Chemical Enrichment of the Intra-Cluster Medium

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Abstract. We investigate the metal enrichment of the intra-cluster medium by using a method that combines N-Body simulations and a semi-analytic model (SAM) of galaxy formation. The cluster of galaxies is simulated in a flat, low density universe, with a numerical resolution that allows the detection of substructures in the dark matter background of the cluster. The phenomenological approach used to model the physical processes involved in the galaxy formation and metal production is applied to the substructures found in the dark matter halos detected at different redshifts. Details of the chemical implementation in the SAM and first results related to the mean properties of the baryonic matter components are presented.

Keywords: galaxies:clusters:general, intergalactic medium

1. Introduction

New generation of X-ray observatories provides a great deal of information on the thermal and chemical properties of the hot gas trapped in the potential well of galaxy clusters. These structures are the largest virialized ones and are good approximations to 'closed boxes', thus being suitable for the study of processes involved in the chemical enrichment of their baryonic components. The detection of Fe K line emission was the most significant observational discovery concerning X-ray clusters. The content of iron in the intra-cluster medium (ICM) supports the fact that some of its hot gas has been originated in the galaxies that reside in the cluster. The physical mechanisms considered for the supply of this enriched gas comprise galactic winds driven by supernovae (SNe) explosions (White, 1991; Renzini, 1997), ram pressure stripping (Mori and Burket, 2000), and early enrichment by hypernovae associated with population type III stars (Loewenstein, 2001). Observations from satellites like HEAO 1, EXOSAR, Ginga and ROSAT indicate that the iron abundances range from 25% to 50% of the solar value. Abundance gradients in the ICM of some clusters have also been measured (White, 2000; Finoguenov et al., 2000; De Grandi and Molendi, 2001), providing clues about the relative contribution of different type of supernovae (SNe) and about the mechanisms that determine the presence (absence) of metallicity profiles in cooling flow (non-cooling flow) clusters. These data put constraints on the origin of metals and helps to understand the physical processes involved in the formation and evolution of galaxies. However, their interpretation leads to controversial results on these topics, and complementary numerical studies are necessary to disentangle the numerous puzzles related to the metal enrichment of the ICM.

2. Hybrid model of ICM chemical enrichment

In a hierarchical structure formation scenario, the structure is formed by the clustering of smaller ones. In order to estimate the impact of the hierarchical build of the structure on the chemical enrichment of the ICM, we used a method that combines cosmological N-Body simulations of cluster of galaxies, and a semi-analytic model (SAM) of galaxy formation (Springel et al., 2001).

We employed the GIF-ΛCDM model with cosmological parameters Ω_o=0.3, Ω_Λ=0.7, $\mathrm{H_o} = 100\,h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, with $h = 0.7$, spectral shape $\Gamma = 0.21$, and was cluster-nomalized to $\sigma_8 = 0.9$. The second most massive cluster in this simulation ($M_{\rm vir} = 8.4 \times 10^{14}\,h^{-1}\,\mathrm{M_\odot}$) was resimulated considering higher resolution in the region immediately surrounding the object with $\approx 2.2 \times 10^5$ dark matter particles of mass $1.4 \times 10^{10}\,h^{-1}\,\mathrm{M_\odot}$. The simulation was carried out with the parallel tree code GADGET.

The partially stripped haloes of cluster galaxies can be identified within the dark matter clumps corresponding to groups and clusters when sufficiently high mass resolution simulations are used. These substructures were found by using the SUBFIND algorithm and were used by the SAM to generate the population of galaxies (Springel et al., 2001). This model was modified to take into account the circulation of metals among the different baryonic components, providing the mean properties of the galaxies and the ICM. Metal production prescriptions were added to the recipes of hydrodynamics of cooling, star formation, supernovae feedback and galaxy-galaxy merging. Stars can contaminate the cold and hot gas because of mass losses during their evolution and metals ejected at the end of their lives. In the present version of the SAM, only the later mechanism is considered by the inclusion of effects of supernovae type II (SNe II) and type Ia (SNe Ia).

The temporal behaviour of the abundances of several chemical elements is followed, instead of adopting the yield as a free parameter like in other semi-analytic models (Kauffmann and Charlot, 1998; Cole et al., 2000; Somerville et al., 2001). The metal production is estimated for each star formation episode. For SNe II, the yield of metals (Woosley and Weaver, 1995) is assumed to be immediately recycled to the cold gas, allowing some fraction to go directly to the hot halo gas (Kauffmann and Charlot, 1998; Cole et al., 2000). The number of SNIa is obtained by assuming a rate between the two types of SNe based on observed values (Tsujimoto et al., 1995: SNRIa/SNRII=0.15 - 0.3). The SNIa ejecta (Iwamoto et al., 1999) are assumed to be produced at a given time after a starburst (0.1 - 1 Gyr). Starbursts induced in major mergers contribute with metals that contaminate the hot gas since the cold gas is assumed to be completely consumed in this process. We consider the metallicity dependence of the cooling rate and of the population synthesis models used to calculate the photometric properties of the galaxies (Kauffmann and Charlot, 1998).

3. Results

The model was normalized following Kauffmann et al. (1999). The parameters introduced were tuned to match observed metallicity properties of the galaxies and the cluster. The metallicity of the stellar population of 'Milky Way' like galaxies can be reconciled with the values observed in the stars of the solar neighborhood (mean metallicity of 0.7 times the solar value) by increasing the yield of heavy elements by a factor of two, taking into account the theoretical uncertainties in the nucleosynthesis calculations (Gibson et al., 1997). However, the metallicity of the hot gas in the cluster could not be reproduced. The value obtained is $\simeq 50\%$ lower than the observed ones. We can figure out the origin of this lack of metals in the ICM by considering mean properties of the cluster. With the parameters adopted, we obtained a mass of hot gas $M_{\rm ICM} = 1.47 \times 10^{14}{\rm M}_{\odot}$ and a total stellar mass of the galaxies contained in the cluster $M_{\star} = 8.27 \times 10^{12}{\rm M}_{\odot}$. Comparing these values with those adopted by White et al. (1993) for the Coma Cluster ($M_{\rm ICM} \simeq 5.5 \times 10^{13}\,h^{-5/2} = 1.34 \times 10^{14}{\rm M}_{\odot}$, $M_{\star} \simeq 10^{13}\,h^{-1} = 1.43 \times 10^{13}{\rm M}_{\odot}$), we found that the stellar mass in the simulated cluster is a factor $\simeq 0.6$ the observed one. This is consistent with the behaviour shown by the B-band luminosity function constructed with the galaxies in the cluster, which matches only the bright end of the composite luminosity function of galaxy clusters obtained by Trentham (1998). Hence, a significant fraction of galaxies is missing in the simulated cluster, which corresponds to stellar mass produced in haloes that are below the resolution limit of the simulation. This leads to a low mass of metals ejected into the ICM.

A relevant indicator of the mean properties of the cluster is the ICM iron mass to light ratio, $M_{\rm ICM}^{\rm Fe}/L_{\rm B}$, where $M_{\rm ICM}^{\rm Fe}$ is the iron content in the ICM, and $L_{\rm B}$ is the optical luminosity of galaxies in the cluster. The observed value of this ratio ranges within $0.01 - 0.02\,\mathrm{M}_\odot/\mathrm{L}_\odot$ (Renzini, 1997). For the simulated cluster, we found $M^{\mathrm{Fe}}_{\mathrm{ICM}}/L_{\mathrm{B}} = 0.019\,\mathrm{M}_\odot/\mathrm{L}_\odot$, in good agreement with observations. This is an important result since it shows that the circulation of metals between the different baryonic components (stars and gas) in the cluster is being well tracked.

These results calls for the analysis of higher resolution simulations that are already available, which also follow the dynamical evolution of gas particles that represent the ICM using smoothed particle hydrodynamics. The analysis of the chemical enrichment of these gas particles will allow us to investigate the processes that give rise to the final spatial distribution of metals in the ICM and its evolution with redshift.

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