Evolution of the metal content of the intracluster medium with hydrodynamical simulations

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ABSTRACT

We present a comparison between simulation results and X-ray observational data on the evolution of the metallicity of the intracluster medium (ICM). The simulations of galaxy clusters have been carried out using a version of the TRee PM-smoothed particle hydrodynamics (SPH) GADGET-2 code that includes a detailed model of chemical evolution by assuming three different shapes for the stellar initial mass function (IMF). Besides the Salpeter IMF, we also used the IMF proposed by Kroupa and the top-heavier IMF by Arimoto and Yoshii. We find that simulations predict significant radial gradients of the Iron abundance, $Z_{Fe}$, which extend over the whole cluster virialized region. Using the Salpeter IMF, the profiles of $Z_{Fe}$ have an amplitude which is in a reasonable agreement with Chandra observations within 0.2 $R_{500}$. At larger radii, we do not detect any flattening of the metallicity profiles.

As for the evolution of the ICM metal abundance out to $z = 1$, it turns out that the results based on the Salpeter IMF agree with observations. We find that the evolution of $Z_{Fe}$ in simulations is determined by the combined action of (i) the sinking of already enriched gas, (ii) the ongoing metal production in galaxies and (iii) the locking of ICM metals in newborn stars. As a result, rather than suppressing the metallicity evolution, stopping star formation at $z = 1$ has the effect of producing an even too fast evolution of the emission-weighted ICM metallicity, with too high values of $Z_{Fe}$ at low redshift within 0.2 $R_{200}$. Finally, we compare simulations with the observed rate of Type Ia supernovae per unit B-band luminosity ($SnU_B$). We find that our simulated clusters do not reproduce the decreasing trend of $SnU_B$ at low redshift, unless star formation is truncated at $z = 1$.

Key words: methods: numerical – galaxies: abundances – intergalactic medium – cosmology: theory – X-rays: galaxies: clusters.

1 INTRODUCTION

The high-quality X-ray observations of galaxy clusters from the current generation of X-ray satellites are allowing now to trace in detail the pattern of the metal enrichment of the intracluster medium (ICM) of galaxies (e.g. Mushotzky 2004; Werner et al. 2008, for reviews). In turn, this information is inextricably linked to the history of formation and evolution of the galaxy population as observed in the optical/near-infrared band (e.g. Renzini 2004, and references therein). A number of independent observations have established that significant radial gradients of the Iron abundance are present in the central regions, $R \lesssim 0.1R_{200}$, of relaxed clusters and groups (e.g. De Grandi et al. 2004; Vikhlinin et al. 2005; Rasmussen & Ponman 2007), with enhancement of the metallicity associated to the brightest cluster galaxies (BCGs), while no evidence has been found that these gradients extend at larger cluster-centric distances (e.g. Snowden et al. 2008). Furthermore, deep exposures with the Chandra and XMM–Newton satellites have now opened the possibility of tracing the evolution of the ICM metal content within the central regions out to the largest redshifts, $z \simeq 1.3$, where clusters have been identified so far. Balestra et al. (2007) and Maughan et al. (2008) have fairly analysed large samples of distant clusters, extracted from the Chandra archive and found that the metallicity of the ICM within the central cluster regions has increased by about 50 per cent since $z \simeq 1$.

This positive evolution of the ICM metallicity in the central cluster regions is apparently in contradiction with the lack of significant
star formation (SF) at low redshift (e.g. Rafferty et al. 2006). Based on a phenomenological approach, Ettori (2005) showed that the evolution of the ICM metallicity is in line with the expectations from the observed cosmic rates of supernova (Sn) explosions and SF. Loewenstein (2006) combined observations of the evolution of the ICM metallicity with data on the Sn rates and star formation rates to infer the relative role played by Type Ia and II Sn (Sn Ia and Sn II, hereafter).

A different approach was pursued by other authors, which considered gasdynamical mechanisms at relatively low redshift as responsible for redistributing previously produced metals. For instance, Cora et al. (2008) suggested that clumps of low-entropy highly enriched gas may sink in the central cluster regions, thereby leading to an increase of the observed emission-weighted metallicity. For instance, ram-pressure stripping of the ISM of merging galaxies has been suggested as a mechanism to pollute at relatively low redshift a metal-poor ICM with highly enriched gas (e.g. Domainko et al. 2006, and references therein), while causing a morphological transformation of cluster galaxies (e.g. Calura, Matteucci & Tozzi 2007; Roediger & Brüggen 2007). Although possible evidence of ram-pressure stripping of cluster galaxies have been detected (e.g. Chung et al. 2007), the question remains as to whether this mechanism dominates the evolution of the ICM enrichment. Indeed, since ram pressure is expected to be more efficient in high-temperature clusters, one expects an increasing trend of metallicity with ICM temperature (e.g. Renzini 1997). If any, observations suggest that hotter systems have a relatively lower metallicity (e.g. Baumgartner et al. 2005), thus suggesting that ram-pressure stripping is not the dominant process in enriching the ICM.

It is clear that understanding the history of the ICM enrichment in cosmological context, during the cluster hierarchical build up, requires describing in detail the gasdynamics related to the merging processes, while including a self-consistent treatment of SF and chemical evolution. In this context, cosmological hydrodynamical simulations offer a unique means to capture in full detail the complexity of these processes (e.g. Valdarnini et al. 2003; Tornatore et al. 2004; Romeo et al. 2006; Tornatore et al. 2007, hereafter T07, see Borgani et al. 2008, for a recent review). In their most advanced versions, chemodynamical simulation codes treat the production of different metal species, released by different stellar populations by resorting to detailed chemical evolution within the clusters, which have been identified in a dark matter (DM) only simulation having a box size 479 h⁻¹ Mpc (Yoshida, Sheth & Diaferio 2001), performed for a flat Λ cold dark matter (ΛCDM) cosmological model with Ωm = 0.3, h₀₀₀ = 0.7, σ₈ = 0.9 and ΩΛ = 0.04. The four extracted Lagrangian regions, centred on these clusters with virial masses in the range Mvir = 1.0–2.3 × 10¹⁵ h⁻¹ M⊙, have been resimulated using the zoomed initial condition (ZIC) technique by Tornen, Bouchet & White (1997), which allows one to increase force and mass resolution in the regions of interest. The high-resolution DM particles have mass mDM = 1.13 × 10¹⁰ h⁻¹ M⊙, and the barionic particles have been added with a mass mgas = 1.7 × 10⁹ h⁻¹ M⊙ in order to reproduce the assumed cosmic baryonic fraction. The basic characteristics of the simulated clusters are summarized in Table 1.

The simulations are performed using the hydrodynamical treecosmological hydrodynamical simulations (SPH) code GADGET-2 (Springel 2005) with the implementation of chemical enrichment by T07, the Plummer-equivalent softening length for gravitational force is set to ϵ = 5h⁻¹ kpc in physical units from z = 2 to 0, while at higher redshifts is ϵ = 15h⁻¹ kpc in comoving units. The simulations include heating from a uniform time-dependent ultraviolet background (Haardt & Madau 1996) and metallicity-dependent radiative cooling based on the tables by Sutherland & Dopita (1993) for an optically thin plasma. The process of SF is described by the subresolution multiphase model by Springel & Hernquist (2003), for which the density threshold for the onset of SF is set to ρ₆ = 0.1 cm⁻³.

While the relevant features of the chemical evolution model are described here below, we address the reader to T07 for a more detailed description. Metals are produced by Sn II, Sn Ia and intermediate and low-mass stars (ILMS), with only Sn Ia and Sn II providing energy feedback. We assume Sn II to arise from stars having a mass

![Table 1. Characteristics of the simulated clusters at z = 0. Column 1: cluster name; column 2: virial mass (units of 10¹⁵ h⁻¹ M⊙); column 3: virial radius (units of h⁻¹ Mpc); column 4: spectroscopic-like temperature within Rvir (keV, see Mazzotta et al. 2004, for its definition).](https://academic.oup.com/mnras/article-abstract/386/3/1265/1057413)

All values of Iron abundance that we will quote in the following are scaled to the solar abundance value by Grevesse & Sauval (1998).

### 2 THE SIMULATIONS

In this paper, we present a set of simulations of four massive isolated clusters, which have been identified in a dark matter (DM) only simulation having a box size 479 h⁻¹ Mpc (Yoshida, Sheth & Diaferio 2001), performed for a flat Λ cold dark matter (ΛCDM) cosmological model with Ωm = 0.3, h₀₀₀ = 0.7, σ₈ = 0.9 and ΩΛ = 0.04. The four extracted Lagrangian regions, centred on these clusters with virial masses in the range Mvir = 1.0–2.3 × 10¹⁵ h⁻¹ M⊙, have been resimulated using the zoomed initial condition (ZIC) technique by Tornen, Bouchet & White (1997), which allows one to increase force and mass resolution in the regions of interest. The high-resolution DM particles have mass mDM = 1.13 × 10¹⁰ h⁻¹ M⊙, and the barionic particles have been added with a mass mgas = 1.7 × 10⁹ h⁻¹ M⊙ in order to reproduce the assumed cosmic baryonic fraction. The basic characteristics of the simulated clusters are summarized in Table 1.

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1 We define the virial mass Mvir as the mass contained within the virial radius Rvir. This is defined as the radius within which the average density is that predicted by the spherical collapse model (for the cosmology assumed in our simulations, ρvir ≡ 100 ρc, with ρc the critical cosmic matter density). More, in general, we define R₅ₐ to be the radius at which the density is Δ times the critical density ρc. Physical quantities with subscript Δ are computed within R₅ₐ.
above $8 \, \text{M}_\odot$. As for the Sn Ia, we assume their progenitors to be binary systems, whose total mass lies in the range $3-16 \, \text{M}_\odot$. Metals and energy are released by stars of different mass by properly accounting for mass-dependent lifetimes. In this work, we assume the lifetime function proposed by Padovani & Matteucci (1993). We adopt the metallicity-dependent stellar yields by Woosley & Weaver (1995) for Sn II, the yields by van den Hoek & Groenewegen (1997) for the ILMS and by Thielemann et al. (2003) for Sn Ia. The version of the code used for the simulations presented here allowed us to follow H, He, C, N, O, Mg, Si and Fe. Once produced by a star particle, metals are then spread to the surrounding gas particles by using the B-spline kernel with weights computed over 64 neighbours and taken to be proportional to the volume of each particle. T07 verified with detailed tests that the final results on the pattern of chemical enrichment are rather insensitive to the weighting scheme (kernel shape and number of neighbours) used to spread metals.

Our simulations include the kinetic feedback model implemented by Springel & Hernquist (2003). According to this scheme, Sn II explosions trigger galactic winds, whose mass upload rate is assumed to be proportional to the star formation rate, $M_w = \eta M_\star$. Therefore, fixing the parameter $\eta$ and the wind velocity $v_w$ amounts to fix the total energy carried by the winds. Our choice of $\eta = 3$ and $v_w = 500 \, \text{km} \, \text{s}^{-1}$ corresponds to assume, for the initial mass function (IMF) by Salpeter (1955), with Sn II releasing $10^{51} \, \text{erg}$ each, nearly unity efficiency in powering galactic outflows.

In our comparison with observational data, we will first explore the effect of changing the IMF. We use the IMF by Salpeter (1955) and that by Arimoto & Yoshii (1987), for which the number $N$ of stars per unit mass interval is defined as $\phi(m) \propto dV/dm \propto m^{-1-\alpha}$, with $\alpha = 1.35$ and 0.95, respectively. Furthermore, we also use the multislope IMF proposed by Kroupa (2001) with $\alpha = -0.7$, 0.3 and 1.3, respectively, for $m \leq 0.08, 0.08 \leq m < 0.5$ and $m \geq 0.5 \, \text{M}_\odot$. Simulations based on the Salpeter IMF have been run for the four clusters, while only simulations of the g51 halo have been carried out for the other two choices of the IMF. In the following, we label the runs that use the Salpeter, Arimoto–Yoshii and Kroupa IMFs and the IMFs with Sal, AY and Kr, respectively.

An important parameter entering in the model of chemical evolution is the fraction $A$ of stars, in the mass range $0.8-8 \, \text{M}_\odot$, belonging to binary systems which explodes as Sn Ia in the single-degenerate scenario (Greggio & Renzini 1983; Matteucci & Greggio 1986). For our reference runs, we will use $A = 0.1$ as suggested by Matteucci & Gibson (1995) to reproduce the observed ICM metallicity (see also Portinari et al. 2004). As we will discuss in the following, the simulation with the AY IMF tends to overproduce Iron. In the attempt to overcome this problem, we also carried out a run with the AY IMF using also $A = 0.05$.

Simulations of galaxy clusters, which include the scheme of feedback adopted here, are already known to produce an excess of low-redshift SF, mostly associated with the BCG (e.g. Romeo, Portinari & Sommer-Larsen 2005; Saro et al. 2006). This recent SF is expected to significantly affect the history of the ICM enrichment. From one hand, it should provide an excess of recent metal production, thus possibly enhancing the enrichment at small cluster-centric radii. On the other hand, a recent SF is also expected to lock back in the stellar phase a significant amount of highly enriched gas, which has shorter cooling time, thus leaving in the hot ICM only relatively metal poorer gas. In order to quantify the effect of recent SF of the ICM enrichment history, we have also simulated the Salz version of the g51 cluster by switching off radiative cooling and SF below $z = 1$, considering both the case in which already formed stars keep producing metals with the appropriate lifetimes (run with cooling stopped, CS hereafter) and the case in which also the metal production is stopped at the same redshift (run with cooling and metal production stopped, CMS hereafter). While this prescription of suppressing low-redshift SF and metal production is admittedly oversimplified, it allows us to address the following questions: (i) to what extent the SF excess in simulations affects the enrichment evolution of the ICM? and (ii) what is the role of gas dynamical processes in redistributing at relatively low redshift the metals that have been produced at earlier epochs?

3 RESULTS AND DISCUSSION

3.1 Metallicity profiles of nearby clusters

The radial profiles of the metal abundance provide a very important record of the chemical enrichment process in galaxy clusters. Indeed, they are determined by the distribution of cluster galaxies, where most of the metals are produced by the mechanisms responsible for their transport and diffusion from the star-forming regions (i.e. galactic ejecta, ram-pressure and viscous stripping, etc.) and by other gas dynamical processes which redistribute them on larger scales (e.g. turbulence and sinking of enriched low-entropy gas).

Here, we compare the profiles of the Iron abundance of simulated galaxy clusters at $z = 0$ with the observational results from Chandra data of a sample of nearby relaxed clusters analysed by Vikhlinin et al. (2005). In Fig. 1, we compare the profiles of $Z_{\text{Fe}}$ from our simulated clusters with the observed profiles of eight clusters having the temperature above 3 keV (see table 1 in Vikhlinin et al. 2005). We point out that the analysis of Vikhlinin et al. (2005) provided information on the total ICM metallicity, i.e. without distinguishing the contribution from different chemical species. However, at the typical temperatures of these clusters and for the typical energy range where the spectral analysis was performed (0.6–10 keV; see Vikhlinin et al. 2005), this observed metallicity is largely dominated by Iron. We want to stress the fact that the simulated clusters are dynamically relaxed (with the last major merger undergone before $z = 0.5$) and therefore suitable for the comparison with this set of observed clusters.

As shown in the left-hand panel of Fig. 1, the simulations based on a Salpeter (1955) IMF produce profiles which are in reasonable agreement with observations. The scatter among the four simulated clusters is quite small, with some increase in the central regions, $R \lesssim 0.1 R_{500}$. Although observations seem to have a larger scatter, it is not clear how much observational uncertainties contribute to it. Changing the IMF (right-hand panel of Fig. 1) clearly turns into a change of the overall amount of the Iron abundance at all radii, with both the $K_r$ and the AY IMFs producing too high profiles. The larger amount of Iron found for these two IMFs is due to the fact that, once normalized, they both predict a larger number of supernovae contributing to the Iron production, with respect to the Sal one.

Besides producing more Sn II, the AY and $K_r$ IMFs also produce a larger number of Sn Ia, since there is a significant overlap between the mass range relevant for Sn Ia and the mass range where these two IMFs are higher than the Sal one.

As for the relative roles of Sn Ia, Sn II and ILMS in the ICM enrichment, we verified that Sn Ia contribute for about 70 per cent of the Iron contained in the diffuse medium within $R_{500}$ for the Sal IMF. This fraction decreases to about 65 per cent for the $K_r$ IMF and about 55 per cent for the AY IMF. Since Sn Ia provide a major contribution to the Iron production, our results are quite sensitive to the choice of the fraction $A$ of stars in binary systems. As a matter of

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fact, this fraction can be considered as a free parameter in a model of chemical evolution. Following a phenomenological approach, for each choice of the IMF its value is determined by the requirement of reproducing some observational data. In our case, we note that decreasing $A$ from 0.1 to 0.05 induces a significant decrease of the $Z_{Fe}$ profile. This sort of degeneracy between the IMF shape and the fraction of binary stars can be broken by looking at the relative abundance of $\alpha$ elements with respect to Iron. For instance, since Oxygen is essentially produced by Sn II, we expect a top-heavier IMF to provide values of O/Fe higher than for a top-lighter IMF. If we suppress the number of Sn Ia for the top-heavier IMF, by decreasing the value of $A$, we further increase the O/Fe ratio, thus allowing to distinguish this case from that of a top-lighter IMF with a higher $A$. We deserve a forthcoming paper to a detailed comparison of simulations with observations of relative abundances for nearby clusters.

The runs with the Sal IMF provide results in closer agreement with the Chandra data, although in all cases the profiles of the simulated clusters are somewhat steeper than the observed ones, with negative gradients extending at least out $R_{500}$ and beyond. This result is at variance with the recent claim by Snowden et al. (2008) who found no evidence for the presence of metallicity gradients at scales $\geq 0.1R_{500}$ from the analysis of a catalogue of 70 clusters observed with XMM–Newton. In the next section, we will compare simulated and observed results on the evolution of the ICM metallicity at small radii, where the simulated and the observed metallicity gradients are in reasonable agreement. If confirmed by independent analyses, the lack of abundance gradients at relatively large radii will provide a non-trivial constraint for chemodynamical models of the ICM enrichment.

Limited numerical resolution could lead to an underestimate of high-redshift enrichment from a pristine population of relatively small under-resolved galaxies. This high-$z$ enrichment should be rather uniform and, therefore, should soften the metallicity gradients. Indeed, T07 found that increasing resolution provides progressively shallower metallicity profiles. However, the effect is visible only at radii $\geq 0.5R_{500}$, while being negligible at smaller radii, which are dominated by the SF associated to the BCG. Another possibility to soften metallicity profiles can be provided by active galactic nuclei (AGN) feedback. For instance, Bhattacharya, Di Matteo & Kosowsky (2007) analysed cosmological simulations of galaxy groups, which include the effect of energy feedback from gas accretion to black holes. They found that the role of this feedback is to redistribute the hot gas, driving it from the inner regions, where it should be more enriched, to the outer part of the halo, and to lower the SF in the inner region. Sijacki & Springel (2006a) used a similar feedback scheme in which energy is used to trigger the formation of high-entropy bubbles. These bubbles rise buoyantly in the ICM, giving rise to a redistribution of the central metal-enriched gas (see also Roediger et al. 2007). Clearly, in this case the request is that the redistribution of metals should not be so efficient as to destroy the metallicity gradients in the central cluster regions (e.g. Böhringer et al. 2004).

### 3.2 Evolution of the ICM metallicity

In this section, we compare the simulation predictions on the evolution of the ICM metallicity with the observational results by Balestra et al. (2007). These authors analysed Chandra observations of 56 clusters at $z > 0.3$ (with the addition of XMM–Newton observations for clusters at $z > 1$) having temperatures above 3 keV. They measured the metallicity in the central regions, with a typical extraction radius of 0.15–0.3$R_{180}$, chosen object-by-object so as to maximize the signal-to-noise ratio (see also Maughan et al. 2008, for a similar analysis). For the low-redshift reference value, Balestra et al. (2007) combined this set of distant clusters with a mix of cool- and non-cool-core clusters at lower redshift. They also pointed out that the observed decrease of $Z_{Fe}$ with redshift is not induced by a decrease of the fraction of cool-core clusters in the past. Therefore, we expect that no significant bias is introduced when comparing the observed evolution with that traced by our set of relaxed simulated clusters. Since it is quite difficult to define a common extraction radius for
Figure 2. The comparison between observations and simulations for the evolution of the Iron abundance, $Z_{\text{Fe}}$. Observational results from Balestra et al. (2007) are shown with open circles, with errorbars corresponding to the 1σ uncertainty in the combined spectral fit performed for all the clusters falling within each redshift bin. The shaded area is the rms scatter among the measured metallicities within the same redshift intervals. Left-hand panel: the dependence of the simulation results on the stellar IMF. The filled squares show the average over the simulated clusters, assuming a Salpeter (1955) IMF (Sal), with errorbars indicating the rms scatter over the four objects. For the g51 cluster only, the open squares are for the run with Salpeter (1955) IMF, the filled and open triangles are for the Arimoto & Yoshii (1987) IMF (AY) with $A = 0.1$ and $A = 0.05$ for the binary fractions, respectively, while the filled circles are for the run with the Kroupa (2001) IMF (Kr).

In the right-hand panel: the effect of stopping SF and metal production at low redshift on the evolution of $Z_{\text{Fe}}$ for the g51 cluster. The filled squares are for the reference (Sal) run shown with the open squares. The filled circles are for the run with radiative cooling and SF stopped at $z = 1$ (CS), while the filled triangles are for the run in which also the metal production is turned-off at $z = 1$ (CMS).

The comparison between observations and simulations for the evolution of the Iron abundance, $Z_{\text{Fe}}$, is shown in the left-hand panel of Fig. 2. Observational results from Balestra et al. (2007) are shown with open circles, with errorbars corresponding to the 1σ uncertainty in the combined spectral fit performed for all the clusters falling within each redshift bin. The shaded area is the rms scatter among the measured metallicities within the same redshift intervals. Left-hand panel: the dependence of the simulation results on the stellar IMF. The filled squares show the average over the simulated clusters, assuming a Salpeter (1955) IMF (Sal), with errorbars indicating the rms scatter over the four objects. For the g51 cluster only, the open squares are for the run with Salpeter (1955) IMF, the filled and open triangles are for the Arimoto & Yoshii (1987) IMF (AY) with $A = 0.1$ and $A = 0.05$ for the binary fractions, respectively, while the filled circles are for the run with the Kroupa (2001) IMF (Kr).

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Although the agreement between the runs based on the Salpeter (1955) IMF and observations is rather encouraging, the question remains as to whether the positive evolution seen in the simulations is just the spurious product of the excess of SF taking place in the central cluster regions. In order to address this question, we compare in the right-hand panel of Fig. 2 the evolution of $Z_{\text{Fe}}$ for g51 when stopping SF and/or metal production at low redshift. Quite remarkably, halting SF below $z = 1$ while allowing already formed stars to keep releasing metals (CS run) has the effect of strongly increasing the positive evolution of $Z_{\text{Fe}}$ in the central region of g51, which turns out to be overenriched by $z = 0$. This leads to the counter-intuitive conclusion that the lack of low-$z$ SF should generate an increase of the enrichment of the hot gas. In order to investigate the origin of this increase, we show in Fig. 3 the emission-weighted metallicity maps of the reference Sal run of g51 at $z = 0$, along with those of the CS and CMS runs. Quite apparently, the metal distribution in the CS simulation is more clumpy than in the reference run. At the cluster centre, a high $Z_{\text{Fe}}$ is clearly visible, which boosts the central emission-weighted metallicity shown in Fig. 2. Indeed, while the emission-weighted $Z_{\text{Fe}}$ increases by about a factor of 2 within $0.2R_{180}$, we verified that the mass-weighted estimate within the same radius increases only by about 10 per cent.
In the reference run, the metals released in the high-density clumps disappear from the hot-diffuse medium due to the efficient gas cooling. As a result, the reference run has a globally higher level of diffuse enrichment, but a lower level of enrichment inside the high-density gas clumps, which dominate the emission-weighted estimate of $Z_{\text{Fe}}$. These results demonstrate that the strongly positive evolution of the emission-weighted metallicity in the CMS run is driven by the accretion of highly enriched dense clumps.

Inhibiting also the production of metals below redshift unity (CMS run) allows us to characterize the role played by gasdynamical processes in redistributing metals produced at higher redshift. As shown in the bottom left-hand panel of Fig. 3, metal clumps are less pronounced than in the CS run. The global enrichment level of the ICM is now significantly lower than in the reference run, although an enhancement in the innermost regions is still visible. The resulting mass-weighted metallicity within $0.2R_{\text{vir}}$ at $z = 0$ decreases by $\sim 60$ per cent with respect to the reference run. Therefore, the stability of the emission-weighted metallicity is due to the competing effects of a more clumpy distribution of metals and of a decrease of the overall ICM metal budget.

The maps of Fig. 3 also illustrate the role of gasdynamical effects in redistributing highly enriched gas. Merging clumps within the cluster virial region leave behind them overenriched tails of stripped gas, which is tempting to explain as due to ram-pressure stripping. However, a significant contribution could be well provided by viscous stripping. Since the SPH scheme is known to be generally characterized by a large numerical viscosity, this may induce an excess of gas stripping from merging haloes. Sijacki & Springel (2006b) showed that the effect of including the Spitzer–Braginskii viscosity in the SPH, on the top of the numerical viscosity, is indeed that of further increasing gas stripping from merging haloes. On the other hand, Dolag et al. (2005) discussed an SPH scheme of reduced viscosity. In this case, the increase of the ‘turbulent’ stochastic gas motions should provide a more efficient diffusion of metals from star-forming regions (Rebusco et al. 2005), while making viscous stripping less efficient. Although it is beyond the aim of this paper to carry out an accurate analysis of the effect of viscosity on the pattern of the ICM enrichment, there is no doubt that this aspect deserves an accurate in-depth investigation.

### 3.3 The Sn Ia rate

The supernova rate represents a useful diagnostic to link the observed evolution of the ICM metallicity to the past history of SF and to shed light on the relative contribution of Sn Ia and Sn II in releasing metals. In particular, the ratio between the Sn rate and the $B$-band luminosity, the so-called SnU$_B$, can be used to distinguish the relative contribution of Sn Ia, which form in binary systems of stars with masses in the range $(0.8–8) \, M_\odot$ and the short-living massive stars that contribute substantially to the $B$-band luminosity of galaxies. In this section, we present a comparison between the results of our simulated clusters and observational data of SnU$_B$ in galaxy clusters from Gal-Yam, Maoz & Sharon (2002), Mannucci et al. (2008) and Sharon et al. (2007).

The simulation analysis finalized to compute the SnU$_B$ proceeds as follows. For each star particle, we know its formation redshift and metallicity. Given the IMF and the lifetime function, this allows us to compute the rate of Sn Ia exploding in each such particle. Furthermore, using the spectrophotometric GALAXEV code (Bruzual & Charlot 2003), we also compute the $B$-band luminosity of each star particle, which is treated as a Single Stellar Population (SSP). Once Sn Ia rates and luminosities are computed for all the star particles, we run the SKID substructure-finding algorithm (Stadel 2001) on their distribution to identify galaxies as gravitationally bound groups of stars. All the star particles not bound to galaxies take part of the intracluster diffuse stellar component (e.g. Murante et al. 2007). We refer to Saro et al. (2006) for a detailed description of the procedure to identify galaxies and assign broad-band luminosities to them.

In order to reproduce the observational procedure, we compute the SnU$_B$ values by also including the contribution of the Sn Ia arising from diffuse stars, while the $B$-band luminosity is computed by including only the contribution of the identified galaxies.

In the left-hand panel of Fig. 4, we compare the SnU$_B$ values from the simulations with different IMFs with observational data. In performing this comparison, one potential ambiguity arises from the definition of the extraction radius, within which luminosities and Sn Ia rates are measured in observations, since different authors use different aperture radii. To address this issue, we computed SnU$_B$ in the simulations within $R_{\text{vir}}$ and verified that the results are left unchanged when using instead $R_{500}$.

Observational data show a declining trend at low redshift. This is generally interpreted as due to the quenching of recent SF, which causes the number of Sn Ia per unit $B$-band luminosity to decrease after the typical lifetime of the Sn Ia progenitor has elapsed. On the other hand, our simulations predict a rather flat evolution of the SnU$_B$, independently of the choice for the IMF, which is the consequence of the excess of low-redshift SF. The runs based on the Sal and Kr IMF produce very similar results. Although the Kr IMF produces a higher rate of Sn Ia, due to its higher amplitude in the $1–8 \, M_\odot$ stellar mass range, this is compensated by the higher values of $L_\odot$. These two IMFs both agree with the observational data at $z \gtrsim 0.3$ within the large observational uncertainties, while they overpredict the rates measured for local clusters. Although the excess of recent SF in the central regions of our simulated clusters...
We have presented results from cosmological SPH hydrodynamical simulations of galaxy clusters with the purpose of characterizing the evolution of the chemical enrichment of the ICM out to redshift $z \approx 1$. The simulations have been performed with a version of the \textsc{gadget}-2 code (Springel 2005), which includes a detailed model of chemical evolution T07. Our simulations have been performed with the purpose of investigating the effect of changing the chemical evolution model and the effect of suppressing SF at $z < 1$. The main results of our analysis can be summarized as follows.

(i) The Iron abundance profiles provided by simulations based on the Salpeter (1955) IMF are in reasonable agreement with the results from \textit{Chandra} observations of nearby clusters by Vikhlinin et al. (2005) at $R \lesssim 0.2 R_{500}$. Simulations based on the IMFs by Kroupa (2001) and Arimoto & Yoshii (1987) both predict too high normalization for these profiles. However, reducing the fraction of stars assumed to belong to binary systems suppresses the enrichment level, thus alleviating the disagreement of a top-heavy IMF with the observed $Z_F$ profiles. Our simulations always predict negative metallicity gradients extending out to $R_{500}$ and beyond, possibly in disagreement with XMM–\textit{Newton} measurements of the Iron metal abundance at relatively large radii (Snowden et al. 2008).

(ii) All our simulations predict a positive evolution of the central Iron abundance, comparable to that observed by Balestra et al. (2007) (see also Maughan et al. 2008). Using a Salpeter IMF also provide an enrichment consistent with observations, while the Kroupa and Arimoto-Yoshii IMFs overpredict the enrichment level at all redshifts. Again, this disagreement can be alleviated by decreasing the fraction of binary systems. It is worth reminding that the observed evolution of the Iron abundance is traced by using a mix of cool- and non-cool-core clusters, while our simulated clusters are all dynamically relaxed. Clearly, a fully self-consistent comparison would require simulating a representative population of clusters, having a variety of morphologies and dynamical states.

(iii) Stopping cooling and SF at $z = 1$ (CS run) have the effect of producing a too strong positive evolution of the emission-weighted metallicity. Indeed, in the absence of SF all the metals released at $z < 1$ by long-living stars are no longer locked back in the stellar phase. As a result, metallicity is enhanced inside high-density haloes and in the central cluster region. The clumpy metal distribution boosts the emission-weighted abundance estimate. This leads to the somewhat counter-intuitive conclusion that suppressing recent SF has the effect of enhancing the positive evolution of the ICM metallicity.

(iv) A comparison of the Sn Ia rate per unit $B$-band luminosity, $\text{SnU}_B$, shows that our simulations are generally not able to reproduce the observed declining trend at low redshift. This result is explained by the excess of recent SF taking place in the

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Comparison between the observed and the simulated evolution of the Sn Ia rate per unit $B$-band luminosity ($\text{SnU}_B$). In both the panels, filled symbols with errorbars refer to observational data from Mannucci et al. (2008) (triangle), Gal-Yam et al. (2002) (squares) and Sharon et al. (2007) (pentagon). Left-hand panel: the effect of changing the IMF. The open squares are for the Salpeter (1955) IMF, the open triangles are for the top-heavy IMF by Arimoto & Yoshii (1987) and the open circles are for the IMF by Kroupa (2001). For the Sal IMF, the shaded area shows the range scatter evaluated over the four simulated clusters, while for the other two IMFs only the result for the g51 cluster is shown. Right-hand panel: the effect of suppressing low-redshift SF and changing the binary fraction on the $\text{SnU}_B$ evolution of the g51 cluster. The open squares and the open circles are for the reference run with Salpeter (1955) IMF and for the same run with cooling and SF stopped at $z = 1$ (CS run), respectively. The filled and the open triangles are for the runs with Arimoto & Yoshii (1987) IMF, using $A = 0.1$ and 0.05 for the fraction of binary stars, respectively.

produces too blue BCGs (Saro et al. 2006), the large number of Sn Ia associated to this SF overcompensate the excess of blue light.

As for the simulation with the $AY$ IMF, it predicts an even higher $\text{SnU}_B$ at low redshift. As shown in the right-hand panel of Fig. 4, decreasing the binary fraction to $A = 0.05$ decreases the value of the $\text{SnU}_B$ by more than a factor of 2. While this helps in reconciling the simulation results with the low-redshift data, it introduces a tension with the data at $z \sim 1$.

Truncating SF at $z = 1$ (right-hand panel of Fig. 4) has the desired effect of decreasing the value of $\text{SnU}_B$ below $z = 0.5$. Quite interesting, for $0.5 \lesssim z \lesssim 1$ the decreasing trend of the Sn Ia rate is compensated by the corresponding decrease of the $B$-band luminosity, while it is only at $z > 0.5$ that the decrease of the Sn Ia rate takes over causes the decrease of the $\text{SnU}_B$ values.

4 CONCLUSIONS
central regions of galaxy clusters. Indeed, excising SF at $z < 1$ produces an evolution of $SnU_\text{a}$ which is consistent with the observed one.

Cluster simulations which only include stellar feedback, like those presented here, are well known to be at variance with a number of observations, such as the temperature profiles in the cool-core regions and a large excess of recent SF in the BCG. Our prescription to quench recent SF is admittedly oversimplified. A more realistic treatment would require introducing energy feedback from gas accretion on to supermassive black holes, which self-consistently follow the hierarchical build-up of the cluster (e.g. Sijacki & Springel 2006a). Still, our results highlight that the positive evolution of the metal abundance in the central regions of simulated clusters cannot be simply interpreted as a consequence of an excess of low-redshift SF. In fact, the evolution of the metallicity pattern is driven by the combined action of the gasdynamical processes, which redistribute already enriched gas, and of SF, which acts both as a source and as a sink of metals. While hydrodynamical simulations probably provide the most complete interpretative framework for observations of the history of the ICM enrichment, they have still to improve in the numerical accuracy for the description of relevant physical processes. There is no doubt that the ever increasing supercomputing power and efficiency of simulation codes should be paralleled by a comparable advance in the reliability of the numerical description of the relevant astrophysical and gasdynamical processes. Only in this way, simulations will become the standard tool to link ICM observations to the global picture of cosmic structure formation.

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