METAL ENRICHMENT IN THE INTRA-CLUSTER MEDIUM

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Abstract. The enrichment of the Intra-Cluster Medium (ICM) with heavy elements is reviewed. There is now good observational evidence for enrichment including abundance ratios and metallicity distributions. Various processes involved in the enrichment process – ram-pressure stripping, galactic winds, galaxy-galaxy interactions, AGN outflows and intra-cluster supernovae – are described. Simulations of the ICM evolution taking into account metal enrichment are presented.

1 Introduction

The hot gas between the galaxies in a galaxy cluster – the intra-cluster medium (ICM) – does not only contain primordial elements, but also heavy elements like Fe, Si, S, or O. From X-ray observations the overall metal abundance is known to be about 1/3 - 1/2 solar (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%) a lot of metals must have been produced within the galaxies and then been transported together with part of the interstellar medium (ISM) into the ICM (Mushotzky 1999, Renzini 2004). This gas transfer affects the evolution of galaxies and of galaxy clusters, therefore it is important to know when and how the transport takes place.

2 X-ray observations of metals in the ICM

X-ray observations can also 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 and interaction in clusters.
Further information comes from observation of the evolution of the metal abundance. X-ray observation can measure abundances to about a redshift of 1. In the redshift interval from 1 to 0 they still seem to be some evolution: an increase of the metallicity of almost a factor of two seems possible (Balestra et al. 2006) – 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, Sanders & Fabian 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.

3 Enrichment processes

Various processes can contribute to the metal enrichment. We review here several enrichment processes, but certainly this list is not complete.

3.1 Ram-pressure stripping

One process that obtains more and more attention is ram-pressure stripping (Gunn & Gott 1972). There is now a lot of observational evidence of stripped galaxies. In the Virgo cluster several examples of ram-pressure affected spiral galaxies have been found by HI observations (Cayatte et al. 1990; Veilleux et al. 1999, Vollmer et al. 1999, Vollmer 2003, Kenney et al. 2004, Vollmer et al. 2004a,b; Koopmann & Kenney 2004, Crowl et al. 2005). Furthermore in Virgo elliptical galaxies stripping features have been discovered (e.g. Rangarajan et al. 1995, Lucero et al. 2005, Machacek et al. 2006a). Also in the Coma and other clusters evidence for ram-pressure stripping has been found (Bravo-Alfaro et al. 2000, 2001). It is even possible that the HI plume of the galaxy NGC4388, that extends to more than 100 kpc, is also a ram-pressure stripping feature.

As ram-pressure stripping is such a common process, there are many models in which the stripping process of galaxies was calculated (Abadi et al. 1999, Quilis et al. 2000, Tonazza & Schindler 2001, Schulz & Struck 2001, Vollmer et al. 2001, Hidding & Sofue 2002, Bekki & Couch 2002, Otmianowska-Mazur & Vollmer 2003, Acreman et al. 2003, Roediger & Hensler 2005, Roediger & Brüggen 2006, Roediger et al. 2006, Mayer et al. 2006).
3.2 Galactic winds

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 (see reviews by Heckman et al. 2003 and Veilleux et al. 2005). A correlation between starburst galaxies and wind is well established (e.g. Dahlem et al. 1998). The outflows consist of a complex multi-phase medium of cool, warm and hot gas. The morphologies of the optical emission-line gas and the X-ray emission as observed with CHANDRA have been studied and found to be quite similar (Strickland et al. 2002, Cecil et al. 2002). This fact can be used to explain the interaction between the gas in the bubbles and the ISM. The accelerated ISM can reach velocities of several hundred km/s (Heckman et al. 2000, Rupke et al. 2002).

With these winds also metals are transported into the ICM. The amount of metals depends on various galaxy parameters, like the total mass of the galaxy or the disc scale length, and on the environmental conditions: e.g. in the centre of massive clusters the pressure of the ICM can suppress the winds (Kapferer et al. 2006). Martin et al. (1999) gives an often used recipe for simulations: the winds outflow rate is a few time the star formations rate. Also Heckman (2003) finds by comparing different techniques the outflow rate of the order of the star formation rate. Other attempts to quantify the outflow rate include physical parameters like the the potential of the galaxy and cosmic rays (Breitschwerdt et al. 1991). Also hydrodynamic simulations of outflows have been performed (Tenorio-Tagle & Munoz-Tunon 1998, Strickland & Stevens 2000).

In some galaxies the winds are not only driven by repeated supernova explosions but also the AGNs are contributing to energy necessary for the wind (see Sect. 3.4). Starbursts with subsequent winds can also be caused by cluster mergers (Ferrari et al. 2003, 2005, 2006), because in such mergers the gas is compressed and shock waves and cold fronts are produced (Evrard 1991, Caldwell et al. 1993, Wang et al. 1997, Owen et al. 1999, Moss & Whittle 2000, Bekki & Couch 2003).

3.3 Galaxy-galaxy interaction

Another possible mechanism for removing material – gas and stars – from the galaxies is interaction between the galaxies (e.g. Clemens et al. 2000, Mihos et al. 2005). While the direct stripping effect is probably not very efficient in clusters due to the short interaction times, the close passage of another galaxy can trigger a star burst (Barnes & Hernquist 1992, Moore et al. 1996, Bekki 1999), which subsequently can lead to a galactic wind (Kapferer et al. 2005). But there can be a competing effect: the ISM might be stripped off immediately by ram-pressure stripping (Fujita et al. 1999, Heinz et al. 2003) and hence the star formation rate could drop. In any case ISM would be removed from the galaxies.

Simulations of interactions between active galaxies show a complex interplay between star formation and the activity of the central active galactic nuclei (Springel et al. 2005).
3.4 AGN outflows

Two types of outflows from AGNs are discussed – jets and winds-like outflows. There is a lot of observational evidence that jets from AGN interacting with the ICM – not only radio jets but also cavities in the ICM found in X-rays (e.g. Blanton et al. 2001, McNamara et al. 2001, Schindler et al. 2001, Heinz et al. 2002, Choi et al. 2004, Fabian et al. 2006), in which the pressure of the relativistic particles of the jet has pushed away the ICM. The jets consisting of relativistic particles can entrain some of the surrounding gas (De Young 1986).

As the jet-ICM interaction can have an effect both on the energetics and the metal enrichment of the ICM several groups have started to calculate this process. Many simulations for the energy transfer have been performed (Zhang 1999, Churazov et al. 2001, Nulsen et al. 2002, Krause & Camenzind 2003, Heinz 2003, Beall et al. 2004, 2006, Dalla Vecchia et al. 2004, Zanni et al. 2005, Sijacki & Springel 2006, Heinz et al. 2006) while only few have attempted to calculate the metal enrichment due to entrainment by jets (Heath et al. 2006, Moll et al. 2006).

Also for wind-like outflows there is some observational evidence. Blue-shifted absorption lines have been observed in UV and X-rays (Crenshaw et al. 2003). Also from X-ray imaging evidence for nuclear outflows have been found (Machacek et al. 2006b). There are hints for a high metallicity of a few times solar (Hamann et al. 2001, Hasinger et al. 2002), for high velocities (Chartas et al. 2002, 2003, Pounds et al. 2003a,b, Reeves et al. 2003) and for considerable mass outflow rates (Crenshaw et al. 2003, Veilleux et al. 2005).

3.5 Intra-cluster supernovae

There is more and more evidence for a population of stars between the galaxies in a cluster (Gerhard et al. 2002, 2005, Cortese 2004, Ryan-Weber et al. 2004, Adami et al. 2004). When these stars explode as supernovae (mainly type Ia) they can enrich the ICM very efficiently because there is no ISM pressure around them to confine the metals (Domainko et al. 2004; Zaritzky et al. 2004; Lin & Mohr 2004). Therefore this population of stars should also be considered for the enrichment processes in the ICM.

4 Simulations of ICM enrichment

Obviously the enrichment of the ICM is a complex process, which is the result of many different mechanisms. Moreover all these mechanism do not act separately, but there is a lot of interplay between them. Furthermore the scales involved range from the sizes of the central regions of AGN to the sizes of galaxy cluster. It is not possible to cover all these scales with a simple simulation. Therefore many groups have developed very different ways to model this complex problem. The questions that are addressed by these simulations concern the amount of metal, the distribution of the metals, the time evolution of the enrichment processes and the ratio of different elements.
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**Fig. 1.** Simulated metallicity map = X-ray emission weighted, projected metal distribution of a merger cluster at $z=0$. The distribution is quite inhomogeneous with stripes in the outer parts. The high metallicity region at the top is caused by a group of galaxies with recent starburst. Overlaid are contours which indicate the origin of the metals: ram-pressure stripping (white) and winds (black).

Some groups use a semi-analytical approach on top of N-body simulations, e.g. they do not follow the motion of the ICM but are able to follow the enrichment not only in clusters but also in the WHIM (warm-hot intergalactic medium, De Lucia et al. 2004, Nagashima et al. 2005, Bertone et al. 2005). They find that mainly the massive galaxies contribute to the enrichment and that there is a mild metal evolution since $z=1$. Other groups perform models without dynamics to estimate
Fig. 2. Comparison of the metal enrichment by ram-pressure stripping and winds in a galaxy cluster at z=0. The figure shows simulated metallicity maps with a diameter of 2.5 Mpc. Ram-pressure stripping yields a more centrally concentrated metallicity distribution.

the effect of different initial mass functions (IMF) on the ICM enrichment (Moretti et al. 2003) and the contributions of different supernova types (Pipino et al. 2002).

In a different method also the dynamics of the ICM is simulated. Some groups use an approach with N-body/SPH simulations combined with semi-analytical models that include detailed yields from type Ia and II supernovae (Valdarnini 2003, Tornatore et al. 2004, Scannapieco et al. 2005, Cora 2006, Romeo et al.
They model radial profiles of different elements, finding relatively steep profiles compared to observations. Also metallicity maps (Cora 2006), different IMFs (Tornatore et al. 2004, Romeo et al. 2006) and cooling efficiencies of galactic objects (Scannapieco et al. 2005) are investigated.

We, the “Hydro SKI team”, have chosen a different approach. In N-body/hydrodynamic simulations with mesh refinement including a semi-analytical method the various enrichment processes are calculated separately with different descriptions (Schindler et al. 2005). So far ram-pressure stripping (Domainko et al. 2006), quiescent and starburst-driven winds (Kapferer et al. 2006), galaxy interactions (Kapferer et al. 2005) and AGN outflows (Moll et al. 2006) have been taken into account – all of them can be switched on and off individually. We furthermore distinguish between ICM and ISM, so that we can model directly virtual observations of X-ray metallicity maps (see Fig. 1).

We find in general an inhomogeneous metallicity distribution in good agreement with the observed metallicity maps (see Fig. 1 and Fig. 2). Obviously the enriched material is not mixed immediately with the ICM. Usually several processes contribute to the metallicity of a cluster. The different processes cause different metallicity distributions and have different time scales. In particular we compared ram-pressure stripping and galactic winds. Ram-pressure stripping is more efficient massive clusters, while winds can be suppressed in the centres of massive clusters. Therefore the metals transferred by ram-pressure stripping yield a relatively steep profile in the centre, while the metallicity due to winds is almost flat. The sum of the metals obtained by both processes together is in good agreement with the observed metallicity slopes. Clusters with sub-cluster mergers have particularly high enrichment rate due to ram-pressure stripping. In such clusters ram-pressure stripping can contribute a factor of 3 more to the enrichment than winds. Mass loss of the galaxies due to winds is stronger at early evolutionary stages and starts to decrease between redshifts of 2 and 1. In this period ram-pressure stripping becomes stronger and exceeds the mass loss rate due to winds.

Metallicity values deduced from X-ray observations cannot be transferred easily into the amount or mass of metals: projection effects and emission weighting (depending on ICM density and temperature) can hide/enhance the metal mass (see Fig. 3). E.g. the emission weighted mean metallicity of a cluster is usually going up and down with time, although there is continuously enriched material falling into the cluster. As there is always also non-enriched material falling into the cluster and they are not mixed immediately, there can be quite large variations (≈ 50%) in the observed mean metallicity. More figure and movies can be found at http://astro.ubk.ac.at/astroneu/hydroskiteam/index.htm.

5 Conclusions

Metal enrichment of the ICM is a complex process. X-ray observations yield now a lot of information on overall metallicities, profiles, 2D maps and abundance ratios. Many different enrichment processes can contribute to the metal abundance. Often the processes are not strictly separated but influence each other. Taking
Fig. 3. Top: Ratio of mass of metal to the mass of the ICM within a spherical volume of radius 500 kpc in arbitrary units. Bottom: X-ray emission weighted metallicity as it would be observed if all the cluster emission observed within a radius of 500 kpc was used to derive a spectrum. Projection effects and emission weighting affect the observed metallicity strongly. That means a determination of the metal mass from the observed metallicity has very large errors.
all processes into account it is not difficult to reach the observed metallicities. The efficiencies of the different processes vary a lot with time and with cluster environment.

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