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Review Article

The Chemical Abundances and the Metal Enrichment in the Universe

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Abstract: There are two different theoretical scenarios in the literature on chemical enrichment and metal synthesis of the Universe: (i) early-time and (ii) late-time. The first scenario suggests that elements are produced before the galaxies gravitationally cluster. The second enrichment mechanism claims that dynamical turbulences of galaxy merger trigger production mechanisms. The chemical elements are therefore synthesized after aggregation of galaxies. The fundamental processes for metal production are the supernova explosions. It is still not clear and there is still an on-going debate whether gravitational clustering of the structure trigger supernova activities and thus the chemical enrichment, or supress the metal production. In this review paper, we present the current situation and provide further insights into the subject.

Keywords: chemical enrichment: supernova: galaxies: clusters

1. INTRODUCTION

In the beginning, nearly fourteen billion years ago, all the matter and all the energy of the known universe was originated from the Big Bang. The lightest elements like hydrogen, deuterium, and helium are formed in the period of baryonic matter formation by key fusion reactions, which were happened within several minutes from the vey beginning (Coc and Vangioni 2017, for a detailed review). Since the temperature in the early universe was so high that heavier chemical elements cannot be produced by the Big Bang nucleosynthesis. As, the universe expanded rapidly, it cooled and nuclear reactions ceased. Further elements are created by nuclear fusion reactions between atoms within the stars by stellar nucleosynthesis (Cameron 1957; Burbidge et al. 1957). Stars are hot enough to burn light elements and convert them to carbon, nitrogen, oxygen etc. by so-called stellar nucleosynthesis. The stars evolve, burn out, become other types of structures and explode as a super nova. The heavy elements were produced in Type Ia (SNIa) and Type II (SNcc) supernova explosions (e.g. Nomoto et al. 2013; Thielemann et al. 2018). Everything in the universe and on Earth originated from stardust, and thus "*we come from stardust*".

After about 500 million years the first stars and galaxies appeared. Galaxies gravitationally bound together and form the largest known structures; galaxy groups and clusters. The galaxy clusters are the largest balanced structures of the universe with their 10^{14}~10^{15} solar masses. Based on the bottom-up structural formation model, smaller structures are formed first and then gravitationally collepse to form larger entities. The hot extended plasma (~2-10 keV) between galaxies, which is often called the intracluster medium (ICM) is filled with metals and heavy elements (Sarazin 1986).

Nucleosynthesis of the elements is a long process starting from the Big Bang continues with stellar evolution and takes place during the structural formations with supernova explosions. Especially considering the heavy elements,

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it is not very clear if supernova nucleosynthesis was more efficient when the hosting galaxy is isolated in the void of free space or the chemical enrichment is suppressed as the environment is getting crowded and dense with the mergers. In this paper, we present the current situation up to date and provide a brief review on the topic.

2. CHEMICAL ENRICHMENT

The period of baryonic matter formation (proton, neutron and the very light elements) takes place in the beginning of time, the Big Bang epoch. The other lighter elements are produced in the stellar environment. On the other hand, the heavy elements are synthesized in supernova explosions. The question is where we can find the heavy elements most abundantly: (i) in the access corridors of the cluster outskirts or (ii) at the very center dense ICM center. The very first evidence of Fe-K emission line from nearby clusters like Perseus, Coma and Virgo are reported from Ariel V and OSO-8 data (Mitchell vd. 1976, Serlemitsos vd. 1977). After ASCA investigation of high metal abundance (0.3 ~ 0.5 $Z_{\odot}$) in the Centaurus cluster (Allen and Fabian 1994; Fukazawa et al. 1994), a decreasing iron (Fe) gradient towards to outskirts is also reported. With the great advent of the detector technologies used in recent missions like *XMM-Newton*, *Chandra* and *Suzaku* larger samples of galaxy clusters are analyzed. The iron peaks in the center is reported in great majority (e.g. Buote et al. 2003), while some other flat central metal profiles (e.g. Lovisari and Reiprich 2018). Based on the observational results two scenarios are proposed to explain the nature of the chemical enrichment in galaxy cluster environments.

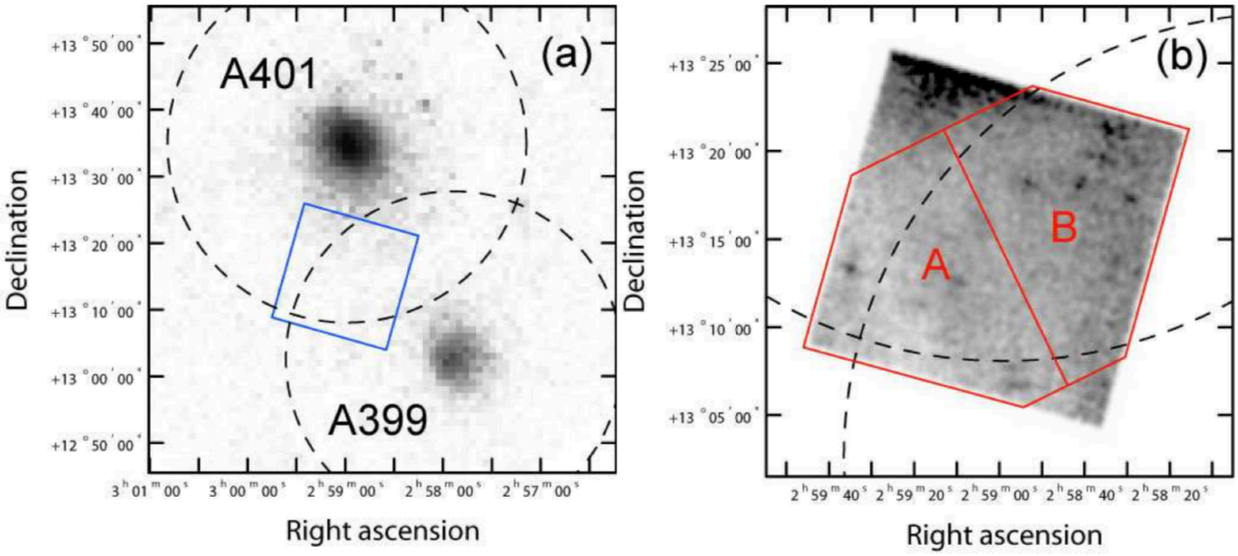

Figure 1: (a) ROSAT PSPC image of A 399/A 401. (b) Suzaku image of the link region. All regions show similar metal abundance, which indicates early type of chemical enrichment (Fujita et al. 2008)

2.1 Early-Time Enrichment

The analysis results of the link region between A399 and A401 *Suzaku* observation have revealed interesting information from beyond the virial radii of the system where two clusters cross each other (Fujita et al. 2008). Figure-1 shows ROSAT image of the binary system and *Suzaku* pointing in between with a tilted blue box. The metalicity values were not as low as it is expected to be. The abundance values are found to be comparable to the inner regions and this uniformity is unlikely to be caused by dynamical turbulences in the ICM. It looked like the galaxies from the outskirts have rich metal abundance before they enter the cluster environment. By referring to this enrichment process from galaxies before the clusters form, Fujita et al. (2008) suggested an Early-Time Enrichment mechanism.

According to this scenario, supernova explosions produce majority of the heavy metals before cluster's formation. And by the galactic winds the metals are transported to ICM at the outskirts. Radial distribution of metal abundances appears to be flat and shows a uniform distribution pattern. Since the metal ejection is predicted to happen in proto-cluster phase, this scenario is called "early-time enrichment". A very recent work on A3112 by *Suzaku* XIS data also confirm the uniformity of metal abundances (~ 0.2 $Z_{\odot}$) out to the cluster's virial radius (Ezer et al. 2017). The radial profile of Fe, Mg, Si and S elements out to R_{500} radius for A3112 are given in Figure-2. The Right-panel shows the sectors where the spectrums were extracted.

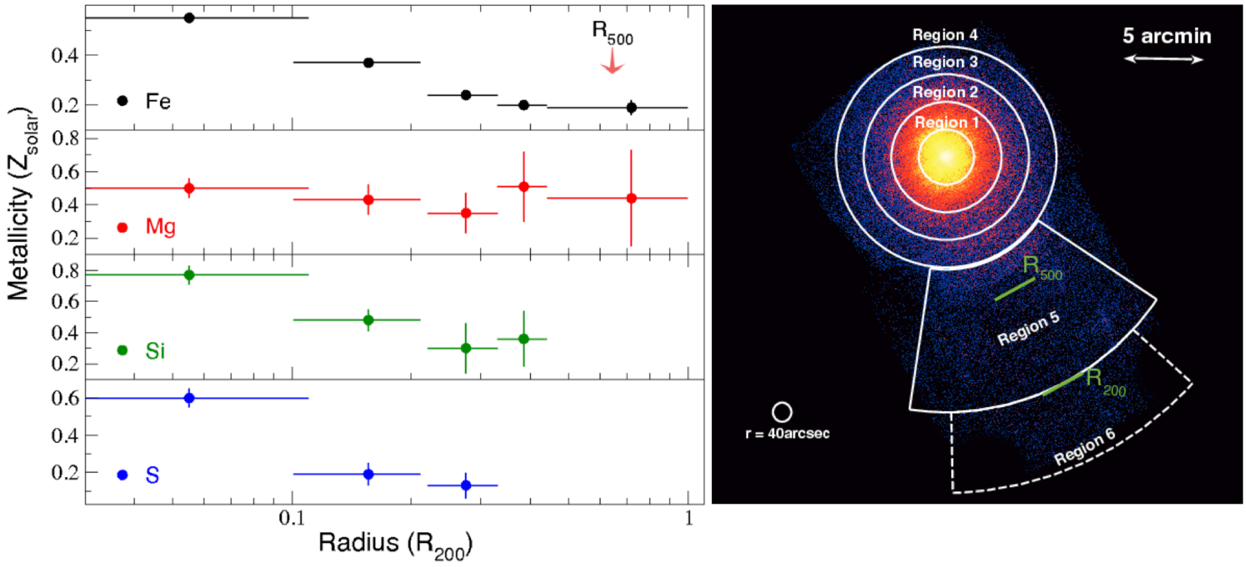

Figure 2: A3112 metal abundances radial distribution of Fe, Mg, Si and S. The regions where the spectrums were extracted are in white sector.

2.2 Late-Time Enrichment

Spatially resolved X-ray spectra from ICM permits to stack metal content of the ICM and distributions of these metals from cluster's center to outer regions. The general observational reports on Fe radial distributions in ICM are to have negative gradients from cluster's core to outskirts. Early works by using ROSAT and ASCA data reporting on such gradients belong to Centaurus clusters (Allen et al. 1994, Fukazawa et al. 1994). They concluded that the iron peak in the core is due to the presence of the cD galaxy located at the center. Following studies performed with more advanced technology and a sample of galaxy clusters also arrived the same conclusion (Grandi et al. 2001, and 2004).

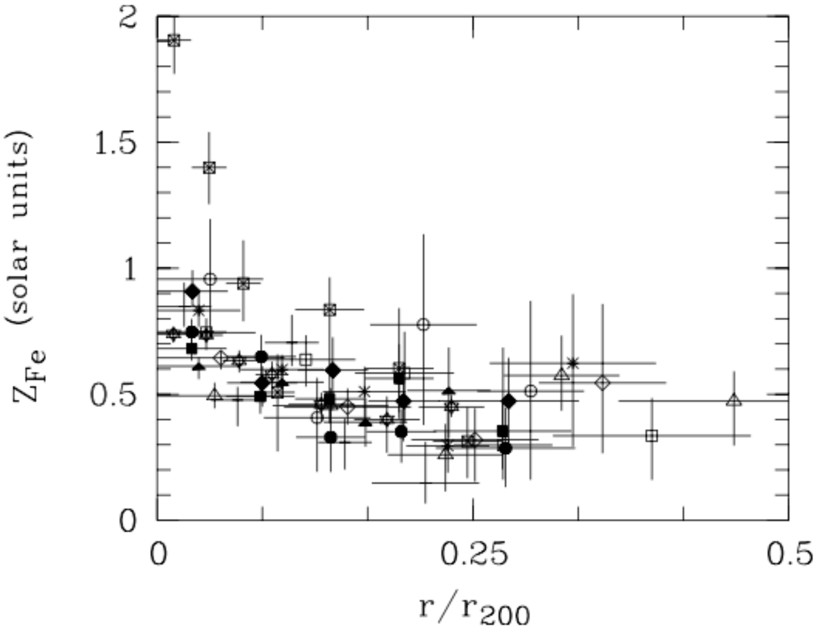

Figure 3: Deprojected iron profiles of 12 cool-core clusters by using BeppoSAX archival observations. The list of the clusters are as follows: A85 (filled circles), A426 (asterisks), A496 (filled lozenges), A1795 (filled triangles), A2029 (open squares), A2142 (open triangles), A2199 (filled squares), A3526 (crossed squares), A3562 (open circles), A3571 (crosses +), 2A 0335+096 (crosses ×), and PKS 0745−191 (open lozenges) (Grandi et al. 2001).

With the advance in technology, new generation X-ray missions were developed and enabled us to reach higher spatial and spectral resolution. After then, in addition to high concentration of iron in the center, the studies also started to report flat distribution of SNcc products such as O (Finoguenov et al. 2000; Böhringer et al. 2001; Tamura et al. 2001; Finoguenov et al. 2002; Matsushita et al. 2003; Sanders et al. 2008; Werner et al. 2006). The main explanation of these results is thought to be caused from the different time-scale nature of these two phenomena. The main difference lies in the origin of these explosions. SNcc results from high-mass-short-lived stars, whereas SNIa is from low-mass-long-lived stars, so that the delay can be around in the order of 10^9 years. Therefore, they stated that the fraction of SNIa to SNcc must increase toward the center.

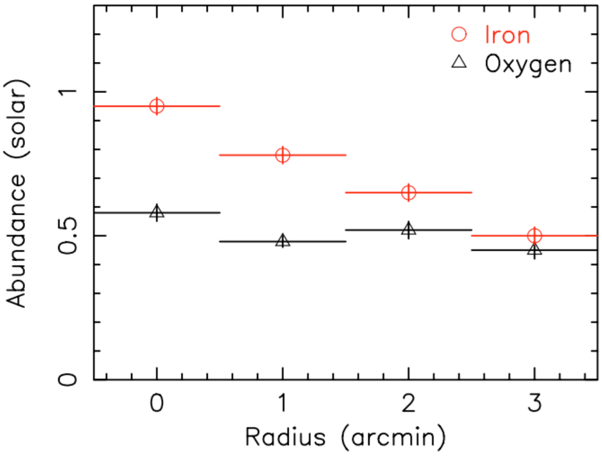

Figure: Radial abundance profiles of O and Fe for M-87 galaxy cluster by using XMM-Newton RGS observations. This figure implies the flat distribution of O together with Fe peaks at the center [Werner et al. 2006].

3. CONCLUSION

Thanks to large field of view of XIS camera, after the launch of Suzaku satellite studies on metal abundances out to virial radius have become possible. A large sample of clusters of galaxies deep observations provides valuable data. The recent study results suggest a uniform distribution, thus favoring early-time enrichment mechanism, which started in the early epochs of the cluster formation.

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