Determination of Iron Abundance of an Intracluster Medium with Resonance Scattering Effect

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ABSTRACT

We have done detailed spectral analysis of Fe-K emission lines in the central core and outer envelope of several clusters of galaxies in order to confirm the resonance scattering effect in an intracluster medium. Observed intensity ratios of Kα/Kβ and He-like/H-like Kα are smaller than values estimated from a thin hot plasma model. This means that Fe abundance could be larger than that derived from a standard spectral fitting method by a factor of two at most. However there still remain some controversial problems to be investigated further.

1. Introduction

Elemental abundances and their radial distribution of clusters of galaxies are normally derived from specral fitting of Raymond-Smith or MEKA model. They indicate that higher the temperature gives lower the abundanece at the critical plasma temperature of 4–5 keV. The fitting of Fe-K line feature is not good enough specially in the central core region, which results in underestimate of Fe abundance. It seems this would be caused by the resonance scattering effect. For instance the optical depth of He-like Fe-Kα resonance line is estimated to be larger than unity in an intracluster medium (ICM). The importance of this effect was pointed out by Gilfanov et al. (1987) and Okumura et al. (1988).

We have tried a detailed spectral analysis of Fe-K emission lines of the Perseus cluster, the Coma cluster, A644, A3266 and so on observed with ASCA taking into account the resonance scattering effect. Fe-K lines were resolved as H-like Kα, He-like Kα and Kβ blended with nickel Kα lines within the energy resolution of GIS and SIS. The finite optical depth of resonance lines causes the reduction of not only line intensities but also mean line energies. Care should be taken to confirm that the plasma temperature of continuum component is consistent with the ionization temperature estimated from emission lines. The intensity ratio of Fe-Kα /Kβ or He-like/H-like Fe-Kα is given as functions of plasma temperature and optical depth, which is smaller than values estimated from a optically thin hot plasma model. This discrepancy would make increase the iron abundance by a factor of two or more. He-like/H-like of Kα lines purely gives iron abundance, so that Kβ line feature even makes it possible to derive nickel one seperately. This observational evidence is critically important to investigate the physical process and origin of iron in intracluster media. We present the analysis method and results thus obtained.

2. Spectral analysis

We have analyzed spatially-resolved spectra of the Per (A426), the Coma (A1656), A644, A3266, A3158 and A1650 observed with GIS and SIS of ASCA, as listed in Table. Standard observation time is 40 ksec for 1 ASCA GIS (c/s). These spectra were divided into the central core (r $<$ 300 kpc) and outer envelope (r = 300 kpc – 1 Mpc) refering to the X-ray surface brightness distribution. Raymond-Smith (R-S) model was fitted to observed spectra in the energy region of 0.5–10 keV and 3–10 keV. We noticed some discrepancy around Fe-Kβ, so that a model spectrum of thermal bremsstrahlung and Gaussian lines (C+L) was fitted to separate emission lines from continuum. Thus we can derive the line intensity and energy of Fe-Kα and -Kβ with GIS (Akimoto et al. 1997) and those of He-like and H-like Fe-Kα with SIS. Intensity ratio (R(a/b)) of Fe-Kα to Fe-Kβ and (R(He/H)) of He-like Fe-Kα to H-like one were compared with those estimated from a optically thin hot plasma model with the electron temperature (kT) derived from the continuum component. These values are summerized in Table. Observed values are systematically smaller than predicted ones shown as "opt. thin" in Table. Statistical errors seem to be 30-50%. Fe-Kα and Fe-Kβ feature include 23 lines in 6.5–7.0 keV band and 18 lines in 7.6–8.2 keV band for model calculation of GIS data, respectively. Fe-Kβ is blended with Ni-Kα lines. SIS can resolve resonance lines of He-like and H-like Fe-Kα.

3. Resonance scattering in ICM

The optical depth (t) of He-like Fe-Kα line is around unity in the central core of ICM, whereas that of continuum component is negligibly small. Therefore the intensity of Fe-Kα lines is significantly reduced depending on t. Radial profile of the intensity is calculated over whole cluster by Gilfanov et al. (1987) and Tawara et al. (1997). The intensity is suppressed in the central core and enhanced in the outer envelope. Total intensity over the cluster could be conserved and become the same as an optically thin case. R(a/b) is a good indicator of the reduction of Fe-Kα, since the optical depth of Fe-Kβ is about 1/5 of Fe-Kα. R(a/b) is given as functions of kT and t. Optical depth is a function of projected radius. This ratio is rather sensitive to plasma temperature below 5 keV. R(He/H) also shows the evidence of resonance scattering, since ion fraction of Fe depends on the plasma temperature. He-like ion starts increasing from kT = 2 keV, whereas H-like ion increasing from kT = 4 keV. Ion fraction and intensity of Kα lines of both ions become equal at kT = 8 keV and 10 keV in the optically thin case, respectively. This means that the resonance scttering effect of R(He/H) is more sensitive in the range of kT = 4–8 KeV, assuming an isothermal plasma. It is important to derive R(a/b) and R(He/H) from observed data. Both values should be consistent to obtain the optical depth. If they are significantly different, isothermal assumption would not be correct.

Table 1: Intensity ratio of Fe-K lines

Cluster	z	r	R-S (3–10keV) kT	Ab	C+L (3-10keV) kT*	R(a/b)	R(a/b)	R(He/H)	R(He/H)
		(′)	(keV)		(keV)	(obs.)	(opt. thin)	(obs.)	(opt. thin)
M87(Vir)	0.0038	8.6	2.3	0.63	2.3	3.6	17	—	—
AWM7	0.0179	6.2	2.1	0.46	2.1	3.9	18	—	—
Per	0.0183	1.2	4.5	0.40	4.6	9.1	9.0	3.8	8.2
		4.3	5.0	0.40	5.2	8.0	8.2	2.3	6.3
		4.3–8.6	7.2	0.34	7.8	6.2	6.7	2.4	2.5
Coma	0.0232	10.0	10.5	0.23	9.6	2.3	6.2	1.6	1.6
A3158	0.0590	3.0	5.3	0.30	5.7	7.8	7.7	2.6	5.0
		10.0	6.3	0.21	6.2	1.9	7.5	—	—
A3266	0.0594	4.6	8.1	0.24	8.1	1.9	6.6	1.9	2.3
		4.6–12.8	9.2	0.22	10.2	5.8	6.1	—	—
A644	0.0704	2.5	6.9	0.27	7.1	4.7	7.0	1.4	2.9
		7.3	7.3	0.29	7.7	9.7	6.7	—	—
A1650	0.0845	2.0	5.2	0.35	5.2	3.7	8.2	2.9	6.3
		6.7	5.8	0.32	5.9	5.6	7.6	—	—

[a]R-S: Raymond-Smith model

[b]C+L: thermal bremsstrahlung (continuum) + Gaussian Lines model

[c]kT*: electron temperature derived from continuum component

[d]r: radial distance (arcmin) from the center of cluster

[e]Ab: abundance relative to cosmic value

[f]R(a/b): intensity ratio of Fe-Kα to Fe-Kβ observed by GIS

[g]R(He/H): intensity ratio of He-like Fe-Kα to H-like one observed by SIS

[h]opt. thin: values estimated from optically thin hot plasma model

[i]statistical errors: <10% for kT and Ab, 30–50% for R(a/b) and R(He/H)

4. Discussion and summary

As shown in Table, observed R(a/b) and R(He/H) are smaller than those estimated from an optically thin plasma, though statistical errors are large. The large deviation of M87 and AWM7 is not possible to explain with the resonance scattering effect, since the reduction rate of Kα line intensity would be within a factor of two. This could be caused by the difference of kT or emission process from a thin hot plasma. kT is derived from the continuum component corresponding to the elctron temperature, so that the ionization temperature is not equal to the electron temperature. Emissivity of Fe-Kα lines steeply increase with kT below 4 keV.

R(a/b) of the Coma cluster is obviously smaller than that calculated from an optically thin model, which is almost the same value obtained over the whole cluster by Tenma satellite (Okumura et al. 1988). This is not the case for the resonance scattering effect, since theTenma value should be equal to that for opt. thin on the assumption of isothermal spherically symmetric plasma. R(He/H) is not sensitive to the optical depth at kT = 9.6 keV.

Molendi et al. reported that R(a/b) of the Perseus cluster observed by Beppo-SAX is significantly smaller than predicted by optically thin hot plasma model, which is inconsistent with R(a/b) but consistent with R(He/H) observed by ASCA. This discrepancy would be reserved for future observations. Anyway iron abundance of clusters listed in Table could be larger than that derived from R-S model.

Present results are not statistically sufficient to confirm the resonance scattering effect. We need at least 100 ksec observation time for one ASCA (c/s) clusters. The XMM observations of clusters of galaxies are promising to make further progress the precise determination of elemental abundances with this method.

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