Metal enrichment processes

S. Schindler · **A. Diaferio**

Abstract There are many processes that can transport gas from the galaxies to their environment and enrich the environment in this way with metals. These metal enrichment processes have a large influence on 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. We review their observational evidence, corresponding simulations, their efficiencies, and their time scales as far as they are known to date. It seems that all processes can contribute to the enrichment. There is not a single process that always dominates the enrichment, because the efficiencies of the processes vary strongly with galaxy and environmental properties.

Keywords galaxies: clusters: general, ISM: jets and outflows, galaxies: ISM, galaxies: interaction

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 (see Werner et al. 2008 - Chapter 16, this volume) resulting in metallicities around 0.5 in Solar units and sometimes even higher values. A large fraction ($\approx 15 - 20$ %) of the total mass of a cluster is in the ICM, whereas the galaxies contribute a substantially smaller fraction ($3 - 5$ %), and the rest is dark matter. It follows that there is more mass in metals in the ICM than in all the galaxies of a

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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 depend 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.

For several of the processes not only observational evidence exists, but also numerical simulations have been performed. We review here both aspects.

2 Ram-pressure stripping

A galaxy passing through the ICM feels an external pressure. This pressure depends on the ICM density ρ_{ICM} and the relative velocity v_{rel} of the galaxy and the ICM. Gunn & Gott (1972) suggested this process already many years ago. They also gave a frequently used prescription for the radius r beyond which the gas of a galaxy is stripped, depending on the ram pressure and the galactic gravitational restoring force. The implicit condition on r reads

$$p_{\mathrm{ram}} = \rho_{\mathrm{ICM}} v_{\mathrm{rel}}^2 > 2\pi G \sigma_{\mathrm{star}}(r) \sigma_{\mathrm{gas}}(r) \tag{1}$$

with p_{ram} being the ram pressure, G the gravitational constant, σ_{star} the stellar surface density, σ_{gas} the surface mass density of the galactic gas.

2.1 Observations

Nowadays the process of ram-pressure stripping receives more and more attention. There is now much observational evidence of stripped galaxies. In the Virgo cluster several examples of spiral galaxies affected by ram-pressure stripping have been found by H I 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, see Fig. 1). 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 Coma and other clusters and groups evidence for ram-pressure stripping has been found (Bravo-Alfaro et al. 2000; Bravo-Alfaro et al. 2001; Kemp et al. 2005; Rasmussen et al. 2006; Levy et al. 2007). Deficiency of H I has been reported as evidence for ram-pressure stripping (Vollmer & Huchtmeier 2007). It is even possible that the H I plume of the galaxy NGC 4388, that extends to more than 100 kpc, is a ram-pressure stripping feature (Oosterloo & Van Gorkom 2005). In the galaxy NGC 7619 stripping features have been found showing a high metallicity in the gas tail behind the galaxy (Kim et al. 2007). The galaxy ESO 137-001 in the cluster Abell 3627 shows a
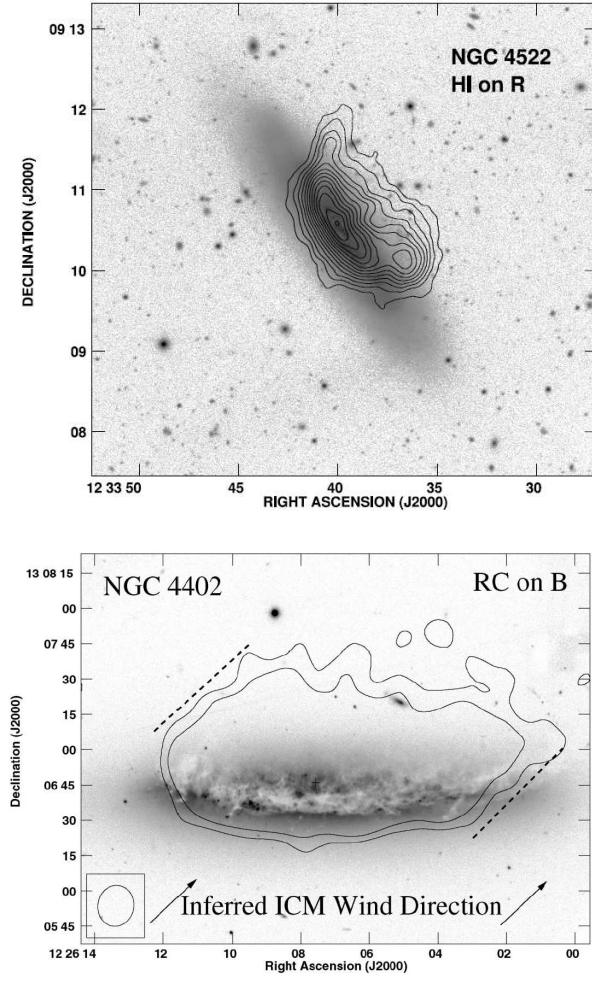
Fig. 1 Two examples of galaxies affected by ram-pressure stripping in the Virgo cluster. Top: H I gas (contours) and stellar light (grey scale, R-band) of NGC 4522. While the stellar distribution looks undisturbed the gas is bent back due to ram-pressure stripping (1.4 GHz radio continuum contours on B-band, from Kenney et al. 2004). Bottom: Similar features in NGC 4402 (from Crowl et al. 2005).

long tail with several star formation regions suggesting that ram-pressure triggers star formation not only within the galaxy but also in the stripped material (Sun et al. 2007). Recently ram-pressure features have also been found in distant clusters (Cortese et al. 2007).

For a review on ram-pressure stripping and H I deficiency see Van Gorkom (2003).

2.2 Simulations

As ram-pressure stripping is such a common process, there are many simulations in which the stripping process of galaxies was calculated for different types of galaxies: spirals, ellipticals and dwarfs (Abadi et al. 1999; Quilis et al. 2000; Mori & Burkert 2000; Toniazzo & Schindler 2001; Schulz & Struck 2001; Vollmer et al. 2001; Hidaka & Sofue 2002; Bekki & Couch 2003; Otmianowska-Mazur & Vollmer 2003; Acreman et al. 2003; Marcolini et al. 2003; Roediger & Hensler 2005; Roediger & Brüggen 2006; Roediger et al. 2006; Mayer et al. 2006; Vollmer et al. 2006, see Fig. 2). The simulations confirm that the process is acting in the expected way. Starting from the outer parts of the galaxy gas is stripped off. Part of this gas is not bound to the galaxies anymore and left in a wide (fragmenting) tail behind the galaxy. Recently even the increase of star formation in and behind the galaxy caused by ram-pressure stripping has been found in simulations (Kronberger et al. 2008a; Kapferer et al. 2008). Brüggen et al. (2008) found that more than half of the cluster galaxies have experienced ram-pressure stripping and hence a considerable fraction of galaxies in a cluster at the present epoch has suffered a substantial gas loss.

An analytical model has been developed to describe ram-pressure stripping for galaxies of different morphologies in different environments (Hester 2006). It describes the stripping of a satellite galaxy's outer H I disk and hot galactic halo.

It was tested with simulations whether the simple, widely used criterion by Gunn & Gott (1972) is a good estimate for the mass loss. Generally it is found that the criterion is a good estimate for the mass loss (Roediger & Brüggen 2007b; Kronberger et al. 2008a) when simulations and analytic estimates are compared for the same conditions (see Jachym et al. 2007 for a comparison with different conditions) - a quite surprising result given the simple assumptions of the criterion, that do not even take into account dark matter.

3 Galactic winds

Already many years ago galactic winds were suggested as a possible gas transfer mechanism (De Young 1978). Many supernova explosions provide large amounts of thermal energy, which can drive an outflow from a galaxy (see reviews by Heckman 2003 and Veilleux et al. 2005). A correlation between starburst galaxies and wind is well established through the finding of hot gas around starburst galaxies (e.g. Dahlem et al. 1998).

Spectacular examples of such winds are seen in the galaxies M 82 (Lynds & Sandage 1963) and NGC 253 (Demoulin & Burbidge 1970).

The outflows consist of a complex multi-phase medium of cool, warm and hot gas (see e.g. the *Chandra* observation of NGC 4631, Wang et al. 2001, Fig. 3). The morphologies of the optical emission-line gas and the X-ray emission as observed with *Chandra* have been found to be quite similar (Strickland et al. 2002; Cecil et al. 2002). Such correlations can be used to understand the interaction between the gas in the bubbles and the interstellar medium (ISM). It was found that the accelerated ISM can reach high velocities of several hundred $\mathrm{km\,s^{-1}}$ (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
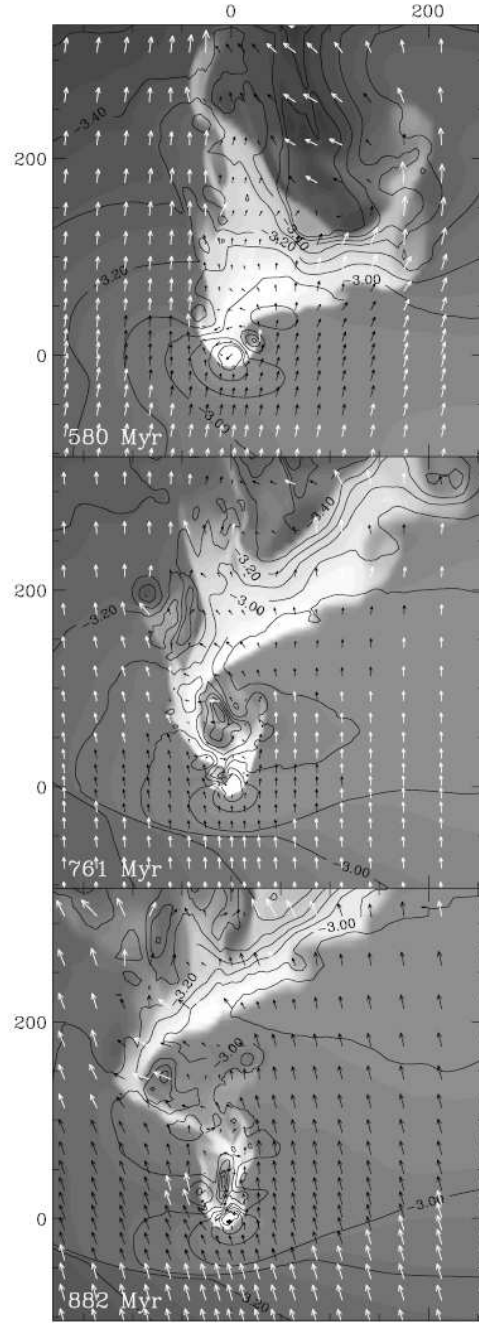
Fig. 2 Simulation of a galaxy in the process of ram-pressure stripping with gas density (grey scale, ranging from 4×10^{-29} to 1×10^{-27} g cm^{-3}), pressure (black contours, logarithmically spaced from $\log(p) = -3.6$ to $\log(p) = -2.6$ in units of 10^{-24} keV cm^{-3}) and velocity vectors (white when Mach number > 1, and black otherwise) at three different times. A cut through a 3D simulations is shown with coordinates in kpc. Due to the ram pressure of the ICM the galaxy loses more and more of its gas (from Toniazzo & Schindler 2001).
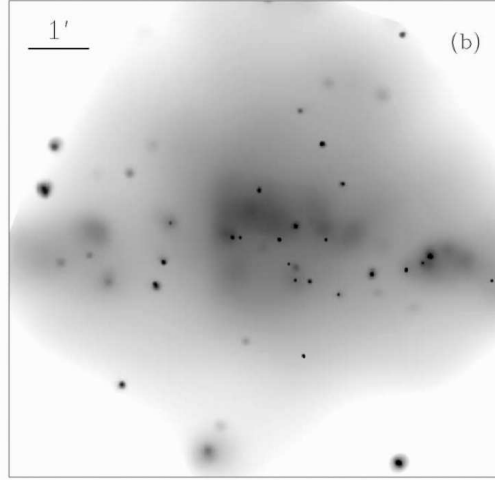
Fig. 3 *Chandra* observation of the edge-on spiral galaxy NGC 4631. It shows the presence of a giant diffuse X-ray emitting corona. The corona has a temperature of $(2-7) \times 10^6$ K and extends as far as 8 kpc away from the galactic plane (from Wang et al. 2001).

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). This suppression typically takes place for ICM pressures above $(0.7-1) \times 10^{12}$ dyne cm^{-2}.

Martin (1999) gives an often used recipe for simulations: the mass outflow rate $\dot{M}$ is proportional to the star formation rate SFR:

$$\dot{M} = \epsilon \, \mathrm{SFR} \tag{2}$$

with ϵ being typically in the range of $1-3$. By comparing different techniques Heckman (2003) also finds that the outflow rate is of the order of the star formation rate. The SFR can be estimated from observations, e.g. from far-infrared luminosities L_{FIR}

$$\frac{\mathrm{SFR}}{1\,\mathrm{M_\odot yr^{-1}}} = \frac{L_{\mathrm{FIR}}}{5.8 \times 10^9 \mathrm{L_\odot}} \tag{3}$$

(Kennicutt 1998). Another way to estimate the SFR is to use the tight relation between the SFR and the surface density of the gas σ_{gas}

$$\Sigma_{\mathrm{SFR}} \propto \sigma_{\mathrm{gas}}^N \tag{4}$$

(Schmidt 1959) with Σ_{SFR} being the surface density of the SFR and the index N having measured values between 1 and 2. Only at densities below a critical threshold value the SFR is almost completely suppressed (Kennicutt 1989). Alternatively the dynamical time t_* can be included

$$\Sigma_{\mathrm{SFR}} \propto \frac{\Sigma_{\mathrm{gas}}}{t_*} \tag{5}$$

with the dynamical time t_* being the local orbital timescale of the disk (Kennicutt 1998). For hydrodynamic simulations this has been extended to include the fraction of stars lost by supernova explosions by Springel & Hernquist (2003)

$$\frac{\mathrm{d}\rho_*}{\mathrm{d}t} = (1 - \beta)\frac{\mathrm{d}\rho_\mathrm{c}}{\mathrm{d}t} \qquad (6)$$

with ρ_* being the density of stars, ρ_c being the cold gas density in the disk and β being the fraction of stars lost by supernova explosions. For a typical initial mass function and a mass threshold of 8 $M_\odot$ for the supernovae a $\beta = 0.1$ is used. These are of course only statistical estimates.

Other attempts to quantify the outflow rate take into account physical parameters like those describing the galaxy's gravitational potential and the effect of cosmic rays (Breitschwerdt et al. 1991). Using the Bernoulli equation, Kronberger et al. (2008b) recently derived an analytic approximation for the mass loss due to thermally driven galactic winds. The mass loss per unit area at a given position of the galactic disc reads

$$\dot{M} = \rho_0 u_0 = \rho_0 \sqrt{v_\mathrm{esc}^2 + 2\Phi_0 - \frac{5}{\gamma}c_0^2}, \qquad (7)$$

with ρ_0 being the gas mass density, u_0 the bulk velocity of the gas, Φ_0 the gravitational potential, c_0 the sound speed (all four quantities at the given position), v_esc the escape velocity, and γ the adiabatic index of the thermal plasma. Hydrodynamic simulations of outflows have also been performed (Tenorio-Tagle & Munoz-Tunon 1998; Strickland & Stevens 2000).

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, which trigger star formation, are produced (Evrard 1991; Caldwell et al. 1993; Wang et al. 1997; Owen et al. 1999; Moss & Whittle 2000; Bekki & Couch 2003).

4 Galaxy-galaxy interaction

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, see Figs. 4, 5 and 6). While the direct stripping effect is mostly not very efficient in clusters due to the short interaction times, the close passage of another galaxy (sometimes called galaxy harassment) 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 (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 galaxies containing an AGN show a complex interplay between star formation and the activity of the AGN itself (Springel et al. 2005).

In order to estimate how likely such interaction events are the number of encounters and mergers needs to be assessed. The number of close encounters that a galaxy experiences within $t_\mathrm{H} = 10^{10}$ years was estimated by Gnedin (2003) in the following way. He assumed a galaxy of size $R_\mathrm{g} = 10$ kpc, a virialised cluster with a one-dimensional velocity dispersion of $\sigma_\mathrm{cl} = 1000$ km s^{-1}, a virial radius of $R_\mathrm{cl} = 1$ Mpc and $N_\mathrm{g} = 1000$
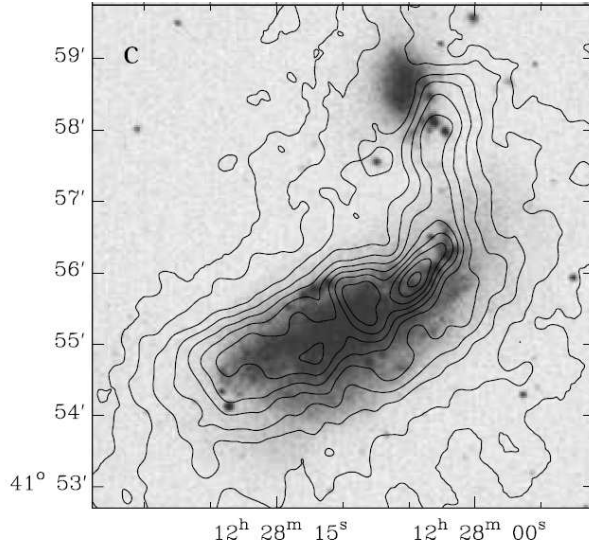
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Fig. 4 Image of the interacting galaxies NGC 4490 / NGC 4485 in H I (contours) and optical R band (grey scale). Some of the gas is lost due to the interaction of the galaxies (from Clemens et al. 2000).
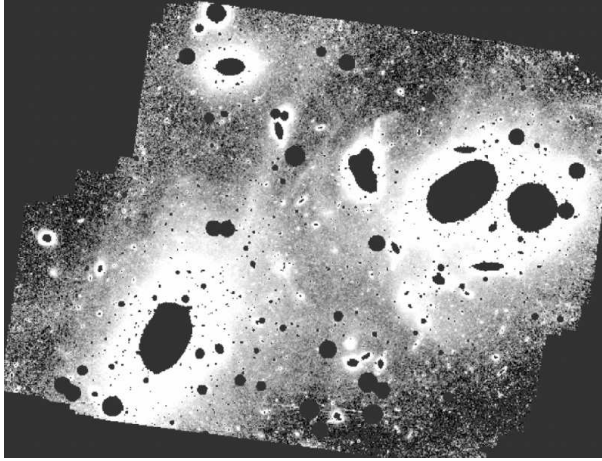

Fig. 5 Very deep observation of the core of the Virgo cluster. Diffuse light is visible between the galaxies which results from stars that have been expelled from the galaxies due to interactions between them (from Mihos et al. 2005).

galaxies uniformly distributed within this radius. With a relative velocity of $\sqrt{2}\sigma_{\rm cl}$ and neglecting the gravitational focussing, he finds

$$N_{\rm enc} \approx \frac{N_{\rm g}}{(4\pi/3)R_{\rm cl}^3}\pi R_{\rm g}^2\sqrt{2}\sigma_{\rm cl}t_{\rm H} \approx 1, \tag{8}$$
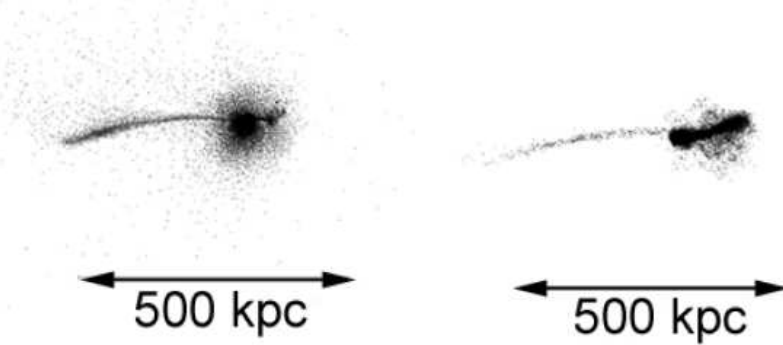
Fig. 6 Simulation of the interaction between two galaxies: distribution of gas (left) and stars (right). Due to the interaction gas and stars can be expelled out to distances of hundreds of kpc (from Kapferer et al. 2005).

i.e. a galaxy is expected to encounter one other galaxy over the course of its evolution. Even though the assumption is very simplifying one sees that an encounter is a relatively frequent event in a cluster. In contrast to this, Gnedin (2003) estimated for the probability to merge with another galaxy

$$P_{\mathrm{mer}} \approx N_{\mathrm{enc}} \left(\frac{\sigma_{\mathrm{g}}}{\sigma_{\mathrm{cl}}} \right)^4 \approx 10^{-3} \tag{9}$$

with a galactic velocity dispersion $\sigma_{\mathrm{g}} = 200$ km s^{-1}. Hence an actual merger is an unlikely event.

Tidal interactions and merging between galaxies are highly non-linear phenomena that can be partly handled analytically (e.g., Binney & Tremaine 1987, chapter 7). Numerical simulations, however, are required for accurate estimates of mass loss rates and the morphological modification of galaxies.

5 AGN outflows

We discuss two types of outflows from AGN: jets and winds-like outflows. There is much observational evidence for AGN jets 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; McNamara & Nulsen 2007), 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 metal-rich gas (De Young 1986).

As the jet-ICM interaction can have an effect on both the energetics and the metal enrichment of the ICM, several groups have calculated this process. Many simulations for the energy transfer have been performed (Zhang et al. 1999; Churazov et al. 2001; Brüggen et al. 2002; 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 the entrainment by jets (Heath et al. 2007; Moll et al. 2007). These simulations found that jets can both heat and enrich the ICM considerably. Another type of simulations calculated the metallicity distribution due to bubble-induced motions coming from a single AGN in the cluster centre (Roediger et al. 2007a). It was found that in this case the metallicity distribution is very elongated along the direction of the motion of the bubbles.

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 has 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 of several thousands or several ten thousands of $\mathrm{km\,s}^{-1}$ (Chartas et al. 2002, 2003; Pounds et al. 2003a,b; Reeves et al. 2003; O'Brian et al. 2005; Dasgupta et al. 2005; Gabel et al. 2006) and for considerable mass outflow rates (Crenshaw et al. 2003; Veilleux et al. 2005). The outflows can be quite strong, e.g. several 10^9 $\mathrm{M}_\odot$ with kinetic energies around 10^{60} erg expelled over the AGN live time of 10^7 years as estimated from spectroscopic studies (Nesvadba et al. 2006).

In some galaxies the winds are not only driven by repeated supernova explosions but also the AGN are contributing to the energy necessary for the wind (see Sect. 3).

6 Intra-cluster stellar population

There is increasing evidence for a population of stars in the space between the galaxies in a cluster (Bernstein et al. 1995; Gonzalez et al. 2002, 2005; Gerhard et al. 2002, 2005; Gal-Yam et al. 2003; Arnaboldi et al. 2004; Cortese et al. 2004; Feldmeier et al. 2004; Ryan-Weber et al. 2004; Adami et al. 2005; Zibetti et al. 2005; Krick & Bernstein 2007). Depending on the mass of the cluster the fraction of intra-cluster stars (= ratio of number of stars between galaxies to total number of stars) can be as high as $10 - 50$ % with the higher fraction being in more massive clusters. This stellar population can originate from stripping of stars from galaxies due to tidal interaction (Cypriano et al. 2006), can be expelled during mergers and the formation of massive galaxies (Murante et al. 2007; Kapferer et al. 2005, Fig. 6) or can have multiple origins (Williams et al. 2007). Simulations show that intra-cluster stars should be ubiquitous in galaxy clusters (Willman et al. 2004) and their numbers should generally increase with time (Rudick et al. 2006). A link between the growth of the brightest cluster galaxy and the intra-cluster light was reported by Zibetti et al. (2005).

When these stars explode as supernovae (mainly type Ia, as it takes a while for the stars to travel away from the galaxies) they can enrich the ICM very efficiently because there is no ISM pressure around them to confine the metals (Domainko et al. 2004; Zaritzsky et al. 2004; Lin & Mohr 2004; Dado et al. 2007).

Considerably more frequent than supernova Ia explosions are their progenitors - the recurrent novae. With about 10^{-4} $\mathrm{M}_\odot$ outflow per nova event and typically supersolar abundances (up to ten times Solar, Gehrz et al. 1998), novae could also contribute to the metal enrichment of the ICM if they have been expelled previously from the galaxies.

A fraction of the AGB stars are also expected to be between the galaxies. These stars have a considerable mass loss with metallicities of about Solar abundances with

slightly enhanced abundances of CNO elements (Wheeler et al. 1989; Zijlstra 2006; Van den Hoek & Groenewegen 1997; Busso et al. 2001; Nordström 2003). As the ratio of planetary nebulae (PNe) to AGB stars is well studied in statistical studies of PNe in the ICM (Feldmeier et al. 1998; Theuns & Warren 1997; Arnaboldi et al. 2003) this ratio may be used to estimate the number of AGB stars.

In conclusion the population of stars should also be considered for the enrichment processes in the ICM – even far away from galaxies.

7 Which of these processes are important for the ICM enrichment?

Several groups have addressed this question already many years ago. David et al. (1991) proposed the first models taking into account the effects of galactic winds on the ICM enrichment. They found that the results depend sensitively on their input parameters: the initial mass function, the adopted supernova rate and the primordial mass fraction of the ICM.

The first 3D simulations calculating the full gas dynamics and the effects of winds on cluster scales were performed by Metzler & Evrard (1994, 1997). They concluded that winds can account for the observed metal abundances in the ICM, but they found strong metallicity gradients (almost a factor of ten between cluster centre and virial radius) which are not in agreement with observations. Gnedin (1998) took into account not only galactic winds, but also galaxy-galaxy interactions and concluded that most of the 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.

That these early results disagree so much is probably due to the large range of scales that is involved. On the one hand the whole cluster with its infall region has to be simulated, on the other hand processes within galaxies or even within the active core of a galaxy are important. It is not possible to calculate all of this accurately in one type of simulation and therefore new methods have been developed.

Recently several simulations for the enrichment have been performed. They calculate the exact composition and evolution of the ISM by varying the initial mass function and the yields of supernova explosions (see Borgani et al. 2008 - Chapter 18, this volume), but it is not distinguished by which process the enriched gas is transported into the ICM. Specially for the 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 of the enrichment processes (Schindler et al. 2005; Domainko et al. 2006; Kapferer et al. 2006; Moll et al. 2007, see Fig. 7). These results are in very good agreement with the observed metallicity maps (see Werner et al. 2008 - Chapter 16, this volume). 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.
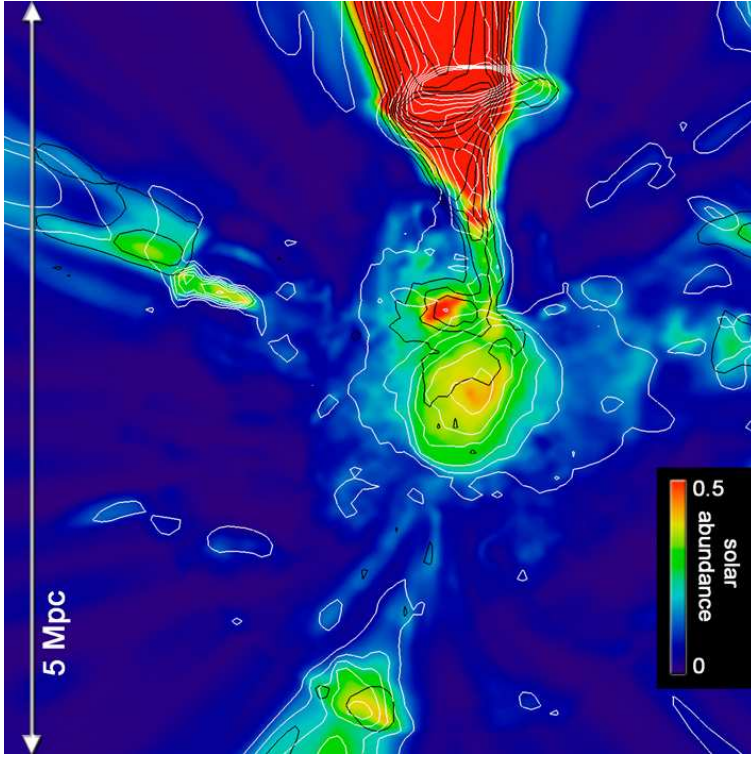
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Fig. 7 Simulated metallicity map, i.e. an X-ray emission weighted, projected metal distribution. The high metallicity region at the top is caused by a group of galaxies with recent starburst. Overlaid contours indicate the origin of the metals: ram-pressure stripping (white) and galactic winds (black) (adopted from Kapferer et al. 2007a).

A detailed comparison between the two enrichment mechanisms - winds and ram-pressure stripping - revealed that these two processes yield different metal distributions (see Fig. 7) and a different time dependence of the enrichment (Kapferer et al. 2007a; Rasia et al. 2007). The 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 centre (Kapferer et al. 2006), so that in massive clusters galactic winds do 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 also Borgani et al. 2008 - Chapter 18, this volume).

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. 8). The reason is that on the one hand galactic winds become weaker because the star formation rate decreases and on the other hand ram-pressure stripping becomes stronger because clusters with ICM have
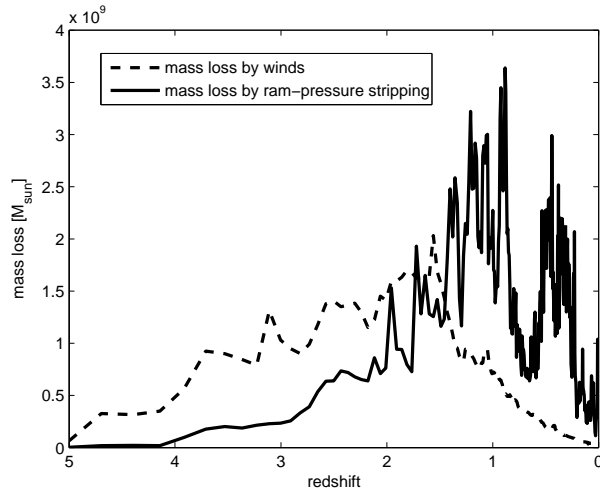
Fig. 8 Mass loss of the galaxies in a simulation taking into account mass loss due to galactic winds (dashed line) and mass loss due to ram-pressure stripping (solid line) at different redshifts (adopted from Kapferer et al. 2007a).

formed/are forming, which is interacting with the galaxies. 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 (Balestra et al. 2007; Maughan et al. 2008) 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.

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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