Enrichment of the Intracluster Medium

Daniel Thomas
Universitäts-Sternwarte München, Scheinerstraße 1, D-81679 München, Germany

Abstract. The relevance of galaxies of different luminosity and mass for the chemical enrichment of the intracluster medium (ICM) is analysed. For this purpose, I adopt the composite luminosity function of cluster galaxies from Trentham (1998), which exhibits a significant rise at the very faint end. The model – adopting a universal Salpeter IMF – is calibrated on reproducing the $M_{Fe}/L_{tot}$, $M_{Fe}/M_*$, and $\alpha/Fe$ ratios observed in clusters. Although the contribution to total luminosity and ICM metals peaks around $L^*$ galaxies ($M^* \approx -20$), faint objects with $M_B > -18$ still provide at least 30 per cent of the metals present in the ICM. In consistency with the solar $\alpha/Fe$ ratios determined by ASCA, the model predicts that $\sim 60$ per cent of the ICM iron comes from Type Ia supernovae. The predicted slope of the relation between intracluster gas mass and cluster luminosity emerges shallower than the observed one, indicating that the fraction of primordial gas increases with cluster richness.

1 Introduction

In their comprehensive analysis of cluster properties, [?] find that the total mass of iron ($M_{ICM}^{Fe}$) in the intracluster medium (ICM) is directly proportional to the luminosity of E/S0 cluster members. In particular there is no correlation with the spiral population. The logical conclusion is that ellipticals and lenticular galaxies dominate the chemical enrichment of the ICM.

On the other hand, there are several indications for additional ICM sources. At the very faint end, the galaxy luminosity function (LF) does not follow the simple [?] shape, but steepens for objects fainter than $M_B \approx -14$ (e.g. Driver et al. 1994). [?] even concludes that the entire ICM gas may originate from dwarf systems, which is in turn doubted by [?]. The role of dwarf galaxies for the ICM enrichment is thus still a controversial issue. Moreover, intergalactic stars which are stripped from galaxies theoretically are predicted to contain 10–70 per cent of the cluster mass (Moore, Katz, and Lake 1996). Indeed, intergalactic planetary nebulae (Mendez et al. 1997) and RGB stars (Ferguson et al. 1998) have been found in the Virgo cluster. Finally, semi-analytic models of hierarchical galaxy formation predict that dwarf galaxies deliver up to 40 per cent of the ICM metals (Kauffmann & Charlot 1998).

The aim of this paper is to analyse the relative contributions from galaxies of different luminosity and mass to the ICM enrichment for a given LF, which is adopted from [?]. The LF can be fit by the following double-power law ($M_B^* = -20.3$, $M_t = -14.1$, $\alpha = -1.2$, $\beta = -0.7^{+0.4}_{-0.2}$):
\[ \phi(L) \sim (L/L^*)^\alpha \exp(-L/L^*) [1 + (L/L^*)^\beta] \] (1)

The slope \( \alpha + \beta = -1.9 \) at the very faint end causes a steep increase of the number of dwarf galaxies, and agrees well with other determinations in the literature (i.e., Zucca et al. 1997). The code of chemical evolution used for the analysis is calibrated on abundance features in the solar neighbourhood and in elliptical galaxies (Thomas, Greggio, and Bender 1998a,b). The slope above 1 \( M_\odot \) of the IMF is assumed universally Salpeter \( (x = 1.35) \).

2 Galaxy-cluster asymmetry

A problem that arises if giant ellipticals (gE) alone enrich the ICM is the so-called galaxy-cluster asymmetry, which predicts sub-solar \( \alpha/Fe \) ratios in the ICM in case of \( \alpha \)-enhanced stellar populations in gEs (Renzini et al. 1993).

Fig. 1. Mg/Fe ratios in the stars (above the thin line) and the ISM (below the thin line) as function of transformed gas fraction (lower x-axis) and respective stellar metallicity (upper x-axis). The results for three different star formation time-scales \( \tau_{\text{SF}} \) of galaxy evolution are shown.

This feature is shown in Fig. 1 where I plot the Mg/Fe ratios of the stars and of the interstellar medium (ISM) as a function of different galaxy metallicities (upper x-axis), hence mass or luminosity. The larger the gas fraction \( f_{\text{trans}} \) (lower x-axis) that is transformed into stars in a galaxy is, the higher becomes its metallicity. The remaining interstellar gas plus the re-ejected metal-enriched fraction from the stars (including SNIa) establishes the ISM, which is assumed to be blown out of the galaxy in a galactic wind. Galaxies that host Mg/Fe overabundant stellar populations owing to their
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short star formation time-scales $\tau_{\text{SF}}$, in turn enrich the ICM with under-abundant Mg/Fe ratios. This pattern is particularly prominent for the most massive (metal-rich) gEs, and stands in conflict to recent data from ASCA that constrain roughly solar $\alpha$/Fe ratios in the ICM (Mushotzky et al. 1996; Ishimaru & Arimoto 1997). A potential solution to this inconsistency is the assumption of a top-heavy IMF in gEs, assigning the main role of ICM enrichment (including Fe) to SNII (Gibson, Loewenstein & Mushotzky 1997).

Fig. 1 shows that alternatively, metal-poor galaxies (i.e. dwarf galaxies) eject material that exhibits roughly solar Mg/Fe ratios, independent of their star formation history. This configuration results from the fact that the smaller the gas fraction which is transformed into stars, the more the (ejected) ISM contains $\alpha$-element rich SNII products.

3 Results

3.1 Model constraints

In order to convolve the galaxy models of different metallicity with the LF, I adopt the $\langle Z \rangle$-$M_B$ relation from [?]. The mass fraction ejected is given by $M_{\text{ej}} = 1 - f_{\text{trans}}$ under the assumption that clusters basically contain gas-poor spheroidal systems. The baryonic mass to light ratios are taken from theoretical metallicity and age dependent SSP models (Maraston 1998).

Clusters which are more rich and luminous contain a larger amount of iron. Together with the iron mass to light ratio $M_{\text{Fe}}/L_{\text{tot}}$ as introduced by [?], the slope of this relation is reproduced in good agreement with the cluster data. The calculated iron mass to stellar mass ratio $M_{\text{Fe}}/M_\star = 0.002$ perfectly covers what is constrained in [?]. The total amount of intracluster gas, instead, is only matched for fainter clusters like Virgo. The increase of gas ejected with cluster luminosity is shallower than determined by observations. A steeper slope in accordance with the data is achieved if $\beta = -1.8$, which fits the field LF data from [?]. For the cluster LF, $2/3$ of the intergalactic gas in rich clusters is predicted not to participate galaxy formation, and must therefore have primordial origin. The [Mg/Fe] ratio in the ejecta of the composite galaxy population is [Mg/Fe] = $-0.1$ dex, which is a bit low but still within the range allowed by ASCA data.

3.2 The luminosity function

Fig. 2 shows the [?] LF and the respective contributions from the galaxies of different $L_B$ to $L_{\text{tot}}$ and number of the galaxies, and to the masses of gas, iron, and magnesium in the ICM.

In spite of the huge number of dwarf galaxies, the main fraction of $L_{\text{tot}}$ comes from galaxies around $L^*$ ($M^* \approx -20$). Since in the present model the production of metallicity is directly related to galaxy mass (hence $L_B$),
Fig. 2. Luminosity function (left-hand y-axis) from Trentham (1998) composite cluster data. The fit (solid line) yields the following values for the parameters of (1): $M^* = -20.3, M_l = -14.1, \alpha = -1.2, \beta = -0.7$. The two long-dashed lines show the fit for $\beta = -0.3$ and $\beta = -0.9$, respectively. The fractional contributions (right-hand y-axis) from the individual luminosity bins (respective galaxy metallicity on the upper x-axis) to total $L_B$ and number of the galaxies are indicated by the solid histograms. The distributions of the ejecta of gas, iron and magnesium are shown by the histograms of different linestyles.

the distributions of iron and magnesium follow that of $L_B$. The mass of gas delivered from the galaxies to the ICM, instead, is much wider spread over the galaxy population. Since metal-poor dwarf systems are less efficient in processing gas to stars, they expel a much larger fraction of their mass than gEs. Finally, it should be emphasized that 63 per cent of the iron in the ICM comes from SNIa, which leads to the nearly solar Mg/Fe ratio predicted by the model. The galaxy-cluster asymmetry is weakened, due to the significant contribution from galaxies fainter than $L^*$.

4 Conclusions

For a given galaxy LF observed in clusters I analyse the fractional contributions to the ICM enrichment from galaxies of the different luminosity bins. The LF covers the whole relevant luminosity range from $M_B = -22$
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to $M_B = -10$, which allows to investigate the significance of dwarf galaxies in a straightforward way. The galaxy evolution model is semi-empirical in the sense that the relation between metallicity and luminosity of the galaxies is taken from observational data.

It turns out that galaxies fainter than $L^*$ down to $M_B \approx -14$ provide an important contribution to the total light of the galaxy population and to the metals found in the ICM. Dwarf galaxies below this threshold, instead, deliver a significant fraction of the total gas mass that is ejected by the galaxy population. Due to the influence of intermediate ellipticals, the resulting Mg/Fe ratio in the ICM can be reproduced consistent with ASCA measurements. SNIa are predicted to produce 63 per cent of the ICM iron, which is a proportion comparable to the solar neighbourhood chemistry as already claimed by [?]. Hence, the ICM is not an archive of SNII nucleosynthesis alone.

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References
