PROCEEDINGS OF SCIENCE

Interaction of galaxies with the intra-cluster medium and ICM metal enrichment

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Sabine Schindler[*†]
University of Innsbruck, Institute of Astrophysics, Austria
E-mail: `sabine.schindler@uibk.ac.at`

Interaction processes between the components of clusters of galaxies are efficient in removing gas from the galaxies and transporting it into the intra-cluster medium. This transport is responsible for the high metallicities found in the intra-cluster medium. So far it is not quite clear what the efficiencies of the various processes and their time dependencies are. The current status of observational evidence in terms of metallicity measurements in clusters, spatial metallicity distribution and metallicity evolution is reviewed in this article. Different types of interaction and metal enrichment processes are discussed: galactic winds, ram-pressure stripping, galaxy-galaxy interaction, jets from AGN, and an intra-cluster stellar population. Results of simulations are presented which take some of these interaction processes into account.

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[*] Speaker.
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1. Introduction

The components of clusters of galaxies – galaxies and intra-cluster medium (ICM) – interact with each other in many ways. There is more and more observational evidence that various types of interaction processes are at work, which remove interstellar medium (ISM) from the galaxies. This removed ISM intermixes with the ICM, so that the nowadays observed ICM is a mixture of both.

The deep gravitational potential wells of clusters retain the integrated products of nucleosynthesis. With the new X-ray observations metals in the intra-cluster gas can be measured in detail. As the intra-cluster gas represents most of the baryonic matter these X-ray observations are of high importance for the understanding of the evolution of clusters and their galaxies. Most of the metals must have been produced within the galaxies and later they have been transported by various interaction processes from the galaxies into the intra-cluster gas. Hence the metals are a good tracer for the interaction processes between galaxies and the intra-cluster gas.

Previous X-ray observations have shown already that the metal abundance in the intra-cluster medium is quite high, about one third in solar units (e.g. Fukazawa et al. 1998 (ASCA), Peterson et al. 2003 (XMM), De Grandi et al. 2004 (BeppoSAX)) and already many years ago there have been attempts to infer the origin of the metals (Arnaud et al. 1992). With the old X-ray satellites ROSAT, ASCA, and BeppoSAX, however, it was hard to draw conclusions on the metal distribution any more detailed than a radial metallicity profile (see e.g. De Grandi et al. 2004) and on the evolution of metals with redshift (Schindler et al. 1999).

The new generation of X-ray satellites XMM and CHANDRA brought a break through in the investigation of the metal enrichment. Their superior spatial and spectral resolution together with the high sensitivity made it possible to measure 2D distributions of metals: metallicity maps (e.g. Schmidt et al. 2002; Furusho et al. 2003; Sanders et al. 2004; Fukazawa et al. 2004; Hayakawa et al. 2004). These maps shows that, the metallicity has clearly a non-uniform distribution and a non-spherical distribution, which leads to very interesting conclusions. The maps explain why the metallicity profiles, in which all metallicities are azimuthally averaged, show a flat distribution in non-cooling cores clusters: due to the accumulation of photons from regions very far apart all variations are smeared out.

Further information could be provided by observations of metals in distant clusters. So far attempts have been made to measure metallicity evolution out to a redshift of 1.2 (Tozzi et al. 2003), but the situation is not very clear yet (Nagashima et al. 2004). Different distributions of Fe and other elements can be observed (e.g. Peterson et al. 2003; Tamura et al. 2004), which allow for conclusions on the contributions of the different types of supernovae.

Together with the metals also energy is transported into the ICM. This topic has received a lot of attention recently because it is considered a possible solution for the cooling/heating balance in cooling core clusters (see Churazov et al. 2002; Böhringer et al. 2004; Fabian 2004).

2. Metal enrichment processes

All these new results have stimulated a lot of discussion on the origin of metals and the energy transfer. Given that most metals must come from cluster galaxies, the high ICM metallicity (0.3

solar) and the small contribution of the galaxy masses to the baryonic matter in a cluster (≈ 20%) the amount of material that has to be transported from the ISM to the ICM must be considerable.

2.1 Galactic winds

Already many years ago galactic winds were suggested as a possible ISM transfer mechanism (De Young 1978). The winds are driven by supernova explosions. Since then winds were often held responsible for most of the gas transport. But recent observations and simulations indicate that other processes can contribute considerably.

2.2 Ram-pressure stripping

One process that obtains more and more attention is ram-pressure stripping (Gunn & Gott 1972). In the Virgo cluster alone at least 7 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) and in elliptical galaxies stripping features have been discovered in X-ray observations (e.g. Rangarajan et al. 1995). Also in the Coma and other clusters evidence for ram-pressure stripping has been found (Bravo-Alfaro et al. 2000, 2001).

2.3 Galaxy-galaxy interaction

Another possible mechanism to remove gas from the galaxies is interaction between the galaxies (e.g. Clemens et al. 2000). 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., in prep.). Star bursts with subsequent winds can also be caused by cluster mergers (Ferrari et al. 2003,2004), 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). But there can also 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.

2.4 Jets from AGN

Jets from AGN interact with the ICM (e.g. Schindler et al. 2001, Blanton et al. 2001, McNamara et al. 2001, Heinz et al. 2002, Choi et al. 2004). As this jet-ICM interaction can have an effect both on the energetics and the metal enrichment of the ICM several groups have started to calculate also this process (Zhang 1999, Churazov et al. 2001, Nulsen et al. 2002, Krause & Camenzind 2003, Heinz 2003, Beall et al. 2004, Della Vecchia et al. 2004).

2.5 Intra-cluster stellar population

There is more and more evidence for a population of stars between the galaxies in a cluster (Gerhard et al. 2002; Cortese 2004; Ryan-Weber et al. 2004; Adami et al. 2004). When these stars explode as supernovae they can enrich the ICM very efficiently (Domainko et al. 2004a; Zaritzsky et al. 2004; Lin & Mohr 2004), therefore this population of stars should also be considered for the enrichment processes.

3. Simulations

Obviously the enrichment of the ICM is a complex process, which is the result of many different mechanisms. Many groups have done already some time ago simulations to quantify one or more of these enrichment mechanisms: winds (David et al. 1991; Metzler & Evrard 1994, 1997) and winds compared to galaxy-galaxy interactions (Gnedin 1998; Aguirre et al. 2001). These old simulations came to very different conclusions. A problem with this kind of simulations was that they had to cover large scales as well as galaxy scales. Therefore the resolution was not very good at small scales and hence the results had large uncertainties, which were probably the reason for the discordant results.

In order to overcome the problem of the large range of scales several groups simulated in detail a single galaxy, which is in the process of being stripped (Abadi et al. 1999; Quilis et al. 2000; Toniazzo & Schindler 2001; Schulz & Struck 2001; Vollmer et al. 2001; Hidaka & Sofue 2002; Bekki & Couch 2002; Otmianowska-Mazur & Vollmer 2003; Schumacher & Hensler 2004). From these simulations of spirals and ellipticals the efficiency and time scales of the stripping process depending on galaxy properties and on ICM conditions can be inferred.

Currently, several approaches are being made to explain the overall enrichment of the ICM. De Lucia et al. (2004) and Nagashima et al. (2004) use a combination of semi-analytic techniques and N-body simulations to calculate the overall ICM metallicity, i.e. they do not predict the distribution of metals in a cluster. They find that mainly the massive galaxies contribute to the enrichment and that there is a mild metal evolution since z=1. Tornatore et al. (2004) and Valdarnini (2003) do hydrodynamic simulations with smoothed particle hydrodynamics that include detailed yields from type Ia and II supernovae, but do not distinguish between the different transport processes. They put most of their emphasis on the amount of iron produced and on profiles. Tornatore et al. find interesting results among them profiles that are significantly steeper than those observed. Springel & Hernquist (2003) use a multi-phase model and include also some enrichment processes.

The Hydro SKI Team in Innsbruck takes a complementary approach. We investigate the transport of the metals from the galaxies into the intra-cluster medium and study in detail the efficiency of the various transport processes, which are neglected by the other groups. In the first simulations, that we have performed so far, we have taken into account two different transport processes – ram-pressure stripping and galactic winds (see http://astro.uibk.ac.at/astroneu/hydroskiteam/index.htm). First preliminary results and techniques have been shown in the contributions by W. Kapferer, W. Domainko and T. Kronberger (see these proceedings) and have been published in Domainko et al. (2004b,c,d,e); Kapferer et al. (2004a,b); Mair (2004); Schindler et al. (2004).

From these simulations we can draw some preliminary qualitative conclusions for the comparison of the enrichment efficiency of ram-pressure stripping and galactic winds (see Fig. 1). We find that ram-pressure stripping is definitely important for the enrichment of the ICM, in contrast to what has been claimed frequently in the past. We also find that the distribution of metals coming from the two processes is different. Ram-pressure stripping is more efficient in the centre of the cluster. The reason is that the stripping rate is proportional to the density of the ICM and propor-

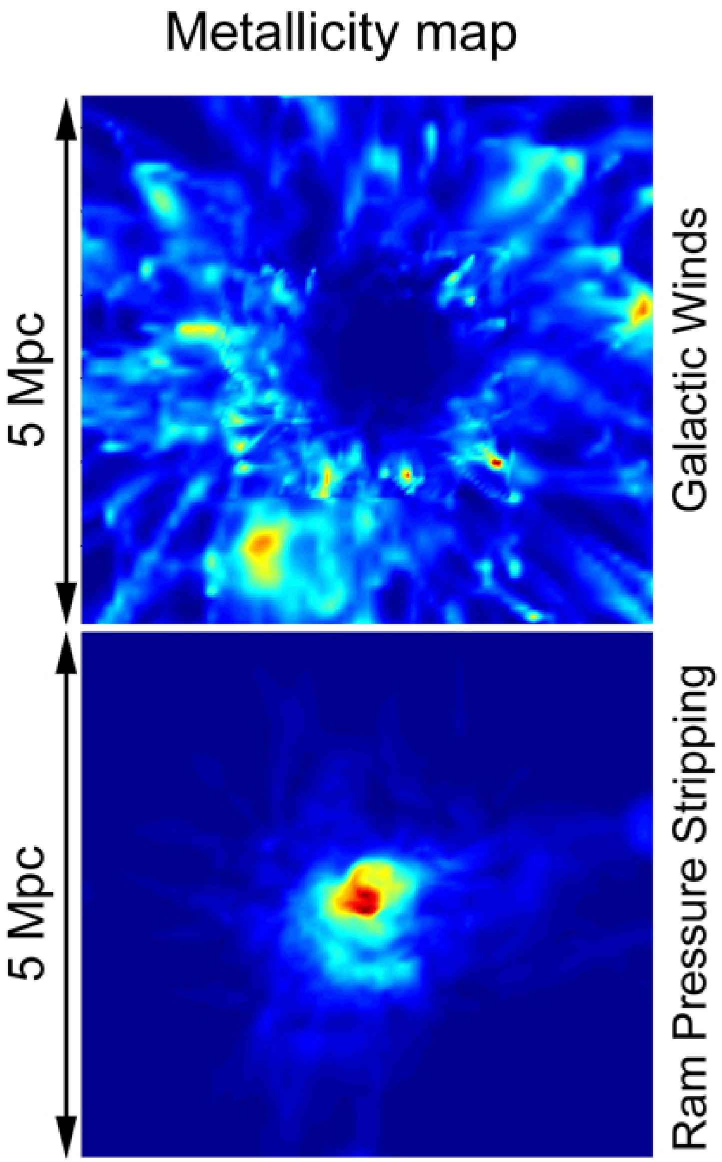

Figure 1: Metallicity distribution in a simulation of a massive, Coma-type cluster. Top: The simulation takes galactic winds into account. The metallicity shows a minimum in the cluster centre, because the ICM pressure in such a massive cluster is so strong that it suppresses winds here. Bottom: In this simulation only the effect of ram-pressure stripping is included. The metallicity distribution is concentrated towards the cluster centre, because stripping is most efficient in the centre.

tional to the square of the velocity of the galaxies. Both ICM density and galaxy velocity increase towards the cluster centre, therefore more gas is lost there. For galactic winds the metallicity maps look very different: in the cluster centre not a lot of ISM is lost due to winds. Again the explanation is clear: in the central parts the ICM pressure is higher therefore a possible galactic wind feels more pressure from outside, which might prevent it from blowing gas away. We find that the mean radius of pressure balance between ICM and galactic wind depends strongly on the dynamical state of the cluster: for a relaxed Coma-like cluster and a Galaxy-like spiral the mean radius of pressure balance is at about 0.8 Mpc, while for a merger in the same cluster the radius is at about 1.2 Mpc. Interesting is also that the different distributions are not dispersed immediately by the motion of the ICM, but they are relatively stable over some Gyrs. This inhomogeneity in the metallicity distribution is on good agreement with recent X-ray observations.

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