Simulations of Metal Enrichment in Galaxy Clusters by AGN Outflows

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Abstract
Aims. We assess the importance of AGN outflows with respect to the metal enrichment of the intracluster medium (ICM) in galaxy clusters.

Methods. We use combined N-body and hydrodynamic simulations, along with a semi-numerical galaxy formation and evolution model. Using assumptions based on observations, we attribute outflows of metal-rich gas initiated by AGN activity to a certain fraction of our model galaxies. The gas is added to the model ICM, where the evolution of the metallicity distribution is calculated by the hydrodynamic simulations. For the parameters describing the AGN content of clusters and their outflow properties, we use the observationally most favorable values.

Results. We find that AGNs have the potential to contribute significantly to the metal content of the ICM or even explain the complete abundance, which is typically $\sim 0.5Z_\odot$ in core regions. Furthermore, the metals end up being inhomogeneously distributed, in accordance with observations.

Key words. Galaxies: clusters: general – Galaxies: active – X-rays: galaxies: clusters – (Galaxies:) quasars: absorption lines – Galaxies: jets

1. Introduction
1.1. The ICM and Its Composition

The main baryonic component of galaxy clusters is the intracluster medium (ICM), a hot ($10^7-8$ K), X-ray emitting plasma. Observations made with modern X-ray observatories like Chandra (e.g. Vikhlinin et al. 2005) or XMM Newton (e.g. Tamura et al. 2004) have revealed that the chemical composition of the ICM is clearly non-primordial, with metal abundances of the order of $\sim 0.5Z_\odot$. Furthermore, metallicity maps are available for the core regions of some very bright clusters (e.g. Sanders et al. 2004; Hayakawa et al. 2004; Durret et al. 2005). Apart from confirming the occurrence of high abundances, these also reveal that the metals are distributed inhomogeneously.

Since heavy elements can only be produced by means of stellar or explosive nucleosynthesis, it is obvious that they originate mainly from cluster member galaxies. This demands for transfer processes which remove the metals from the galaxies. Among the first suggested transfer processes were ram-pressure stripping of interstellar gas (Gunn & Gott 1972) and galactic winds (De Young 1978).

Various groups have performed simulations on metal enrichment in clusters. De Lucia et al. (2004) used a combination of N-body simulations and semi-analytic techniques to follow the formation, evolution and chemical enrichment of galaxies, including flows of gas and metals into and out of galaxies. They find that most of the metals currently in the ICM have been ejected at $z > 1$ and that massive galaxies are the most important contributors to the ICM metallicity. Nagashima et al. (2005) took a similar approach with similar results. However, both groups do not predict the distribution of the metals in a cluster. Tornatore et al. (2004) combined N-body and SPH (smoothed particle hydrodynamics) simulations to create metallicity profiles of clusters, with a model that includes star formation as well as supernovae to produce heavy elements, but did not distinguish between different metal transport processes.

Our group distinguishes not only between different metal transfer processes, but also between the ICM and gas that belongs to galaxies. The enrichment efficiency of ram-pressure stripping, galactic winds and merger-driven starbursts have been studied by Domainko et al. (2006), Kapferer et al. (2006) and Schindler et al. (2005). Both processes were found to be able to significantly enrich the ICM, but they are not sufficient enough to explain the complete abundance. Galaxy-galaxy interactions and intracluster supernovae (Kapferer et al. 2005)
Domainko et al. (2004) have also been found to be possible contributors to the metal content of the ICM.

In this paper, we demonstrate that AGNs can also contribute significantly to the metallicity of the ICM. So far, investigations on the impact of AGNs on galaxy clusters have been oriented almost exclusively towards heating of the ICM (e.g. Sijacki & Springel 2006), as this provides a possible solution to the cooling flow problem. In this work, however, we do not put the emphasis on energy transfer, but on metal transfer.

1.2. AGNs and Outflows

Observational evidence for wind-like outflows from AGNs exists in the form of blueshifted absorption lines in UV and X-ray spectra. These lines are supposed to be created by matter moving away from the AGN, often with very high velocities (e.g. Chartas et al. 2003). Reviews on the subject can be found in Crenshaw et al. (2003) and Veilleux et al. (2005). The absorption occurs at various distances from an AGN’s central engine, from subkiloparsec to galactic scale, and in both radio-quiet and radio-loud AGNs. The inferred mass outflow rates are vague. Crenshaw et al. (2003) concludes that they are comparable to the mass accretion rates (which would likely leave a large range from \( \lesssim 0.001 M_\odot \text{yr}^{-1} \) for low-luminosity AGNs to \( \sim 100 M_\odot \text{yr}^{-1} \) for quasars and powerful radio galaxies) and Veilleux et al. (2005) propose the range 0.1 . . . 10\( M_\odot \text{yr}^{-1} \) and suggest that there is a strong mass loading of the outflow by the galactic ISM. Morganti et al. (2005) assessed outflow rates ranging from \( \sim 1 \) to over \( 50 M_\odot \text{yr}^{-1} \) from the spectra of several radio-loud AGNs and estimated that the kinetic energy of the outflows might be sufficient to remove the gas from the bulges of the galaxies. A very distant (\( r \sim 28 \text{kpc} \)), massive (\( \sim 2 \cdot 10^9 M_\odot \)) absorber has been found by Hamann et al. (2001) in the vicinity of a radio-loud AGN, which indicates a mass outflow rate of \( \sim 10 M_\odot \text{yr}^{-1} \) provided that the material originates from the AGN and was expelled continuously over an assumed lifetime of \( 10^8 \text{yr} \). The composition of the outflows is likely to be rich in metals; Hamann et al. (1997) gives a lower limit of \( \sim Z_\odot \) and says there is evidence for metallicities greater than 10\( Z_\odot \). The possibility of super-solar ICM metallicities around AGNs has been confirmed by the observations of Iwasawa et al. (2004).

AGN jets in clusters are found to be very extended, reaching \( \sim 100 \text{kpc} \) into the ICM (e.g. Owen et al. 1985). Thus, they are an obvious candidate for the transfer of metal-rich matter into the ICM. The aforementioned Morganti et al. (2005), for example, ascribe their findings on interactions between radio jets and the surrounding material. The possibility that AGN entrainment is efficient was confirmed in early simulations of super-sonic jets by De Young (1986), who estimated that a total of \( 10^{-7} M_\odot \) of ambient material can be entrained by typical jets. This is interesting because an AGN must plough its way through metal-rich regions like the broad emission line region. The metallicity is probably very high there (Hasinger et al. 2002, Baldwin et al. 2003) found \( \sim 15 Z_\odot \) for the BEL region in one particular quasar. The jets themselves, being outflows per se, are uninteresting with respect to metal enrichment, as they probably consist either of protons and electrons or positrons (Hirota et al. 2005).

Further evidence for galactic mass loss through AGNs is found in semi-analytic models imposed on large-scale structure formation simulations: Croton et al. (2006) find that AGNs are able to alter their host galaxies, thus inducing outflows of gas.

2. Methods

2.1. Numerical Methods

We use combined N-body and hydrodynamic techniques, together with a semi-numerical galaxy formation code, to simulate the different components of galaxy clusters. The dark matter N-body simulations, which yield the gravitational potential of the dark matter, are performed using a tree code (Barnes & Hut 1986) with constraint realizations of Gaussian random fields as initial conditions (Hoffman & Ribak 1991, van de Weygaert & Bertschinger 1996). The semi-numerical galaxy formation and evolution code (van Kampen et al. 1999) determines where galaxies form and provides galaxy properties. Finally, the hydrodynamic code models the ICM. It uses the PPM (piecewise parabolic method) with a shock-capturing scheme (Colella & Woodward 1984, Fryxell et al. 1989) and computes the properties of the ICM in four nested, cubical grids (Ruffert 1992), each of which is centered at the cluster center, with the largest having a volume of (20 Mpc)\(^3\) and the smallest (2.5 Mpc)\(^3\). Each grid consists of 128 \( \times \) 128 \( \times \) 128 cells. Thus, we obtain the highest resolution in the cluster center. As initial condition for the gas, hydrostatic equilibrium is used. While the N-body tree code and the semi-numerical galaxy formation code start at \( z = 20 \), the hydrodynamic simulation starts at \( z = 1 \), thus covering only about 58% of the simulation time. We adopt a \( \Lambda \text{CDM} \) cosmology with \( \Omega_\Lambda = 0.73, \Omega_m = 0.27, \sigma_8 = 0.93 \) and \( h = 0.7 \). For more information on the methods, see Kapferer et al. (2005).

2.2. AGN Outflows

In the hydrodynamic simulations, outflows from AGNs are added to the model ICM at the respective position of the AGN host galaxy, altering the density, chemical composition, momentum and energy of the ICM there. An outflow is either put
Table 1. Number of galaxies, average absolute value of the velocity and velocity dispersion (measured by the population standard deviation) of the three model clusters at $z = 0$. Only galaxies within $r \leq 2$ Mpc have been taken into account.

<table>
<thead>
<tr>
<th>cluster</th>
<th>number of galaxies</th>
<th>average velocity [km s$^{-1}$]</th>
<th>velocity dispersion [km s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>679</td>
<td>1694</td>
<td>828</td>
</tr>
<tr>
<td>2</td>
<td>396</td>
<td>1078</td>
<td>539</td>
</tr>
<tr>
<td>3</td>
<td>464</td>
<td>1322</td>
<td>623</td>
</tr>
</tbody>
</table>

into the cell where the AGN host resides (one cell in the innermost grid has a volume of $(19.5 \text{kpc})^3$) or it is distributed “jet-like” along a series of cells in the shape of bipolar outflows, emanating from the launching AGN host up to 100 kpc to either side.

To determine the AGN content and characterize the outflows, a series of parameters has been introduced. In the absence of a comprehensive theoretical understanding of AGN triggering and outflows, we have constrained these parameters using values from observations. The AGN fraction $f_{\text{AGN}}$ is the fraction of galaxies that host AGNs with outflows. Multiwavelength observations of clusters by Martini et al. (2006) have shown that the value for AGNs in general is about 5%. Assuming that 10% of all AGNs are radio-loud, we obtain $f_{\text{AGN}} = 0.05$ for outflows attributed to all AGNs (AGN winds) and $f_{\text{AGN}} = 0.005$ for outflows that are specific to radio-loud AGNs (entrainment by jets). We assume $f_{\text{AGN}}$ to be fixed with time. Furthermore, we select AGN hosts randomly among the cluster members, relying upon the findings of Miller & Owen (2002), who discovered that the radial distribution of AGNs is similar to that of cluster galaxies in general.

The duty cycle or lifetime $\tau_{\text{AGN}}$ determines how long an outflow lasts. Martin (2004) finds, collecting a broad variety of estimates, that the lifetime of AGNs is in the range $10^6$–$10^8$ yr. He also notes that it is not clear whether the activity is episodic, with individual active periods much shorter than the total active lifetime. Whether outflows are present during the entire time is also arguable, of course. Nevertheless, we use the upper limit, $\tau_{\text{AGN}} = 0.1$ Gyr, as a standard value and refer to Sect. A.2 for a discussion on the effect of shorter duty cycles.

The mass outflow rate $M_{\text{out}}$ refers to the amount of material that an AGN galaxy loses to the ICM. As mentioned in Sect. A.2, there are no good constraints on this quantity from observations, but outflows of the order of solar masses per year seem to be possible in at least some cases. The same holds true for the outflow metallicity $Z_{\text{out}}$; the value seems to be at least super-solar (Iwasawa et al. 2001). We adopt $5Z_{\odot}$ as a standard value. Note that the results for different metallicities are easily found, see Sect. A.2 for details.

Finally, there is the outflow temperature $T_{\text{out}}$. We adopt the temperature of the WHIM (warm and highly ionized medium) outflow (see Sect. A.2) proposed by Elvis (2000), which is $10^8$ K.

![Figure 1](image1.png)

**Figure 1.** Number of galaxies within $r \leq 2$ Mpc with respect to the cluster center as a function of cosmic time. The humps indicate merging events.

![Figure 2](image2.png)

**Figure 2.** Average absolute value of the velocity of all galaxies within $r \leq 2$ Mpc as a function of cosmic time. The humps indicate merging events.

3. Properties of the Model Clusters

Three different model clusters have been used in this work. Model cluster 1 is a rich cluster with an extraordinarily deep potential. Galaxies, detached or in small lumps, are attracted by its potential during the time interval in which the ICM is simulated. This and the formation of new galaxies raise the total number of galaxies within $r \leq 2$ Mpc from 613 at $z = 1$ to 679 at $z = 0$, see Fig. A.1. This cluster also exhibits the highest average velocities and the highest velocity dispersion, see Tab. A.1.

Model cluster 2 differs considerably from model cluster 1. It contains far less galaxies and is characterized by several merging events, which are visible as humps in the average velocity evolution curve shown in Fig. A.2. At $z = 1$, the cluster consists mainly of two subclusters, separated by a distance of about 3 Mpc from each other. The subclusters approach each other and start to merge about 4.4 Gyr later. At $z = 0$, the
Table 2. Average galaxy number density \( n \) and average ICM density \( \rho \) within \( r \leq 1 \) Mpc with respect to the cluster center during the simulated time interval from \( z = 1 \) to \( z = 0 \) (in runs without AGN outflows). The super- and subscripts give the greatest fluctuations from the mean. The ratio \( \rho/n \), which is listed additionally, can be loosely interpreted as a “gas mass per galaxy”. It characterizes the enrichment behavior of the clusters in our simulations: the ICM gets enriched more if \( \rho/n \) is low and vice versa.

<table>
<thead>
<tr>
<th>cluster</th>
<th>( n ) [Mpc(^{-3})]</th>
<th>( \rho ) ([10^{−24} \text{ kg m}^{-3}])</th>
<th>( \frac{\rho}{n} ) ([10^{10} \text{M}_\odot])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>96.6 ( \pm 16.8 )</td>
<td>22.2 ( \pm 2.4 )</td>
<td>3.4 ( \pm 0.4 )</td>
</tr>
<tr>
<td>2</td>
<td>45.1 ( \pm 26.2 )</td>
<td>3.1 ( \pm 0.9 )</td>
<td>1.1 ( \pm 0.5 )</td>
</tr>
<tr>
<td>3</td>
<td>78.4 ( \pm 16.6 )</td>
<td>9.6 ( \pm 1.1 )</td>
<td>1.8 ( \pm 0.1 )</td>
</tr>
</tbody>
</table>

Table 3. Parameter sets for the simulations presented in this section. From left to right: fraction of galaxies with AGN outflows, duty cycle, outflow rate, outflow metallicity, outflow temperature and energy outflow rate (per AGN). The ejected material is distributed point-like in parameter set (a) and jet-like in parameter set (b), see text.

<table>
<thead>
<tr>
<th>( f_{\text{AGN}} )</th>
<th>( \tau_{\text{AGN}} ) [Gyr]</th>
<th>( M_{\text{out}} ) ([\text{M}_\odot \text{ yr}^{-1}])</th>
<th>( Z_{\text{out}} ) ([Z_\odot])</th>
<th>( T_{\text{out}} ) ([\text{K}])</th>
<th>( \dot{E}_{\text{out}} ) ([\text{J} \text{s}^{-1}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.05</td>
<td>0.1</td>
<td>0.5</td>
<td>5</td>
<td>10(^6) \cdot 6.0 \cdot 10^{34}</td>
</tr>
<tr>
<td>b</td>
<td>0.005</td>
<td>0.1</td>
<td>5</td>
<td>5</td>
<td>10(^6) \cdot 6.0 \cdot 10^{34}</td>
</tr>
</tbody>
</table>

4. Results

4.1. Metallicity Distributions

The parameters for the simulations presented in this section are listed in Tab. 3. In the simulations (a) we assume that every AGN in the cluster has a moderate, wind-like outflow, whereas in the simulations (b) we assume that radio-loud AGNs initiate massive outflows through entrainment by extended jets. The material is initially distributed in just one cell in the former case, and in several cells in the shape of bipolar jets in the latter, see Sect. 2.2. The specific values of the parameters are accounted for in Sect. 2.2. They have been tuned such that the total amount of metals released into the ICM is about equal in both cases, which facilitates a comparison. Forthwith, “2b” refers to model cluster 2 in simulation (b) etc.

Figure 3 illustrates how the metals are added to the ICM, and how they are affected by the ICM dynamics in the case of the merging cluster 2 with jet-like outflows from radio-loud AGNs (b). At \( z = 1 \), the simulation starts with the ICM having \( Z = 0 \). Metal-rich material from AGNs is inserted at various positions. It has the same velocity as the AGN host galaxy and is accelerated along with the rest of the ICM towards the center of the cube, where the merging occurs. The jet-like shape in which the material is initially distributed is quickly disrupted by this movement. In the end, we find a blurred, but inhomogeneous region of high metallicity in the cluster center. The simulation clearly shows that much of the metals that ended up in the center were ejected at much larger radii.

The average metallicities in the cluster cores of the models in all simulations can be found in Tab. 4. The emission weighted projection does not reveal the true metallicity; rather, it is approximately 60% higher. Although more than twice the amount of metals are ejected in the case of cluster 1 (the rich cluster) compared to cluster 2 (the poor, merging cluster), the latter has a metallicity which is on average more than three times as high. Cluster 3 lies in between. This correlates well with the values of \( \rho/n \) listed in Tab. 2. A cluster with a low \( \rho/n \) gets enriched more than a cluster with a high \( \rho/n \) and vice versa.

The radial profiles of the 2D metallicity, depicted in Fig. 4, show that most of the material ends up in the center of the clusters. Artificial X-ray emission weighted metallicity maps of the standard cluster 3 in both simulation scenarios are depicted in Figs. 5 and 6. The parameter set (b) was chosen such as to compensate a lower AGN fraction with a higher outflow rate. Nevertheless, the differences between (a) and (b) are quite dramatic, as a comparison of Fig. 5 with Fig. 6 shows. The map...
Figure 3. Distribution of the metals in simulation 2b. (a), (b), (c) and (f) show the evolution of the distribution in the innermost grid. The metals released into the ICM by the individual AGNs follow the merging process and get mixed quite thoroughly. Nevertheless, the final distribution is not homogeneous. (e) depicts slices through the final distribution, revealing that most metals reside in the core region. (d) shows what X-ray observations of the model cluster would ideally offer, if the model cluster was observed through an X-ray telescope with high resolution and high sensitivity.

Figure 4. Radial metallicity profiles, created from the metallicity maps at $z = 0$. The bin width is 0.2 Mpc and the values in the bins have been weighted with the X-ray surface brightness. The profiles are slightly different for the two simulations (a) and (b).

in Fig. 5 shows a pockmarked structure, whereas the map in Fig. 6 is dominated by single outflows that have not yet mixed with the surrounding material.

The initial distribution of the outflowing material (point-like or jet-like) turned out to be only of minor consequence to the resulting metallicity distribution. The jet-like structures quickly ($\lesssim 1$ Gyr) dissolve.

Considering the fact that we have only simulated about half of the time that might be at the disposal to AGNs for enriching the ICM, and keeping in mind that AGNs might have been more numerous before $z = 1$, we see that both scenarios may explain the observed metal abundances in the ICM (e.g. Schmidt et al. (2002) find $Z \approx 0.3$...0.6 in the core, $r \leq 125$ kpc, of the Perseus cluster). Also, in accordance with observations, the distribution is invariably inhomogeneous.

4.2. Parameter Variations

Since the parameters describing the outflows and the outflow-capable AGN population of a cluster are not constrained very well, it is worthwhile to make a parameter study. Of course, we know that the population of AGNs is very inhomogeneous. The way we used the parameters here is only a crude approximation to get a first notion of how they affect the resulting metallicity.
Where the material was distributed into just one cell) can create features in the X-ray surface brightness and the temperature maps, where the ICM is both brighter and cooler than the surroundings. These features are caused by gas that is both cooler and denser than the surroundings, where material ejected by AGNs has not yet mixed thoroughly with the ambient medium. This is interesting because surface brightness maps from observations are available at much higher resolution and for larger regions than metallicity maps. If lots of AGNs have massive outflows like that (e.g. 5% of the total galaxy population), both the surface brightness and temperature maps from the simulations reveal a flaky structure which is not compliant with observations. Therefore, we discarded such models.

\( Z_{\text{out}} \) only affects the resulting metallicity values, not their distribution. This is to be understood as follows: a metallicity map resulting from a simulation where \( Z_{\text{out}} = x \) can be reproduced from a metallicity map from a similar simulation where \( Z_{\text{out}} = y \) by multiplying the latter with \( x/y \). Given that \( T_{\text{out}} \) is the same, a different \( Z_{\text{out}} \) means a different \( E_{\text{out}} \) (as the latter depends on the molecular weight), but the difference is minor. Thus, one can easily convert a map like that in Fig. 5 into one in which \( Z_{\text{out}} \) is different by simply multiplying the values on the colorbar with the respective factor.

\( T_{\text{AGN}} \) determines how often the hosts of AGNs are changed. Thus, a shorter duty cycle means that the metal-rich gas from AGN outflows is dispersed more right from the start. This yields smoother metallicity maps.

\( T_{\text{out}} \), together with \( M_{\text{out}} \) and \( Z_{\text{out}} \), determines the energy outflow rate \( E_{\text{out}} \). Putting a significant amount of energy into a cell of the model ICM results in vigorous convective movement, as a large portion of the energy is converted into kinetic energy. The resulting metallicity map is much smoother and has a lower peak. For the simulations presented in the preceding sections, this would happen if \( T_{\text{out}} \sim 10^6 \text{ K} \). Below that, the value of the temperature is irrelevant to the final result.

**5. Conclusions and Outlook**

We find that, using a variety of assumptions based on observations, outflows from AGNs can contribute significantly to the metal content of the ICM or even explain its complete abundance. Furthermore, the resulting metallicity distribution resulting from the simulations is always inhomogeneous, in agreement with observations. We showed that the allowable range for the AGN outflow rate can be constrained by comparing the simulations with observations; general outflow rates \( \gtrsim 5 M_\odot \text{ yr}^{-1} \) yield unrealistic results if the material is initially distributed in a volume of \( \lesssim (20 \text{ kpc})^3 \).

However, AGNs are currently not understood well enough to definitely estimate their importance concerning metal enrichment. Apart from a better understanding of AGNs including triggering mechanisms and the origin of the apparent differences between them, the following questions need to be addressed: What is the exact outflow rate of AGN outflows leaving the galaxy? How are outflows initially distributed in the ICM? Is the outflow continuous? How significant is the role of AGN jets? And how does all this depend on the properties of the host galaxy? A self-consistent model of AGN outflows and jet simulations in a realistic, non-homogeneous environment.
ment would be helpful and will hopefully provide quantitative answers to some of these questions in the future.

The cluster simulations are currently being improved by the implementation of new initial conditions for the hydrodynamic simulations that will allow us to start them at a higher redshift. Preliminary tests showed that this results into larger gas velocities which leads to better intermixture between the material ejected by the galaxies and the ICM, especially in the outskirts of the model clusters. However, the inhomogeneity seems to be preserved. Future plans also include the discrimination of different elements instead of only discriminating between hydrogen&helium and metals. However, most important is certainly a better understanding of AGN outflows.

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