for the redshift and the equivalent width (EW) obtained from the observational results for each cluster of galaxies are tabulated in table 2. X-ray emission from a thin hot plasma in collisional ionization equilibrium was calculated for cosmic abundance (Allen 1973), $N(\mathrm{Fe})/N(H)=4\times10^{-5}$, using the atomic data compiled by Mewe et al. (1985). The emission lines of iron originating from the transitions $n=2$ to $n=1$ and those from $n=3$ to $n=1$ in the ionization states concerned were summed and defined as iron Kα and Kβ, respectively. The con-

Table 2. The physical properties of clusters of galaxies.

Physical quantity	Cluster of galaxies		
	Coma	Ophiuchus	Perseus
Redshift z	0.0235[a]	0.028[b]	0.0183[a]
Emission integral[c] (10^{67} cm^{-3})	9.59	14.5	15.1
Line energy corrected for the redshift			
iron Kα (keV)	6.73±0.05	6.74±0.06	6.67±0.03
iron Kβ (keV)	8.00±0.16	8.16±0.11	7.90±0.26
Equivalent width (EW)			
iron Kα (eV)	292±41	310±49	429±49
iron Kβ (eV)	112±41	169±54	78±56
Iron abundance relative to cosmic value[d]	0.32±0.05	0.49±0.08	0.42±0.05

[a] Cluster redshifts from the compilation by Sarazin et al. (1982).
[b] Johnston et al. (1981).
[c] $H_0=50$ km s^{-1} Mpc^{-1} is used.
[d] Derived from the equivalent width of iron Kα.

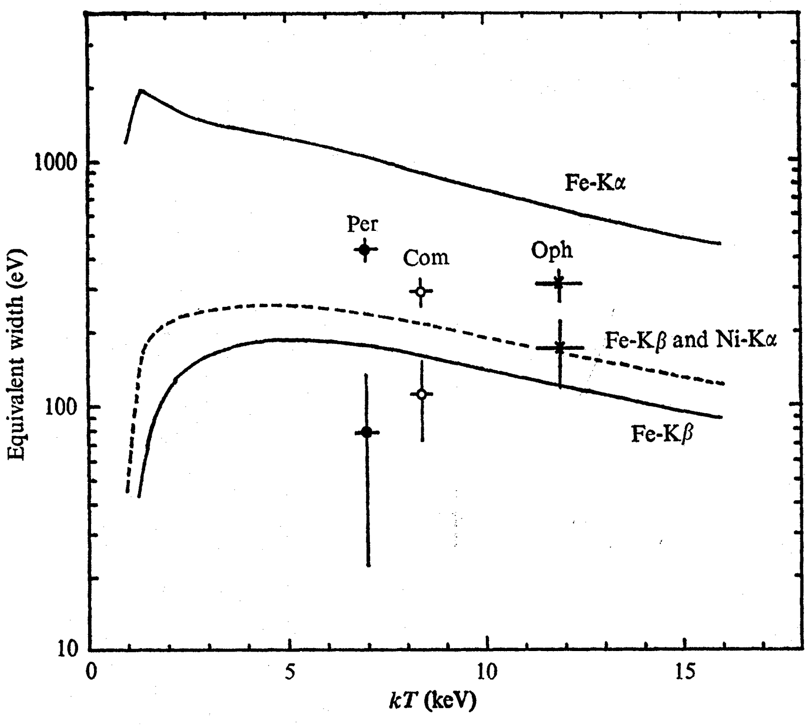


Fig. 2. The equivalent widths of iron Kα and Kβ calculated for an isothermal model in collisional ionization equilibrium under the assumption of N(Fe)/N(H)$=4\times10^{-5}$ and N(Ni)/N(H)$=2\times10^{-6}$ are shown as a function of kT by solid lines. The dashed line shows the sum of iron Kβ and nickel Kα. The observed values are plotted against the corresponding continuum temperature corrected for the redshift.

tribution of nickel Kα to iron Kβ is also estimated assuming an abundance N(Ni)/N(H) $=2.0\times10^{-6}$. Hereafter iron Kβ always includes the contribution of nickel Kα. The calculation of iron K lines was carried out with 35 lines in Fe VIII (6.391 keV)–Fe XXVI (6.973 keV) for iron Kα and 40 lines in Ni X (7.469 keV)–Fe XXVI (8.670 keV)

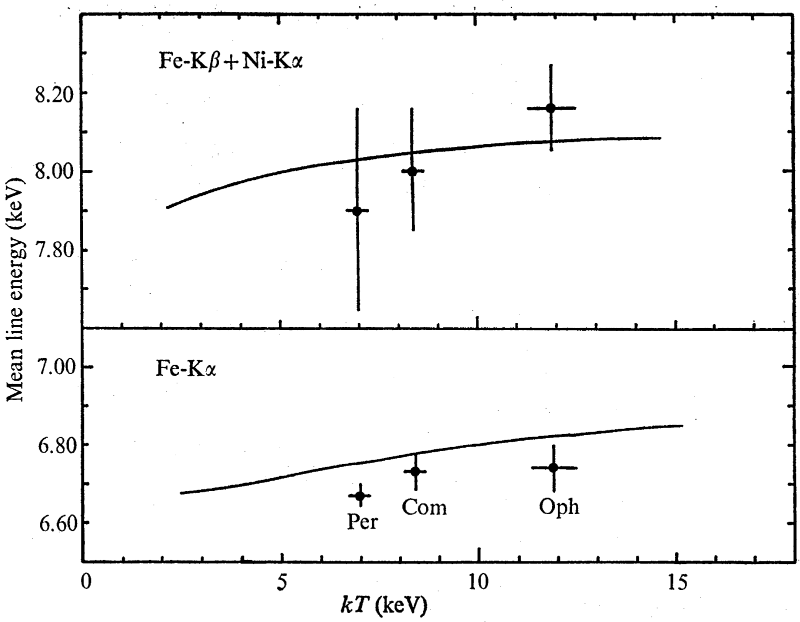


Fig. 3. The mean line energies of iron Kα and Kβ are shown as a function of kT, calculated with the same model as in figure 2. The observed values for the three clusters are plotted against the corresponding continuum temperature corrected for the redshift.

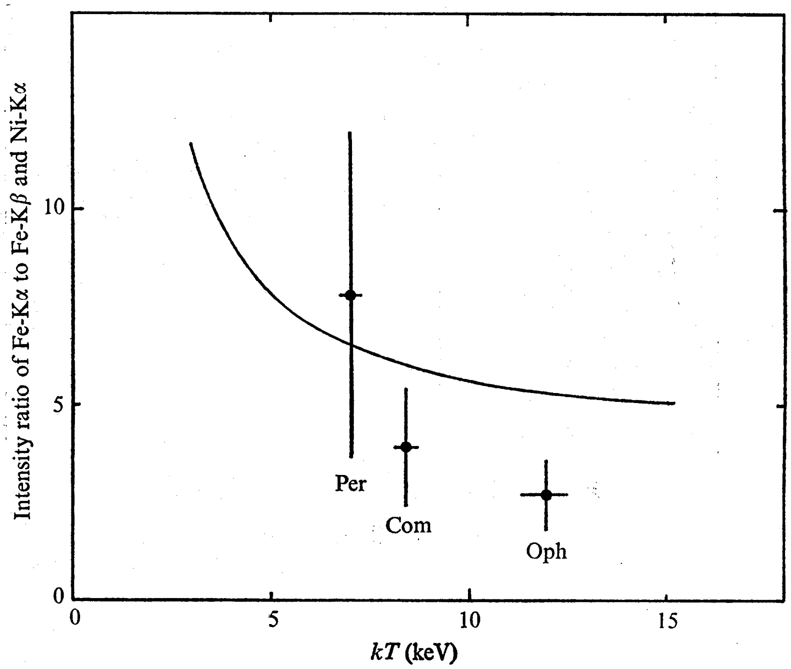


Fig. 4. The intensity ratio of iron Kα to iron Kβ are shown as a function of kT, calculated with the same model as in figure 2. The observed values for the three clusters are plotted against the corresponding continuum temperature corrected for the redshift.

for iron Kβ. The equivalent width, the mean line energy of iron Kα and iron Kβ, and the intensity ratio of iron Kα to Kβ calculated for a thin hot plasma as a function of the continuum temperature are shown in comparison with the observed values in figures 2, 3, and 4, respectively. The mean line energy is defined as the emissivity-weighted mean for the emission lines concerned. The abundances of iron relative to the cosmic value derived from the equivalent width of iron Kα are also listed in table 2.

The calculated values of the equivalent width of iron Kα are two times higher than the observed ones, whereas those of iron Kβ are almost consistent with each other within large errors. This fact indicates the underabundance of iron in an intracluster gas. The observed line energies of iron Kα are somewhat lower than the calculated ones, which indicates evidence for a temperature gradient in the intracluster gas. The observed Kα/Kβ intensity ratios for Coma and Ophiuchus are lower than the calculated ones by 1.3σ and 2.3σ, respectively.

According to recent theoretical and observational investigations, an isothermal model for cluster X-ray emission is found to be not realistic to interpret cluster properties. Since our detector has insufficient angular resolutions to obtain spatially resolved spectra, it is somewhat difficult to obtain model-independent parameters. Our observational results only show the average values of the temperature, the line intensity, and the line energy over the whole cluster. The difference between the observed and calculated iron Kα line energies could be explained by considering a nonisothermal model in a way similar to the work by Sarazin and Bahcall (1977). It is not possible to reproduce the discrepancy of the Kα/Kβ line ratio in a nonisothermal model, because at all reasonable temperatures the theoretical line ratio exceeds the observed one (figure 4). This could be accounted for, at least in part, in terms of the radiative transfer of resonance lines of He-like and H-like iron ions in the intracluster medium.

Radiative transfer in a hot plasma was investigated by Loh and Garmire (1971), Felten et al. (1972), and Pozdnyakov et al. (1979), who focused on the deformation of the line profile by Compton scattering in an optically thick plasma. In the case of an optically thin hot plasma, the Thomson scattering optical depth is much less than unity, whereas the resonance scattering optical depth is much larger than the Thomson scattering optical depth. When the resonance-line photon travels over a distance comparable to the mean free path of Thomson scattering, the scattering of the photon by an electron will change its energy and shift it toward the continuum. This process may be applicable to the intracluster medium and may reduce the intensity of iron Kα. For a spherical isothermal plasma with an electron density of 10^{-3} cm^{-3}, a radius of 1 Mpc, a temperature of 8 keV, and cosmic abundances, the resonance scattering optical depth of the He-like iron Kα resonance line (6.70 keV) is estimated to be 0.4, which is not large enough to reduce the line intensity. Gil'fanov et al. (1987) have calculated the distortion of the surface brightness distribution of resonance lines of iron Kα, taking into account the resonance scattering and the density distribution in an intracluster gas. The reduction of the intensity of resonance lines is significant in the core region, whereas the total intensity over the whole cluster is not changed. Therefore, this result does not account for our observational results.

4. Discussion

In this section we describe the properties of the Coma, Ophiuchus, and Perseus clusters in comparison with the previous observational results and an isothermal model discussed in section 3. The following observational parameters characterize the properties of the intracluster gas: (1) the mean line energies of iron Kα, (2) the equivalent widths of iron Kα and Kβ, (3) the intensity ratios of iron Kα to iron Kβ, (4) the line widths of iron Kα, (5) the continuum temperature, and (6) the emission integral.

4.1. Comparison with Previous Observations

a) The Coma cluster

The Coma cluster, which is classified as an evolved system without a dominant central galaxy (Forman and Jones 1982), has been intensively investigated both observationally and theoretically. The plasma temperature of the intracluster gas obtained by previous observations (Jones and Forman 1978; Mushotzky et al. 1978; Mitchell et al. 1979; Henriksen and Mushotzky 1986) is in the range of 6.0–8.85 keV, which is consistent with our continuum temperature 8.2 ± 0.3 keV. The intensity and the equivalent width of the iron K emission line are 1.0×10^{-3} photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ and 160–320 eV, respectively. However, the line energy of iron K has so far remained poorly determined with conventional proportional counters, although Henriksen and Mushotzky (1986) derived energies of 6.55 keV for iron Kα and 7.8 keV for iron Kβ. We determine the mean line energies of iron Kα and Kβ to be 6.58 ± 0.05 keV and 7.82 ± 0.16 keV. These line energies corrected for the redshift are somewhat lower than the values estimated from the isothermal model for the redshift corrected continuum temperature of 8.4 keV, as shown in figure 3. The equivalent width of iron Kα is 292 ± 41 eV which gives an iron abundance relative to the cosmic value, $N(\mathrm{Fe})/N(\mathrm{H})=4.0\times10^{-5}$, of 0.32 ± 0.05. The observed intensity ratio of iron Kα to Kβ is 3.9 ± 1.5, compared to the value 6.1 estimated from an isothermal model with the continuum temperature of 8.4 keV, whereas HEAO-1 HED obtained this ratio to be ~1 with large errors (Henriksen and Mushotzky 1986).

b) The Ophiuchus cluster

The X-ray spectrum of the Ophiuchus cluster observed by HEAO-1 (Johnston et al. 1981) was fitted with a thermal bremsstrahlung spectrum of temperature of 8 ± 2 keV and an iron emission line with an equivalent width of 450 ± 150 eV. The X-ray spectrum obtained by the EXOSAT ME detector yielded a temperature of 9.4 (+1.5, −1.2) keV and an abundance of 0.21 (+0.11, −0.10) (Arnaud et al. 1987). The X-ray spectrum observed by Tenma is well expressed by a continuum temperature of 11.6 ± 0.6 keV and two emission lines corresponding to iron Kα and Kβ. The equivalent widths of iron Kα and Kβ are 310 ± 49 eV and 169 ± 54 eV, respectively. The iron abundance derived from the equivalent width of iron Kα is found to be 0.49 ± 0.08 relative to the cosmic value, although the equivalent width depends strongly on the plasma temperature. The mean line energy of iron Kα is obtained to be 6.56 ± 0.06 keV, whereas that obtained by the EXOSAT GSPC (Arnaud et al. 1987) is 6.77 (+0.15, −0.12) keV. This discrepancy might be compromised by the contribution of iron Kβ which is not mentioned in the EXOSAT result. As shown in figure 3, the mean line energy of iron Kα corrected for the redshift is lower than the value 6.81 keV estimated from an isothermal model with a continuum temperature of 11.9 keV corrected for the redshift. The plasma temperature derived from the observed line energy lies in the range 3–11 keV. This fact indicates the existence of a cooling component in the core region obtained by Arnaud et al. (1987). The observed line width of iron Kα seems to be explained by composite lines which arise from He-like and H-like ions in a plasma of a temperature of around 10 keV. The intensity ratio of iron Kα to iron Kβ is 2.7$\pm$0.9, which should be compared with the value 5.7 estimated from an isothermal model.

c) The Perseus cluster

The Perseus cluster has been as well investigated as the Coma cluster. The Seyfert galaxy NGC 1275 is located at the center of the cluster. The surface brightness profile observed by the Einstein HRI and IPC showed evidence for a cooling flow in the core region (Fabian et al. 1981; Branduardi-Raymont et al. 1981). Thus it is likely that the X-ray spectrum in the 1–10-keV band emitted from the whole cluster is a composite of several temperature components.

The continuum temperature of 6.9$\pm$0.3 keV obtained by Tenma is consistent with that of the previous observations which were in the range of 6.4–7.5 keV (Serlemitsos et al. 1977; Jones and Forman 1978; Mushotzky et al. 1978; Mitchell et al. 1979; Mushotzky and Smith 1980). Recently Ulmer et al. (1987) have obtained the continuum temperature to be 3.6 (+0.2, −0.1) keV for the inner region (within 6′) and 6.1 (+0.7, −0.5) keV for the outer region (an annulus from 6′ to 20′) in the 1–10-keV band with a set of proportional counters on board Spartan 1. The observed mean line energy of iron Kα, 6.55$\pm$0.03 keV, is corrected for the redshift and compared with 6.75 keV estimated from the continuum temperature as shown in figure 3. This discrepancy could be resolved by taking into account the two temperature components observed by Ulmer et al. (1987). This means that our results also show evidence of a temperature distribution in the cluster. The temperature derived from the line energy of iron Kα is as low as or lower than 4 keV but the line width of iron Kα is consistent with a single emission line. The intensity ratio of iron Kα to iron Kβ is 7.8$\pm$5.3, which is consistent with the value 6.5 estimated from an isothermal model with the temperature 7.0 keV corrected for the redshift as shown in figure 4. The iron abundance relative to the cosmic value is derived to be 0.42$\pm$0.05 from the equivalent width of iron Kα.

4.2. *Mean Line Energy and Isothermality*

The mean line energies of iron Kα for these three clusters obtained by Tenma are lower than the values estimated from an isothermal model at the respective continuum temperature. Especially the deviations are more significant for Ophiuchus and Perseus and indicate the existence of a cooling component. This means that the assumption of isothermality is not valid for these clusters, although the continuum component is well expressed by a single temperature. The uncertainty of the line energies of iron Kβ is so large that they cannot place any constraint on the emission model.

4.3. *Equivalent Width and Iron Abundance*

On the assumption of an isothermal model, the equivalent width is simply derived from the ratio of the line intensity to the continuum intensity at the line energy. The iron abundances are derived from the difference in the equivalent widths between the observed and calculated as shown in figure 2. The iron abundance for Coma is lower than those of the other two clusters. This fact is probably related to the existence of a cooling component, since the Coma cluster does not show any central excess emission in the surface brightness profile observed by the Einstein IPC (Abramopoulos and Ku 1983; Jones and Forman 1984). As seen in figure 2, the equivalent width monotonically decreases with the increase in the plasma temperature. This means that the contribution of the iron Kα line originated from a cooling component is larger than that of the continuum component, which results in the higher abundance, if the continuum component is expressed by a single temperature. Of course, it is not possible to separate the temperature components from our spectral fitting. The line energy is also shifted to the lower energy side by the contribution of the cooling component as understood from figure 3. This tendency is consistent with our observational results. The iron abundance of clusters accompanying the cooling component is probably higher than that of Coma-like clusters.

4.4. *Intensity Ratio of Iron Kα to Kβ*

The observed intensity ratios are lower than the values estimated from an isothermal model except for Perseus. This difference cannot be explained by the nonisothermality of intracluster gas, since the contribution of the cooling component cannot make this difference smaller. A simple explanation is the overabundance of nickel, which contradicts the underabundance of iron. As discussed in section 3 resonance scattering is no more effective for the reduction of the intensity of iron Kα. Mitchell and Mushotzky (1980) obtained a Kα/Kβ ratio of 3 for the Centaurus cluster with the continuum temperature of 2.68 keV, which is far below the value estimated from an isothermal model as understood from figure 4. This problem is an open question at this time.

5. Conclusion

The X-ray spectra of the Coma, Ophiuchus, and Perseus clusters of galaxies observed by the GSPCs on board Tenma can be moderately well explained as emission from an isothermal plasma in collisional ionization equilibrium. The abundance of iron relative to the cosmic value is derived to be 0.32 ± 0.05, 0.49 ± 0.08, and 0.42 ± 0.05 for Coma, Ophiuchus, and Perseus, respectively. The mean line energies of iron Kα corrected for the corresponding redshifts are found to be 6.73 ± 0.05 keV, 6.74 ± 0.06 keV, and 6.67 ± 0.03 keV for Coma, Ophiuchus, and Perseus, respectively. However, in all three cases these line energies are somewhat lower than those estimated from the continuum temperature. This fact indicates that there exists a temperature distribution in these clusters, though our observations cannot directly resolve the various temperature components. Higher-resolution spectroscopic observations should give clues to clarify these phenomena. Of course, spatially resolved spectroscopic observations will be most decisive in tackling these currently controversial problems of X-ray emission from clusters of galaxies.

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