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Metal Enrichment Processes in the Intra-Cluster Medium: Simulations versus Observations

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Abstract This paper reviews metal enrichment processes - processes that transport gas from the galaxies to their environment and enrich the environment in this way with metals. The efficiency of the processes is important for the evolution of both the galaxies and their environment. Various processes can contribute to the gas transfer: ram-pressure stripping, galactic winds, AGN outflows, galaxy-galaxy interactions and others. It seems that all the processes can contribute to the enrichment. There is not a single process that always dominates the enrichment. The efficiencies of the processes vary strongly with galaxy and environmental properties.

Key words: galaxies: evolution — galaxies: clusters: general — intergalactic medium — X-rays: galaxies: clusters

1 INTRODUCTION

The gas between the galaxies in a cluster - the Intra-Cluster Medium (ICM) - does not only contain primordial elements, but also a considerable amount of heavy elements like Fe, Si, S, or O, resulting in metallicities around 0.5 in solar units and sometimes even higher values (e.g. Tamura et al. 2004). Given the large mass fraction of the ICM in a cluster (15%–20%) compared to the mass fraction of the galaxies (3%–5%) the conclusion is that there are more metals in the ICM than in all the galaxies of a cluster. This means that a lot of metals must have been transported from the galaxies into the ICM. This gas transfer affects the evolution of galaxies and of galaxy clusters. When galaxies lose their gas, the star formation rate decreases and consequently the properties of the galaxies change. Depending on the time and the efficiency of the gas removal the evolution of the galaxies is more or less affected. Therefore it is important to know when, where and how the gas transport takes place.

Various processes are discussed that can contribute to the metal enrichment - some depending only on internal properties of the galaxies, others on the environment or the combination of both. We review here several enrichment processes: ram-pressure stripping, galactic winds, AGN outflows, galaxy-galaxy interactions and the effect of an intra-cluster stellar population. Please note that this list is certainly not complete and further processes might also contribute a small fraction to the metal enrichment of the ICM. Furthermore, some processes influence each other, which makes the picture even more complicated.

2 ENRICHMENT PROCESSES

Various processes can contribute to the metal enrichment. One process that obtains more and more attention is ram-pressure stripping (Gunn & Gott 1972). As a galaxy is passing through the ICM it feels an external pressure and consequently gas is stripped off the galaxy. The process depends on the pressure of the ICM, on the relative velocity of ICM and galaxy and on the depth of the potential well of the galaxy. There is now a lot of observational evidence of stripped galaxies in clusters (e.g. Cayatte et al. 1990; Crowl et al. 2005).

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Already many years ago galactic winds were suggested as a possible gas transfer mechanism (De Young 1978). Repeated supernova explosions provide large amounts of thermal energy, which can drive an outflow from a galaxy (Heckman et al. 2003; Veilleux et al. 2005). The amount of metals transported depends on various galaxy parameters, like the total mass of the galaxy or the disc scale length, and also on the environmental conditions.

Another possible mechanism for removing material – gas and stars – from galaxies is the interaction between the galaxies (e.g. Clemens et al. 2000; Mihos et al. 2005). While the direct stripping effect might not always be very efficient in clusters due to the short interaction times, the close passage of another galaxy can trigger a star burst, which subsequently can lead to a galactic wind.

Outflows from AGNs should be considered. There are two types of AGN outflows: jets and winds-like outflows. The jets consisting of relativistic particles can entrain some of the surrounding metal-rich gas (De Young 1986). Wind-like outflows are estimated to have a high metallicity of a few times solar (Hasinger et al. 2002), high velocities of several thousands or several ten thousands of km/s (Chartas et al. 2002) and considerable mass outflow rates of several $10^9 M_\odot$ (Crenshaw et al. 2003; Veilleux et al. 2005; Nesvadba et al. 2006).

There is increasing evidence for a population of stars in the space between the galaxies in a cluster (e.g. Arnaboldi et al. 2004). Depending on the mass of the cluster the fraction of intra-cluster stars can be as high as 10%–50% with a high fraction being in more massive clusters. These stars can contribute to the enrichment via supernovae Ia, outflow from novae and AGB stars. Therefore the population of stars should also be considered for the enrichment processes in the ICM – even far away from galaxies.

3 X-RAY OBSERVATIONS OF METALS IN THE ICM

X-ray observations can distinguish the lines of different elements, e.g. elements like Si, S, O from core collapse supernovae or the elements Fe and Ni from supernovae Ia (Baumgartner et al. 2005; Ettori et al. 2002; Sanders et al. 2004; Finoguenov et al. 2002) and can hence give information on the origin of the metals in clusters. Further information comes from observations of the evolution of the metal abundance. X-ray observations can measure abundances out to about a redshift of 1. In the redshift interval from 1 to 0 they still seems to be some evolution: an increase of the metallicity of almost a factor of two seems possible (Balestra et al. 2007; Maughan et al. 2007) – but the errors are still quite large.

Also the metallicity distribution can be measured by X-ray observations. Azimuthally averaged metallicity profiles show a relatively flat distribution in “normal” clusters, while there is an increase in the central metallicity in cool core clusters (De Grandi et al. 2004; Vikhlinin et al. 2005; Pratt et al. 2006). Even more instructive are measurements of the 2D distribution of metals – metallicity maps. Although it is not easy to derive them, because in each pixel enough photons for a spectrum have to be accumulated and then fitted with a model, many groups have derived recently quite detailed metallicity maps (e.g. Sanders et al. 2004; Durret et al. 2005; O‘Sullivan et al. 2005; Sauvageot et al. 2005; Werner et al. 2006; Hayakawa et al. 2006; Finoguenov et al. 2006; Bagchi et al. 2006). These maps all show an inhomogeneous distribution of the heavy elements with several maxima, quite different patterns and a non-spherically symmetric distribution. The range of metallicities measured in a cluster from minimum to maximum metallicity comprises easily a factor of two.

4 RESULTS

In order to find out which of these processes are important for the enrichment several simulations have been performed. Some groups calculate the exact composition and evolution of the ISM by varying the IMF (see e.g. Tornatore et al. 2004; Tornatore et al. 2007), but they do not distinguish by which process the enriched gas is transported into the ICM. Specially for these transport processes a new simulation method has been developed, in which N-body/hydrodynamic simulations with mesh refinement including a semi-analytical method have been combined with separate descriptions of the various enrichment processes, which can be switched on and off individually (Schindler et al. 2005).

The results obtained with this method show an inhomogeneous distribution of the metals independent on the enrichment processes (Schindler et al. 2005; Domainko et al. 2006; Kapferer et al. 2006; Moll et al. 2007, see Fig. 1).

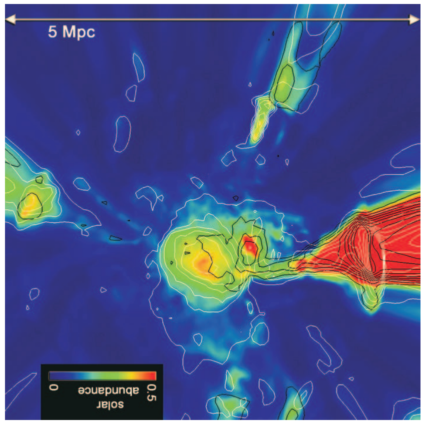

Fig. 1 Simulated metallicity map = X-ray emission weighted, projected metal distribution. The high metallicity region at the top is caused by a group of galaxies with recent starburst. Overlaid contours indicate the origin of the metals: ram-pressure stripping (white) and galactic winds (black) (adopted from Kapferer et al. 2007a).

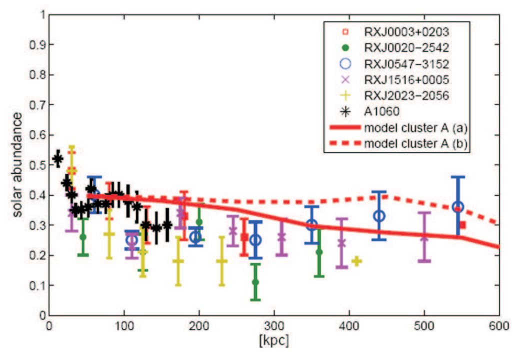

Fig. 2 Metal profiles of observed clusters and simulated clusters in which both processes - galactic winds and ram-pressure stripping - have been taken into account (from Kapferer et al. 2007a).

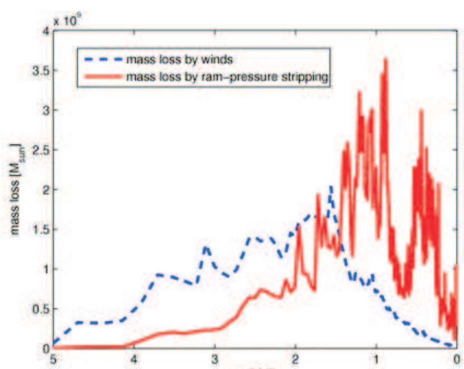

Fig. 3 Mass loss of the galaxies in a simulation taking into account mass loss due to galactic winds (dashed line) and mass loss due to ram-pressure stripping (solid line) at different redshifts (adopted from Kapferer et al. 2007a).

These results are in very good agreement with the observed metallicity maps. The gas lost by the galaxies is obviously not mixed immediately with the ICM. There are usually several maxima visible in the metallicity distribution, which are not necessarily associated with the cluster centre. The maxima are typically at places where galaxies just have lost a lot of gas to ICM of low density, mostly due to star bursts. The metallicities vary locally between 0 and 4 times solar.

A detailed comparison between the two enrichment mechanisms - winds and ram-pressure stripping - revealed that these two processes yield different metal distributions (see Fig. 1) and a different time dependence of the enrichment (Kapferer et al. 2007a). The spatial distribution of ram-pressure stripped gas is more centrally concentrated. The reason for this is that the ICM density as well as the galaxies velocities are larger in the cluster centre, so that ram-pressure stripping is very efficient there. Galactic winds, however, can be suppressed by the high pressure of the ICM in the cluster centre (Kapferer et al. 2006), so that in massive clusters galactic winds hardly contribute to the central enrichment. The resulting radial metal profiles are correspondingly relatively flat for galactic winds and steep for ram-pressure stripping. When both processes are taken into account they are in good agreement with the observed profiles (see Fig. 2).

The time scales for the enrichment are also different for the two processes (Kapferer et al. 2007a). The mass loss of galaxies due to winds is larger at high redshifts. Between redshifts 2 and 1 ram-pressure stripping becomes more important for the mass loss and it is by far more efficient at low redshift (see Fig. 3). In total the mass loss due to ram-pressure stripping is usually larger than the mass loss due to winds, in some cases up to a factor of three.

Generally it is very hard to provide numbers for the relative efficiencies of the various processes as the efficiencies depend strongly on the properties of the clusters. In a massive or in a merger cluster, for example, ram-pressure stripping is very efficient.

The simulated metallicities can be converted to artificial X-ray metallicities, metallicity profiles, metallicity maps and metallicity evolution. There is in general a good agreement between these quantities derived from simulation and observation (Kapferer et al. 2007b). The metallicity values are in the right range and the spatial distribution and the evolution are in good agreement with the observations. Also the evolution of the metallicity since $z = 1$ found in observations can be reproduced by the simulations. Of course there is a large scatter in all these quantities, because they vary very much from cluster to cluster both in simulations and observations.

Another result of the simulations is that the estimate of the iron mass in a cluster can have large errors due to the inhomogeneous metal distribution. When estimating the iron mass from observations it is assumed that the metallicity is constant in each radial bin or even in the whole cluster. But due to the starbursts often high metal concentrations are found in regions of low density, which hardly contribute to iron line in the spectrum. Therefore the iron mass is systematically underestimated – sometimes up to a factor of three.

Summarising, from the comparison of observations with simulations it seems clear that several processes are involved in the metal enrichment and none of them can be ruled out immediately as being not efficient enough. The processes can also influence each other (e.g. AGN outflows can enhance an existing galactic wind or one process can suppress another one). Obviously the interaction between galaxies and the ICM is a very complex issue. In order to know what is really going on at the transition between galaxies and ICM many more observations and simulations are needed.

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