Intra-Cluster Medium Enrichment and the Dynamical State of Galaxy Clusters

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Abstract. The effects of cluster mergers on the metal enrichment of the intra-cluster gas in clusters of galaxies are reviewed. Mergers can influence the metal production as well as the gas ejection processes, which transport the gas from the galaxy potential wells into the intra-cluster gas. Several processes are discussed: ram-pressure stripping, galactic winds and star formation activity. Simulations on different scales ranging from galaxy size to large-scale structure are presented.

1. Introduction

X-ray spectra of the intra-cluster gas show metal lines indicating that the gas cannot be only of primordial origin, but a considerable fraction of the gas must have been processed in the cluster galaxies and subsequently been transported from the galaxies into the intra-cluster medium (ICM). The amount of metals is not negligible: the total mass of iron in the ICM is of the same order of magnitude as the iron mass in all the galaxies of a cluster (Mushotzky 1999). Information about the transport processes can be obtained for example by X-ray observations of clusters. Metal distribution and evolution depend sensitively on the transport processes involved. In some clusters the distribution of heavy elements was found to be non-uniform, but increasing towards the cluster centre (see e.g. De Grandi & Molendi 2001; De Grandi this volume). Also ratios of heavy elements deviating from solar ratios were found by XMM observations (e.g. Kaastra et al. 2001). The evolution of heavy elements was hardly measurable with previous X-ray satellites such as ROSAT and ASCA (Schindler 1999), but XMM and CHANDRA finally provide the opportunity to measure metallicities reliably out to redshifts of about $z \approx 1$.

Several processes have been suggested to explain the transport of gas from the galaxies to the cluster: galactic winds driven by supernovae (De Young 1978), ram-pressure stripping (Gunn & Gott 1972), interaction between individual galaxies and jets from active galaxies. Two of these processes, galactic winds and jets, are driven by internal processes within the galaxies. In CHANDRA observations several clusters have been found in which the pressure of the relativistic particles in the jets pushes away the ICM leaving depressions in the X-ray emission (Perseus: Fabian et al. 2000, Hydra-A: McNamara et al. 2000, RBS797: Schindler et al. 2001). The other two processes, ram-pressure stripping and galaxy-galaxy interaction, are also influenced by their surroundings,
for instance by a cluster merger. Ram-pressure stripping occurs when a galaxy is moving through the ICM approaching the cluster centre. At a certain point the pressure from the ICM is so strong that the galaxy potential is not deep enough to retain the galactic gas. The gas is stripped off starting from the outer parts of the galaxy and is lost to the ICM. Two spectacular examples where the stripping process can be observed are two galaxies in the Virgo cluster, NGC4501 and NGC4548 (Cayatte et al. 1990).

The metal production rate in the galaxies, or equivalently the star formation activity, is also influenced by external processes. A cluster merger, for example, causes a compression in the gas which could trigger a star burst.

2. Effects of Cluster Mergers

Mergers of clusters have strong effects both on the physical quantities of the cluster and on the observable quantities. The most prominent features of mergers are shock waves. The strongest shocks emerge after the collision of two clusters. The shocks propagate outwards mainly in direction of the original collision axis (Schindler & Müller 1993, see Fig. 1). Also before the actual collision bow shocks can occur.

The shocks are not only the major heating source of the inter-cluster gas and sites of particle acceleration, but they also change the density and the temperature distribution of the ICM considerably. The change in the density distribution is the main influence on the stripping rate, because the ram pressure is proportional to $\rho_{ICM} \times v_{rel}^2$, with $\rho_{ICM}$ being the density of the ICM and $v_{rel}$ being the relative velocity of the galaxy and the ICM. Mergers cause also gas motions and turbulence in the ICM. As the ram pressure depends quadratically on the relative velocity $v_{rel}$ these motions can increase the stripping rate strongly.

During and after a merger the ICM is mixed by turbulent gas motions. These motions can change the distribution of heavy elements within a galaxy cluster. Also indirect effects of mergers can influence the metallicity. Examples of such indirect effects are the increase of the magnetic field during mergers (see Fig. 2), the increased X-ray luminosity, the high number of radio galaxies, and offsets between the ICM and the dark matter/galaxy distribution.

3. Influence on the Star Formation Activity

An important question is whether cluster mergers increase the star formation rate in galaxies, i.e. the production rate of heavy elements. The star formation rate can be affected by cluster mergers in two ways.

The interstellar medium in a galaxy can be compressed during a merger, because of the higher pressure in the surrounding ICM. This compression of the galactic gas would lead to an increased star formation rate. This effect was predicted in simulations by Evrard (1991). Also in a number of observations a connection between mergers and enhanced star formation rate has been found, e.g. in the Coma cluster (Caldwell et al. 1993), in A2111 (Wang et al. 1997), in A2125 (Owen et al. 1999), and in several other clusters (Moss & Whittle 2000).
Figure 1. Temperature contours of the ICM after a major merger. The original collision axis goes from the upper left corner to the lower right corner. Two shocks, visible as steep gradients in the temperature, are propagating outwards along this axis (from Schindler & Müller 1993).

In contrast to these results Fujita et al. (1999) found a decrease of the star formation activity due to a merger. In simulations they see that the interstellar medium in the galaxies is stripped off due to the increased ram pressure during the merger, so that the galaxies lose most of their gas. Therefore less gas is left to fuel the star formation process and hence the star formation activity decreases. Fujita et al. (1999) found an increase of post-starburst galaxies at the moment of the subcluster collision, which indicates that a rapid drop in star formation must have occurred.

4. Simulations of Gas Transport Processes

Several groups used numerical simulations to investigate the effect of different gas transport processes. In these simulations the dynamics of the clusters is usually followed by a combination of N-body and hydrodynamic calculations to account for the different cluster components: the collisionless components, dark matter and galaxies, which are best simulated by N-body simulations, and the ICM, which can be simulated by hydrodynamic methods.
Figure 2. Area exceeding a certain threshold of Faraday rotation measure versus redshift $z$ as found in magneto-hydrodynamic simulations. Different shades of grey correspond to different thresholds: 5 rad/m$^2$ (black), 20 rad/m$^2$ (dark grey) and 50 rad/m$^2$ (light grey). The area is normalized to the area emitting 95% of the cluster X-ray luminosity. During the core passages of two subclusters (at $z \approx 0.5$ and $z \approx 0.2$) and the subsequent rebounces (at $z \approx 0.3$ and at $z \approx 0.0$ and an additional one at $z \approx 0.7$ from an older core passage) an increase in the rotation measure, i.e. in the magnetic field, is visible. Different projection directions are shown as different line types (from Dolag et al., in prep.).
Figure 3. Gas density (grey scale) and pressure (contours) of a galaxy moving downwards towards the cluster centre. The arrows show the Mach vectors (white when $M > 1$, black otherwise). The gas of the galaxy is stripped due to ram pressure (from Toniazzo & Schindler 2001).
4.1. Simulations on Cosmological Scales

Cosmological simulations accounting for the effects of galactic winds were performed e.g. by Cen & Ostriker (1999). They found that the average metallicity increases from 0.01 solar at z=3 to 0.2 solar at present. The metallicity distribution in their models is not constant but denser regions have generally higher metal abundances. Gnedin (1998) took into account not only galactic winds but also galaxy-galaxy interactions and concluded that most metals are ejected by galaxy mergers. In contrast to this result Aguirre et al. (2001) found that galaxy-galaxy interactions and ram-pressure stripping are of minor importance while galactic winds dominate the metal enrichment of the ICM. A problem with this kind of simulations is that they must cover a huge range of scales - cosmological scales down to galaxy scales. Therefore the resolution is not very good at small scales and hence the results have large uncertainties. This is probably the reason for the discordant results.

4.2. Simulations with Galactic Winds

The effects of supernova driven winds were also investigated with models on cluster scales. David et al. (1991) calculated the first models finding that the results depend sensitively in the input parameters: the stellar initial mass function, the adopted supernova rate and the primordial fraction of intra-cluster gas. In the first 3D models calculating the full gas dynamics and the effects of galactic winds on cluster scales Metzler & Evrard (1994, 1997) showed that winds can account for the observed metal abundances. Very strong metallicity gradients were found (almost a factor of ten between cluster centre and virial radius) which are not in agreement with observations. The authors found that these metallicity gradients are hardly affected by cluster mergers. From simulations on galaxy scales, however, Murakami & Babul (1999) concluded that galactic winds are not very efficient for the metal enrichment in clusters of galaxies.

4.3. Ram-pressure Stripping on Galaxy Scales

Another process which is important for the metal enrichment is ram-pressure stripping: as a galaxy approaches the cluster centre it experiences an increasingly higher pressure from the ICM and at some point the galaxy potential is not strong enough to retain the galactic gas. The gas is stripped off starting from the outer regions of the galaxies and the metals are released into the ICM.

Simulations of ram-pressure stripping are relatively difficult because not only must the conditions of the gas inside the galaxy and the potential of the galaxy be taken into account, but also the conditions of the surrounding medium. In several early models the stripping process was calculated (Takeda et al. 1984, Gaetz et al. 1987, Portnoy et al. 1993, Balsara et al. 1994). Recently, high resolution, 3D simulations were carried out to study the stripping process in different types of galaxies. Abadi et al. (1999) and Quilis et al. (2000) performed simulations of spiral galaxies. They found that the interstellar medium can be stripped off if it is not homogeneous. For dwarf galaxies Mori & Burkert (2000) found in their simulations (2D) that the gas can be easily stripped off when these galaxies move through the intra-cluster medium. Simulations of elliptical galaxies (Fig. 3; Toniazzo & Schindler 2001) showed that also this type of galaxies are affected by ram-pressure stripping and that the galaxies can even
Figure 4. Evolution of the gas mass within the galaxy for different galaxy orbits in a cluster. Four different models are displayed which show very different behaviour of the gas mass. As the galaxy approaches the cluster centre the gas is stripped off resulting in very low galactic gas masses. In the subsequent apocentric part of the orbit the galaxy can accumulate gas from the surroundings and also from internal processes. Hence the galactic gas mass increases. Therefore a quasiperiodic behaviour can be observed in some models (from Tonazzo & Schindler 2001).
accumulate some gas when they approach the apocentres of their orbits (see Fig. 4). Also the X-ray morphologies of simulated and observed galaxies in the process of stripping are compared.

All these simulations showed that ram pressure stripping can be an important metal enrichment process for the ICM. Merging activity increases the effect even more because the ram pressure is proportional to $\rho_{ICM} \times v_{rel}^2$ with $v_{rel}$ being the relative velocity of intra-cluster gas and galaxies. During mergers, not only is the ICM density $\rho_{ICM}$ increased but also the relative velocities are higher than in a relaxed cluster. Therefore a large influence of merging processes on the stripping rate is expected. In order to verify and quantify this we are currently performing new comprehensive models on cluster scale which include the stripping process in parametrised form (see Fig. 5). Results will be presented soon.

5. Summary and Conclusions

Cluster mergers have important effects on the metal enrichment process in clusters of galaxies. Both the metal production and the gas ejection processes are influenced, but so far it is not clear to what extent. It is still controversial whether the star formation rate is increased or decreased after a merger. It is also controversial which of the gas transport processes dominate at the different stages of cluster evolution, how much galactic gas each of the processes can contribute to the metal enrichment of the ICM and how this contribution is changed by mergers. Furthermore, it is unclear how much the metal distribution in the ICM is changed by mergers of subclusters. Detailed simulations, including all transport processes and all cluster components/physics, together with observations of the new X-ray satellites XMM and CHANDRA, will give final answers soon.

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Figure 5. Evolution of the galactic gas mass of an elliptical galaxy in parametrised form as the galaxy orbits in a cluster (from Faltenbacher et al., in prep).
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