Metal Enrichment Histories in the Intracluster Medium with Suzaku

Yuya Shimoda1, Madoka Kawaharada2, Kosuke Sato3, Nobuhiro Okabe4, Takaya Ohashi5, Yoshitaka Ishisaki5, Ikuyuki Mitsuishi5, Hiroki Akamatsu6 and Makoto S. Tashiro1

1 Department of Physics, Saitama University, 255 Shimo-Okubo, Sakura, Saitama 338-8570
2 Institute of Space and Astronautical Science, JAXA, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara 252-5210
3 Department of Physics, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601
4 Kavli Institute for the Physics and Mathematics of the Universe, Todai Institutes for Advanced Study, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583
5 Department of Physics, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji, Tokyo 192-0397
6 SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584, CA, Utrecht, The Netherlands

E-mail(YS): shimoda@heal.phy.saitama-u.ac.jp

Abstract

We conducted a systematic study of metal abundance for a sample of 62 clusters of galaxies observed with Suzaku. The redshift distribution of the sample ranges from $z = 0.02$ to 1.16. We looked into correlations between metal abundances and various cluster properties such as redshift, temperature, total mass, and galaxy luminosities as well as cluster types such as cool core/merging/AGN. In the results, Fe synthesized in SN Ia has already been well enriched before $z > 1$ in relaxed clusters, and its abundance has increased in time by starburst activities. Si, mainly synthesized in SN cc, shows higher abundance with the size of clusters, and this result suggests either metal escape from low-mass systems or higher starburst activities in massive clusters.

Key words: galaxies: clusters — X-rays: galaxies: clusters — X-rays: ICM

1. Introduction

Clusters of galaxies are the largest virialized structures in the universe, and they gravitationally bind hot thin-thermal plasma (intracluster medium: ICM). The ICM is enriched with metals synthesized in stars and supernova (SN) explosions. These metals are highly ionized in collisional ionization equilibrium and the excited metal ions emit atomic lines in the X-ray range. The majority of supernovae are classified into type Ia (SN Ia) or core collapse type (SN cc). The emission line properties observed in the X-ray spectrum reflect integrated activities of both types of supernovae in the galaxies, and enable us to study chemical enrichment evolution history of the ICM, which is a major component of the known baryons in the universe.

Recently, XMM-Newton and Chandra have expanded the metal abundance study to higher redshift clusters. Using XMM-Newton and Chandra data of 56 clusters at $0.3 \leq z \leq 1.3$, Balestra et al. (2007) measured the iron abundance $Z_{Fe}$ within a spatial region of $0.15 \, r_{200}$ to $0.3 \, r_{200}$. They found that the clusters at $z > 0.5$ exhibit similar abundance of $Z_{Fe} \approx 0.25$ solar, while clusters at $z < 0.5$ exhibit a significantly larger abundance of $Z_{Fe} \approx 0.4$ solar. After the launch of Suzaku, studies of alpha elements have been performed. The metal abundances synthesized mainly in SNe cc, such as Mg, Si and S, in the ICM have been measured outside cool-core regions up to $0.3 \, r_{200}$ for several nearby clusters and groups ($z \sim 0.001$; e.g. Sato et al. 2008, 2009, 2010). They showed that the number ratio of SNe cc to Ia is $3 : 5$ and Fe has been synthesized predominantly by SNe Ia. A similar result was reported in de Plaa et al. (2007) using data of XMM-Newton. In order to conclude the metal enrichment history of the ICM observationally, it is crucial to measure metal abundances of α elements and iron families separately in clusters at high redshifts. This is beyond the ability of X-ray observatories currently in orbit, and would be one of major sciences in future X-ray missions with huge effective areas. However, Suzaku has the ability to pilot that survey for bright sources at medium redshifts (Shimoda et al. 2013). Throughout this paper, cosmological parameters of $H_0 = 71 \, \text{km \, s}^{-1} \, \text{Mpc}^{-1}$ and $\Omega_M = 0.27$ are adopted. The definition of one solar abundance is taken from Lodders (2003). Errors are given at the 90% confidence level unless otherwise stated.
2. Target and Data Reduction

2.1. Target

Suzaku has observed a number of clusters of galaxies, and has archived observations of 116 clusters and groups as of 2013 March. We reduced targets according to the target selection criteria listed below: 1) High-resolution Chandra data can be utilized; 2) No luminous objects such as AGNs are present in the FOV; 3) The Suzaku FOV covers \( r_{200} \) at least. The final selected sample consists of 62 objects \((0.02 < z < 1.16)\).

2.2. Data reduction

We applied the standard screening criteria for both Suzaku and Chandra data. After that, we extracted XIS spectra within circular regions of \( 0.3 \, r_{200} \) for our sample and fitted with \( apec \) model where the background spectra were simultaneously fitted with the X-ray background model. This radius is crucial to estimate an average temperature and metal abundances in the ICM.

3. Result

In figure 1, we plotted \( Z_{\text{Fe}} \) and \( Z_{\text{Si}} \) as a function of the temperature, with the information of dynamical state. As shown in the distribution of red squares, merging clusters exhibit rather constant \( Z_{\text{Fe}} \) around \( 0.4 \, Z_{\text{solar}} \) and show signs of high temperature clusters, while relaxed clusters indicate higher abundance. Thus, \( Z_{\text{Fe}} \) is fairly constant with the cluster size, but probably divided into two groups regarding the merging status of the clusters. \( Z_{\text{Si}} \) shows positive correlation with the cluster size. Similar results were reported by the ASCA observations (Fukazawa et al. 1998), and they explained this trend as a larger fraction of SNe cc products escaped from relatively shallower gravitational potential of poorer systems.

We summarize the general pictures of the metal enrichment history of the ICM, in phase 1 to 5: 1) In the early epoch of cluster formation \((z \sim 2)\), the ICM was enriched by the supernovae explosions. SNe cc was dominant than SNe Ia with the ratio of \( N_{\text{cc}}/N_{\text{ia}} \sim 3.5 \) during the era; 2) In the following cluster merging era, the ICM temperature increased; 3) Starburst activity was triggered by the merging in the member galaxies. SN cc was dominant because of short lifetime and then starburst activity ceased shortly by the gas loss due to winds before SN Ia explosion occurred; 4) During the merging period, the deviation from equilibrium state of the ICM became significant. Metals in the ICM escaped from the gravitational potentials of the cluster, or starburst activity was enhanced with the growth of clusters, and the fraction of SN cc products increased than that of SN Ia products; 5) After the starburst activity, clusters became relaxed, but the average temperature has increased from the pre-merging level because of the larger gravitational potential.

The detailed studies of the metal enrichment histories will be reported in a separate paper (see also Shimoda 2014).

References

Shimoda, Y. 2014, PhD thesis, Saitama University