Metal enrichment histories from galaxies to clusters

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Abstract

With Suzaku, we derived O, Mg, S, Si and Fe abundances of hot intracluster medium (ICM) in clusters of galaxies, and groups of galaxies, and hot interstellar medium (ISM) in elliptical, S0, and spiral galaxies. Especially for regions of low surface brightness, the XIS provides better sensitivity to faint lines of O and Mg, which are predominantly synthesized by supernovae (SN) II.

The derived abundance ratios, O/Fe, Mg/Fe, Si/Fe and S/Fe of the ICM, scatter around unity, i.e., the solar ratio, adopting the new solar abundances defined by Lodders (2003). Observed clusters and groups of galaxies with a bright central galaxy show similar Fe abundances of about 0.5 solar at 0.1–0.2r_{180}. In contrast, the metal-mass-to-light ratios for clusters of galaxies tend to be higher than those in groups of galaxies. If metal enrichment occurred before the cluster or group formations, the poor systems would carry relatively smaller metal mass with smaller gas mass, while metal abundance would be similar.

The derived Fe abundances of the ISM in elliptical galaxies are about 0.5–1.0 solar, indicating a low rate of present metal supply into the ICM. To account for Fe mass in the ICM, the past average rate of SNe Ia was much larger. The derived O and Mg abundances of the ISM in these galaxies are consistent with stellar metallicity which reflects formation histories of these galaxies. Observed low O/Fe ratio of the ISM in a S0 galaxy, NGC 4382, indicates different formation histories between this S0 galaxy and elliptical galaxies. The abundance pattern of the hot ISM in spiral galaxies may depend on their starburst activities.

Key words: X-rays: intracluster medium —clusters of galaxies: intracluster medium — galaxies: chemical evolution

1. Introduction

The metal abundances in the ICM and the hot X-ray emitting ISM in galaxies provide important clues to understand the metal enrichment history and evolution of galaxies.

O and Mg are predominantly synthesized in SNe II. Abundance measurements spanning the range of species from O to Fe are therefore needed to obtain unambiguous information on the formation history of massive stars. XMM-Newton provides the means to measure O and Mg abundances in some systems, but reliable results have been obtained only for the central regions of very bright clusters or groups of galaxies dominated by cD galaxies.

Regarding early-type galaxies, the metal abundances in the ISM give us important information about the present metal supply into the ICM through SNe Ia and stellar mass loss. In addition, O and Mg abundances should reflect the stellar metallicity and enable us to look directly into the formation history of these galaxies.

Suzaku (Mitsuda et al. 2007) is the fifth Japanese X-ray astronomy satellite and was launched on 2005 July 10. The XIS instrument (Koyama et al. 2007) has an improved line spread function due to a very small low-pulse-height tail below 1 keV coupled with a very low background. Despite its smaller field of view ($18' \times 18'$) and poorer spatial resolution ($\sim 2'$) compared with the MOS instruments aboard XMM-Newton, the XIS has some advantages. The MOS's instrumental Al line causes problems measuring the Mg abundance in somewhat fainter

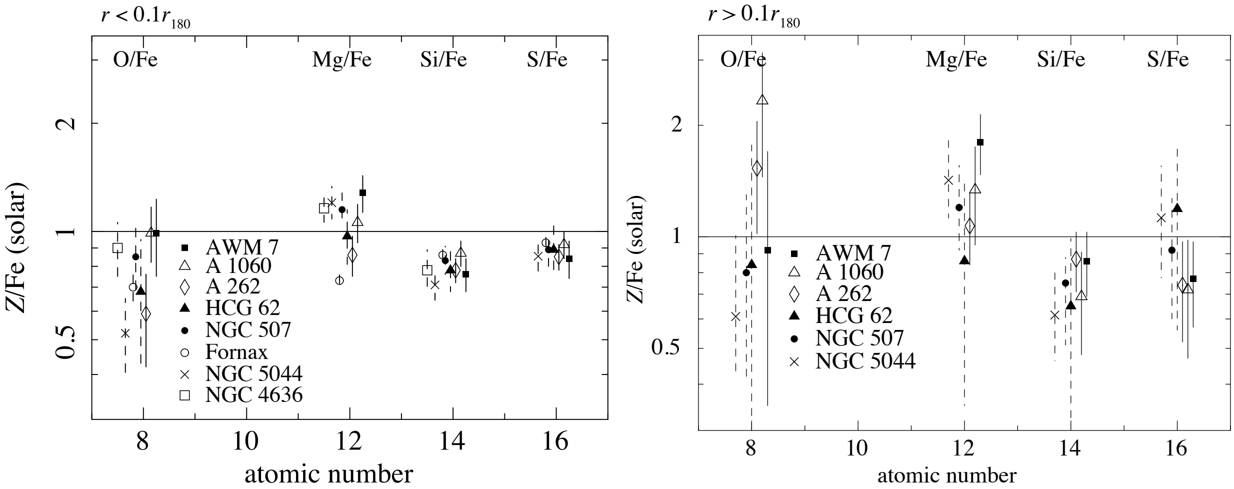

Fig. 1. The abundance ratios of O, Mg, Si, and S divided by the Fe abundance (in units of solar ratio) of ICM within 0.1 r_{180} (left panel), and 0.1–0.2 $\sim 0.3r_{180}$ (right panel) in clusters of galaxies(solid lines), AWM7 (closed squares; Sato et al. 2008), Abell 1060 (open triangles; Sato et al. 2007), and Abell 262(open diamonds; Sato et al. 2009a), and those in groups of galaxies(dashed lines), the HCG 62 group (closed triangles; Tokoi et al. 2008), the NGC 507 group (closed circles; Sato et al. 2009b), the Fornax clusters (open circles;Matsushita et al. 2007), the NGC 5044 group (crosses;Komiyama et al. 2009), and NGC 4636 (open squares;Hayashi et al. 2009).

systems, due to a strong instrumental Al line and the Mg lines are particularly useful in cluster outskirts, since the strong Galactic O line cause difficulty in the measurement of O emission from nearby clusters. Especially for regions of low surface brightness or equivalent width, the XIS also provides better sensitivity to O lines and has excellent sensitivity at the iron K-line energies.

In this paper, we adopt the new solar abundances given by Lodders (2003). Recently, the solar photospheric abundances of C, N, O, and Ne decreased by 0.2 dex, considering three-dimensional hydrodynamical model atmospheres and non-local thermodynamic equilibrium (Asplund 2005 and references therein). The new solar O and Fe abundances relative to H are 4.90×10^{-4} and 2.95×10^{-5}, respectively, by number (Lodders 2003). These values differs from 8.51×10^{-4} and 4.68×10^{-5}, which are the "photospheric" values of O and Fe, respectively, given by Anders and Grevesse (1989). Unless otherwise specified below, errors are quoted at 90% confidence.

2. The abundances of O, Mg, Si, S and Fe in the ICM

We have derived abundances of O, Mg, Si, S and Fe in ICM in clusters of galaxies with ICM temperatures are 2–4 keV, Abell 262 (Sato et al. 2009a), Abell 1060 (Sato et al. 2007) and AWM7 (Sato et al. 2008), and a poor cluster, the Fornax cluster (Matsushita et al. 2007), and groups of galaxies, the HCG 62 group (Tokoi et al. 2008), the NGC 5044 group (Komiyama et al. 2009), and NGC 4636 (Hayashi et al. 2009). Figure 1 summarizes the abundance patterns of the ICM.

Using the solar abundance by Feldman (1992), the O abundances in the ICM are a factor of two lower than those of Mg, Si, S, and Fe. However, adopting the new solar abundance by Loddars (2003), within $r < 0.1r_{180}$, the abundance patterns become closer to the solar abundance ratio (Figure 1). If the initial mass function of stars in clusters is close to that in our Galaxy, and most of SNe have been already exploded, the abundance pattern should naturally be similar to the solar abundance pattern. Then, the Fe have been mostly produced by SNe Ia.

In contrast, outside $r > 0.1r_{180}$ of the clusters of galaxies, Mg and O may show somewhat flatter radial distributions than Fe and Si (Figure 1), although the errors are fairly large. Then, SNe II metal enrichment may become more important in the outer regions of clusters.

The radial profiles of Fe abundance in these systems are summarized in Figure 2. The three clusters of galaxies have similar Fe abundance at ~0.5 solar from 0.05 to $0.3r_{180}$. The Fe abundances of the groups and the Fornax cluster are close to the level observed in these clusters. In contrast, enhanced Fe abundance within $0.05r_{180}$ should reflect Fe accumulation in the central galaxies.

2.1. Oxygen and Iron mass-to-light ratios in ICM

Ratios of ICM metal mass to the total light from galaxies in clusters or groups, i.e., metal-mass-to-light ratios, are key parameters in investigating the chemical evolution of the ICM. With the Suzaku satellite, the oxygen-mass-to-light ratio (OMLR) as well as the iron-mass-to-light ratio (IMLR) of the three clusters of galaxies and several groups of galaxies were measured up to 0.2–$0.3r_{180}$ (Figure 3). The OMLR, and IMLR for clusters of galaxies with $kT \sim 2-4$ keV tend to be higher than those in

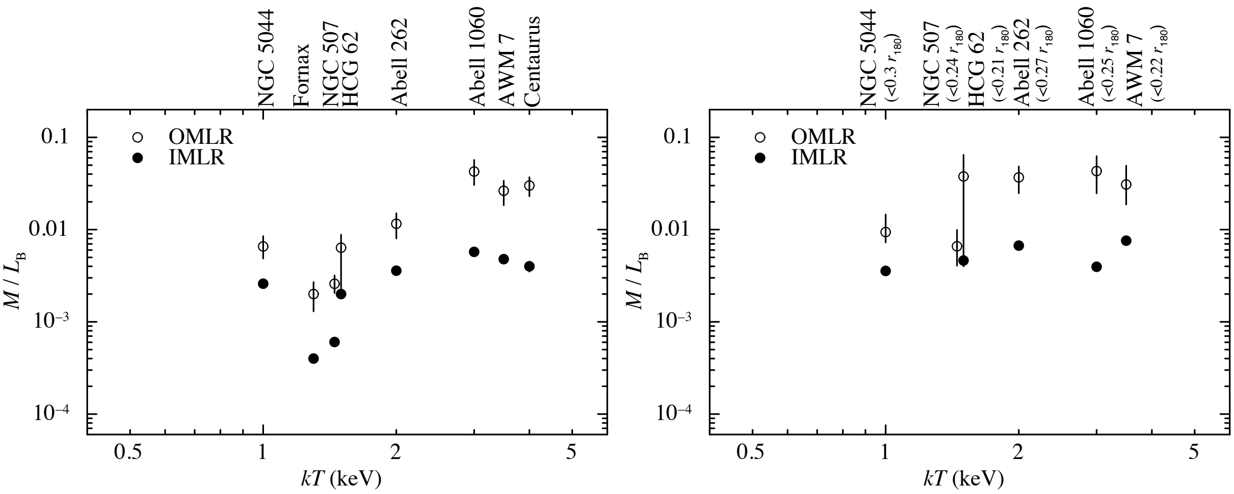

Fig. 3. Integrated IMLR (closed circles), and OMLR (open circles) at **(Left)** $r = 0.1\ r_{180}$ or **(Right)** $r \sim 0.3\ r_{180}$ using the B-band luminosity.

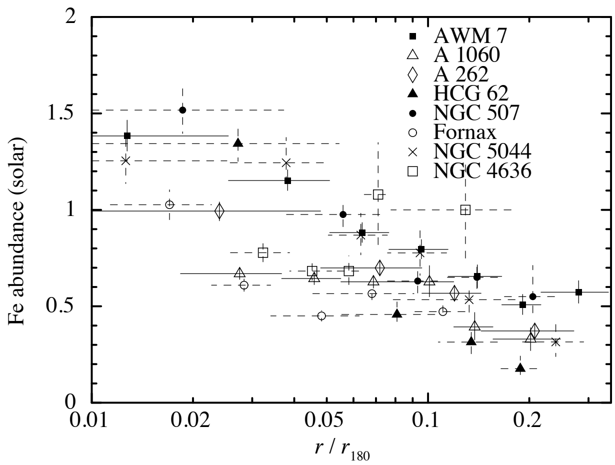

Fig. 2. The radial profiles of the Fe abundance (in units of solar abundance) of ICM in clusters of galaxies (solid lines) and groups of galaxies (dashed lines).

groups of galaxies and the poor cluster of galaxies with $kT \sim 1$ keV.

The difference in the OMLR values between groups and clusters is about a factor of 3–6, and systematically larger than the IMLR difference, which is a factor of 2–3. Among groups, the NGC 5044 group and HCG 62 have the highest IMLRs, which are comparable to those of clusters. In contrast, OMLR of the NGC 5044 appears to be lower than those of clusters. Among the groups and poor clusters, the Fornax cluster shows the lowest IMLR and OMLR. In the Fornax cluster, the asymmetric X-ray emission may point to large-scale dynamical evolution, which might have hampered the strong concentration of hot gas in the center.

The poor systems also differ from richer systems in that the gas density profile in the central region is significantly flatter and the relative entropy level is correspondingly higher (e.g. Ponman et al. 1999). These peculiar central characteristics in the poor systems are thought to be best attributed to an injection of energy (preheating) into the gas before clusters have collapsed (e.g. Kaiser 1991). Note also that more recent observations and simulations of entropy profiles indicate some modification to this simple picture (e.g. Ponman et al. 2003).

Metal distribution in the ICM can be a powerful tracer of the history of such a gas heating in the early epoch, since the relative timing of metal enrichment and heating should affect the present amount and distribution of metals in the ICM. To look into this, we assume that all galaxies synthesize a similar amount of metals per unit stellar mass. If metal enrichment occurred before the energy injection, the poor systems would carry relatively smaller metal mass with smaller gas mass than those in rich clusters, while metal abundance would be quite similar to those in rich clusters. In contrast, if metal enrichment occurred after the energy injection, the metal mass becomes comparable to those in rich clusters and indicates a higher abundance. The difference in O and Fe distributions would constrain the timing of energy injection, since O was synthesized by SN II during galaxy star formation, while Fe was mainly produced by SN Ia much later than this period.

The OMLR shows a larger difference in clusters and groups than the IMLR does, which may reflect the condition that SN II products are more extended in groups due to the effect of preheating. Fe was synthesized later by SN Ia, and may be irrelevant to preheating. To further investigate the problem of heating and enrichment, we need numerical simulations including the effect of the preheating and metal enrichment by both SN II and SN

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3. Abundance pattern of hot intersteller medium in early-type galaxies

We derived abundance pattern of O, Ne, Mg and Fe of ISM of four elliptical galaxies, NGC 720 (Tawara et al. 2007), NGC 1399 (Matsushita et al. 2007), NGC 1404 (Matsushita et al. 2007), NGC 4636 (Hayashi et al. 2009), and two S0 galaxies, NGC 1316 (Konami et al. 2009), and NGC 4382 (Nagino et al. 2009) observed with Suzaku.

The Fe abundances of the ISM in these galaxies are about 0.5–1 solar, indicating that present SN Ia rate is relatively low. In order to accumulate the observed high IMLR in clusters, SN Ia rate should have been higher in the past. The O, Ne and Mg abundances are consistent with stellar metallicity. As summarized in Figure 4, their abundance patterns of the ellipticals and an S0 galaxy, NGC 1316 are not so different from the solar pattern, using new solar abundance by Loddars (2003). These galaxies are giant galaxies and their ISM temperatures are 0.6∼1 keV. Considering the metal-enrichment from present SN Ia, the near-solar abundance pattern of the ISM in these galaxies indicates an enhanced α/Fe ratio of stellar materials in the entire galaxy. In contrast, a S0 galaxy, NGC 4382, with an ISM temperature of 0.3 keV, has a smaller O/Fe ratio in the ISM. This result means that the ISM in this galaxy contains more SN Ia products. Further studies to obtain more samples of the ellipticals ad S0 galaxies would enables us to understand the formation process of these galaxies in more detail.

4. Abundance pattern of hot insterstellar medium in spiral galaxies

With Suzaku, abundance pattern of O, Ne, Mg, Si, and Fe of hot ISM in starburst galaxies, the cap region of M 82 (Tsuru et al. 2007), and NGC 4631 (Yamasaki et al. 2009), and a non-starburst galaxy, NGC 4258 (Konami et al. 2009) were derived. The observed abundance ratios of halo region of the two starburst galaxies are close to those of SN II. This result indicates that starburst activities pollute intergalactic space with SN II products. In contrast, these ratios of the disk regions of NGC 4631 and NGC 4258 are close to the new solar abundance by Loddars (2003). Therefore, the new solar abundance pattern may be common among normal spiral galaxies.

5. Conclusion

Suzaku observations of hot gas in clusters of galaxies, groups of galaxies and galaxies give us new information of O, and Mg abundances of the gas. The metal distribution can be used as a tracer of the past history of star formation, and thermal history in these systems.

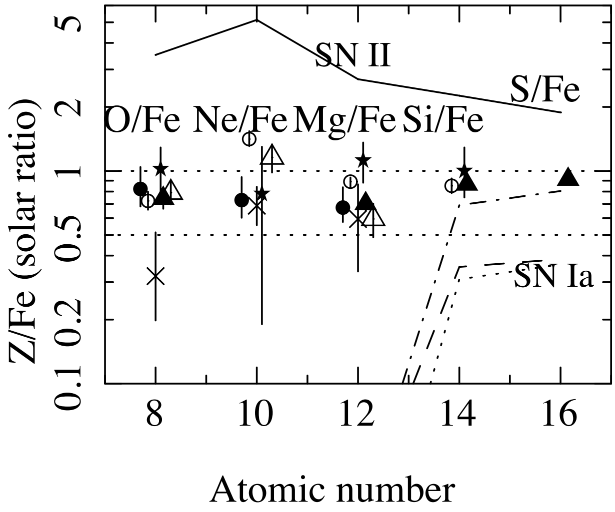

Fig. 4. The abundance ratios of O, Ne, Mg, Si, and S divided by the Fe abundance (in units of solar ratio) of hot ISM in elliptical galaxies, NGC 720 (closed circles; Tawara et al. 2008), NGC 4636 (open circles; Hayashi et al. 2009), NGC 1399 (closed triangles; Matsushita et al. 2007), NGC 1404 (open triangles; Matsushita et al. 2007), and two S0 galaxies, NGC 4382 (crosses; Nagino et al. 2009), and NGC 1316 (asterisks; Konami et al. 2009). The solid line corresponds to abundance pattern of SN II by nucleosynthesis model (Nomoto et al. 2006) and dotted, dashed and dot-dashed lines correspond to those of SN Ia by Iwamoto et al. (1999)

References

Anders E. &Grevesse N., 1989, Geochimica et Cosmochimica Acta 53, 197
Asplund M. et al. 2005, ARA&A, 43, 481
Hayashi K. et al. 2009, PASJ in press
Iwamoto K. et al. 1999, ApJS, 125, 439
Kaiser, N. 1991, ApJ, 383, 104
Komiyama M. et al. 2009, PASJ, 61S, 337
Konami S. et al. 2009, PASJ in press
Konami S. et al. 2009, submitted to PASJ
Koyama K. et al. 2007, PASJ, 59, 23
Lodders K. et al. 2003, ApJ, 591, 1220
Matsushita K. et al. 2007, PASJ, 59, 327
Mitsuda K. et al. 2007, PASJ, 59, 1
Nagino R. et al. submitted to PASJ
Nomoto K. et al. 2006, Nuclear Physics A, 777, 424
Ponman T.J. et al. 1999, Nature, 397, 135
Ponman T.J. et al. 2003, MNRAS, 343, 331
Sato K. et al. 2007, PASJ, 59, 299
Sato K. et al. 2008, PASJ, 60, 333
Sato K. et al. 2009a, PASJ,61, 365
Sato K. et al. 2009b, PASJ, 61, 365
Tawara Y. et al. 2008, PASJ, 60, 307
Tokoi K et al. 2008, PASJ, 60, 317
Tsuru T.G. et al. 2007, PASJ, 59, 269
Yamasaki N.Y. et al. 2009, PASJ, 61, 291