On the evolution of the Fe abundance and of the Type Ia supernova rate in clusters of galaxies

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ABSTRACT

The study of the Fe abundance in the intracluster medium (ICM) provides strong constraints on the integrated star formation history and supernova rate of the cluster galaxies, as well as on the ICM enrichment mechanisms. In this Letter, using chemical evolution models for galaxies of different morphological types, we study the evolution of the Fe content of clusters of galaxies. We assume that the ICM Fe enrichment occurs by means of galactic winds arising from elliptical galaxies and from gas stripped from the progenitors of S0 galaxies via external mechanisms, due to the interaction of the interstellar medium with the ICM. The Fe-rich gas ejected by ellipticals accounts for the X_{Fe,ICM} values observed at \( z > 0.5 \), whereas the gas stripped from the progenitors of the S0 galaxies accounts for the increase of X_{Fe,ICM} observed at \( z < 0.5 \). We test two different scenarios for Type Ia supernova (SN) progenitors and we model the Type Ia SN rate observed in clusters, finding a good agreement between our predictions and the available observations.

Key words: galaxies: abundances – galaxies: clusters: general – galaxies: evolution – galaxies: fundamental parameters – intergalactic medium.

1 INTRODUCTION

The hot intracluster gas contains a large amount of highly ionized heavy elements, which can be detected by means of X-ray observations. Among these elements, Fe is the easiest to detect in the X-rays and its abundance in the intracluster medium (ICM) provides strong constraints on the integrated star formation history and supernova rate (SNR) of the cluster galaxies (Matteucci & Vettolani 1988; Renzini 1997). In the last few years, thanks to the deep X-ray observations of the Chandra and XMM–Newton satellites, it has been possible to study the evolution of the intracluster Fe abundance out to redshift \( z \sim 1.3 \), corresponding to a lookback time of \( \sim 9 \) Gyr. Tozzi et al. (2003), found that the average Fe abundance of the ICM at \( z \sim 1 \) is comparable with the local value \( X_{Fe} \sim 0.45X_{Fe,\odot} \), without detecting significant evidence of evolution from a sample of 18 clusters at \( 0.3 < z < 1.2 \). In a more recent paper, Balestra et al. (2007) extended the analysis of Tozzi et al. (2003) to a sample of 56 clusters with redshifts \( 0.3 \leq z \leq 1.3 \). For \( z > 0.5 \) they found a constant average Fe abundance \( X_{Fe} \sim 0.38X_{Fe,\odot} \), whereas for \( z < 0.5 \) they found significant evidence of evolution, parametrized by a power law of \( X_{Fe}(z) \propto (1+z)^{-1.28} \) and implying that at the present time the average ICM Fe abundance is a factor of 2 larger than at \( z \sim 0.5 \) in the central regions, at radii \( R \leq 0.3R_{500} \).

The main producers of Fe in clusters are Type Ia supernovae (SNe; Matteucci & Vettolani 1988; Renzini et al. 1993; Pipino et al. 2002; Ettori 2005; Loewenstein 2006). Two possible mechanisms have been proposed to explain the ICM Fe enrichment, i.e. SN-driven galactic winds (Renzini et al. 1993; Pipino et al. 2002) and enrichment processes linked to environmental effects, such as ram pressure stripping, tidal stripping or viscous stripping of Fe-rich gas from cluster galaxies (Gunn & Gott 1972; Domainko et al. 2006, see also Cora et al., in preparation). In this Letter, by means of chemical evolution models for galaxies of different morphological types, we study the evolution of the Fe content of clusters of galaxies. We start from two main observables, i.e. the Fe abundance and the Type Ia SN rate, and test different models which can account for the observed evolution of both quantities. Our aim is to determine which galaxies are the main producers responsible for the observed evolution of the Fe content of the ICM, and what are the relative roles of galactic winds and environmental effects in this process. The plan of this Letter is as follows. In Section 2 we describe the chemical evolution models. In Section 3 we present our results and their comparison with the observed abundances. Finally, in Section 4, some conclusions are drawn.

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2 THE CHEMICAL EVOLUTION MODELS

In this Letter we use two chemical evolution models, one describing an elliptical galaxy, the other describing an S0 galaxy. We assume that these two kinds of objects are responsible for the chemical enrichment of the ICM. This is supported by the fact that in local clusters, the intracluster Fe mass is correlated only with the luminosity of elliptical and S0 galaxies (Arnaud et al. 1992). The common features between these two models are (i) the stellar nucleosynthesis prescriptions and (ii) the adopted stellar initial mass function (IMF).

(i) For massive stars, we adopt the Fe yield of Woosley & Weaver (1995) for a solar chemical composition, which has proven to be the best choice for the Milky Way (François et al. 2004). For the Type Ia SNe, we adopt the Fe yields of Iwamoto et al. (1999).

(ii) For both models, we assume a Salpeter (1955) IMF constant in time.

A detailed description of the chemical evolution equations used in this work can be found in Matteucci & Greggio (1986). For the chemical evolution of ellipticals we adopt the model of Pipino et al. (2002), where we direct the reader for details. The elliptical galaxy forms by means of a rapid collapse of pristine gas where star formation occurs at a very high rate ($\sim \text{1000 } M_\odot \text{ yr}^{-1}$). After a time-scale which depends on its mass, the galaxy develops a galactic wind due to the energy deposited by SNe into the interstellar medium (ISM). After the onset of the wind, no star formation (SF) is assumed to take place. The wind develops as soon as the thermal energy of the ISM exceeds its gravitational binding energy. The thermal energy is evaluated by taking into account feedback from SNe and stellar winds. The binding energy is calculated considering a massive, diffuse dark matter halo around the galaxy. The main parameters of this model are the baryonic mass $M_{\text{bary}} = 10^9 M_\odot$, the SF efficiency $\nu_E = 11 \text{ Gyr}^{-1}$, and an effective radius $R_{\text{eff}} = 3 \text{ kpc}$ (see table 1 of Pipino et al. 2002).

We assume that S0 galaxies originate from disc galaxies, in which at a late stage SF stops owing to massive gas loss by means of some external mechanism, represented by interactions with the ICM, collisions or tidal stripping (Larson, Tinsley & Caldwell 1980; Boselli & Gavazzi 2006). We assume that, as soon as the SF stops, the galaxy starts to lose enriched gas at a constant rate. At the final stage of its evolution, the S0 galaxy has ejected all of its gas and consists only of a stellar disc.

This scenario is supported by a large set of observations. The first is the Butcher & Oemler (1978) effect, i.e. the increase with redshift of the fraction of blue cluster galaxies, which seems strictly connected to the decrease of the fraction of cluster S0 galaxies with redshift (Dressler et al. 1997; Poggianti et al. 1999; van Dokkum et al. 2000; Fasano et al. 2000; Tran et al. 2005). Another indication comes from the presence of anemic spirals in clusters, which are likely to represent the missing link between cluster gas-rich discs and S0 galaxies (van den Bergh 1976; Elmegreen et al. 2002; Boselli et al. 2006). The fact that the S0 fraction is at a maximum in the cluster cores (Dressler et al. 1997; Helsdon & Ponman 2003) tells us that environmental effects, rather than internal effects, are the main drivers for the formation of S0s.

To calculate the enrichment due to the gas loss accompanying the transition from gas-rich discs to S0s, we use the two infall model by Chiappini, Matteucci & Gratton (1997). In this model, the first infall creates the halo and the thick disc, on a time-scale of $\sim 1$ Gyr. The second infall gives rise to the thin disc. The spiral disc is approximated by several independent rings, 2 kpc wide, without exchange of matter between them. The time-scale for the disc formation is assumed to increase with the galactocentric distance ($\tau = 8$ Gyr at the solar circle), thus producing an ‘inside-out’ scenario for the disc formation. The main parameters of this model are the time-scale for the inner halo formation ($\tau_{\text{HL}} = 1$ Gyr), the thin disc time-scale $\tau_D$, which is a function of the galactic radius, and the total surface mass density profile at the present time, $\sigma(R)$, as a function of the radius $R$, for which we use an exponential law $\sigma(R) \propto e^{-R/|R_0|}$, where $R_0 = 3.5$ kpc (Romano et al. 2000), in analogy with the Milky Way. The last parameter is the SF efficiency $\nu_{\text{SF}} = 1 \text{ Gyr}^{-1}$. In the disc, the time at which the SF is assumed to stop is determined in order to reproduce the observed Fe abundance in the ICM (Section 3.1). With this choice of the parameters, for the disc of an average S0 galaxy we predict a present-day stellar mass of $M_{*,\text{S0}} = 4 \times 10^9 M_\odot$.

We adopt a Lambda cold dark matter cosmology ($\Lambda$CDM, $\Omega_0 = 0.3, \Omega_{\Lambda} = 0.7$) and $h = 0.7$. For all galaxies, we assume that the star formation started at redshift $z = 10$, corresponding to a lookback time of 13 Gyr. The spectral evolution of all the galactic morphological types has been calculated by means of the spectrophotometric code by Jimenez et al. (2004). By means of this code, we have computed the present-day colours, finding for S0s $(B-V) = 0.96-0.98$ and $(U-B) = 0.47-0.5$, in excellent agreement with the available observational values (Schweizer & Seitzer 1992).

2.1 The Type Ia SN rate

We assume that Type Ia SNe originate from the explosion of a C/O white dwarf (WD) in a close binary system, where the companion is either a red giant or a main-sequence star. This is the single-degenerate (SD) model (Whelan & Iben 1973). Here, for the Type Ia SN rate, we study the two different formulations discussed in Matteucci et al. (2006, hereinafter M06). In the first formulation, (Greggio & Renzini 1983; Matteucci & Recchi 2001, hereinafter MR01), the Type Ia SN rate is given by

$$ R_{\text{IA}}(t) = A_{\text{IA}} \int_{M_{\text{min}}}^{M_{\text{max}}} \phi(M_B) \left[ \int_{m_M}^{0.5} f(\mu) \psi(t - \tau_{M_B}) d\mu \right] dM_B $$

where $A_{\text{IA}}$ represents the fraction of binary systems with total mass $M_B = M_B/M_\odot \leq M_{\text{max}}$ which produce Type Ia SNe. The quantity $\mu = M_B/M_\odot$ is the ratio between the secondary component of the binary system (i.e. the originally less massive one) and the total mass of the system $M_B$, and $f(\mu)$ is the distribution function of this ratio. Statistical studies (see MR01) indicate that mass ratios close to 0.5 are preferred, so the formula

$$ f(\mu) = 2^{1+\beta}(1 + \beta)\mu^{\beta} $$

is commonly adopted, with $\beta = 2$ (Matteucci & Recchi 2001). $\tau_{M_B}$ is the lifetime of the secondary star in the system, which determines the time-scale for the explosion. The assumed value of $A_{\text{IA}}$ is fixed by reproducing the present-time observed rate (Matteucci et al. 2003, M06). For the masses $M_{\text{min}}$ and $M_{\text{max}}$, we use the values $3 M_\odot$ and $16 M_\odot$, respectively (Greggio & Renzini 1983).

The second formulation for the Type Ia SN rate is based on the recent results by Mannucci, Della Valle & Panagia (2006, hereafter MVP06) which, on the basis of the relation between the Type Ia SN rate and the colour of the parent galaxies, their radio power as measured by Della Valle et al. (2005) and cosmic age, concluded that there are two populations of progenitors of Type Ia SNe. According to these results, the above observations can be accounted for if half of the SNe Ia explode within $10^7$ yr after the formation of their progenitors, while the rest explode during a wide period of time.
extending up to 10 Gyr. Following Greggio (2005), in this new formulation, dubbed as MVP06, the Type Ia SN rate is
\[ R_{\text{IA}}(t) = k_\nu \int_{\tau_{\text{in}}}^{\tau_{\text{in}}} \psi(t - \tau) DT D(t) \tau, \]
where \( k_\nu \) is the number of stars per unit mass in a stellar generation and contains the IMF. The function \( DT D(t) \) is the delay time distribution given in equations (7) and (8) of M06. A more detailed description of the two different formulations used to model the Type Ia SN rate, as well as their effect on the chemical evolution of spirals, ellipticals and irregular galaxies, can be found in M06.

3 RESULTS

3.1 The evolution of the Fe abundance in the ICM

We assume that, immediately after the Fe ejection into the ICM, the Fe mass is distributed homogeneously, i.e. we assume that the ICM is well mixed. We estimate the ICM abundance by evaluating, at each redshift \( z \), the comoving density of the Fe ejected by ellipticals and S0 galaxies \( \rho_{\text{Fe,ICM}}(z) \) and dividing this number by the comoving density of hot gas in clusters of galaxies. Following the approach of (Calura & Matteucci 2003, 2004), to obtain \( \rho_{\text{Fe,ICM}}(z) \) we use the present-day cluster \( B \) luminosity density (LD), which can be calculated as
\[ \rho_{\text{B}}(0) = \frac{\rho_{\text{B}}(M/L_B)_{\odot}}{2.1 \times 10^{-4} \text{ M}_\odot \text{ Mpc}^{-3}}, \]
where we have used the total cluster mass density \( \rho_{\text{cl}} = 1.6 \times 10^{13} \text{ M}_\odot \text{ Mpc}^{-3} \) (Fukugita & Peebles 2004, hereinafter FP04; Reiprich & Böhringer 2002) and the cluster gravitational mass-to-light ratio \( (M/L_B)_{\odot} = 300 \text{ M}_\odot \text{ L}_\odot^{-1} \) (Fukugita, Hogan & Peebles 1998, hereinafter FHP98; Loewenstein 2004). The number density of luminous galaxies in clusters can be calculated as
\[ n_{\text{gal,cl}} \frac{L_{\text{B},cl}}{L_{\text{B}}} = 2.1 \times 10^{-4} \text{ Mpc}^{-3}, \]
where we have used the value \( L_{\text{B},cl} = 2.6 \times 10^{10} \text{ L}_\odot \) for the characteristic luminosity of local clusters (Beijersbergen et al. 2002). If \( M_{\text{Fe,E}}(z) \) and \( M_{\text{Fe,S0}}(z) \) are the cumulative masses of Fe ejected into the ICM at redshift \( z \) by a typical elliptical and a typical S0, respectively, the comoving density of the Fe in the ICM is
\[ \rho_{\text{Fe,ICM}}(z) = n_{\text{gal,cl}} \frac{L_{\text{B},cl}}{L_{\text{B}}} \left[ f_E M_{\text{Fe,E}}(z) + f_{S0} M_{\text{Fe,S0}}(z) \right]. \]

The quantities \( f_E \) and \( f_{S0} \) are the fractions of ellipticals and S0 galaxies in clusters, respectively. We assume that the fraction of ellipticals does not vary with redshift. This is equivalent to neglecting the merging of the galaxies across the redshift range discussed in this Letter. The validity of this approximation has been widely tested by (Calura & Matteucci 2003, 2006a,b) and Calura, Matteucci & Menci (2004). At \( z = 0.5 \), we assume that a fraction \( f_{S0} \) of all the cluster galaxies starts transforming from blue discs into S0s.

The ICM Fe abundances observed by Balestra et al. (2007) are determined considering only the innermost cluster regions, i.e. within \( r \leq (0.15-0.3)R_{\text{vir}} \), where \( R_{\text{vir}} \) is the virial radius. To compare our predictions with the data by Balestra et al. (2007), we need to consider the ICM mass density within the same cluster regions as the ones explored by these authors. For simplicity, we assume that all the Fe ejected by luminous E and S0 galaxies in the ICM is contained within \( 0.3R_{\text{vir}} \). This is expected on the basis of the highly concentrated spatial distribution of bright galaxies in clusters (Biviano & Salucci 2006). In the local Universe, the total ICM mass density is \( \rho_{\text{ICM}} = 2.45 \times 10^{-3} \text{ M}_\odot \text{ Mpc}^{-3} \) (FP04). We assume that this quantity is constant across the redshift range \( 0 \leq z \leq 1.5 \). By assuming for the ICM mass density profile the beta profile \( D_{\text{ICM}}(r) \propto \left[ 1 + (r/r_c)^2 \right]^{-1.5} \), with \( r_c = 0.625 \) and \( r_c = 0.06R_{\text{vir}} \) (Cavaliere & Fusco-Femiano 1978; Biviano & Salucci 2006), the fractional ICM mass within \( \sim 0.3R_{\text{vir}} \) is \( F_{\text{ICM,0.3R}_{\text{vir}}} \simeq 0.2 \). The ICM mass density within \( 0.3 R_{\text{vir}} \) is simply
\[ \rho_{\text{ICM,0.3R}_{\text{vir}}} = F_{\text{ICM,0.3R}_{\text{vir}}} \rho_{\text{ICM}} = 4.9 \times 10^{-7} \text{ M}_\odot \text{ Mpc}^{-3}. \]
At this point, we can calculate the Fe abundance in the ICM as a function of redshift, as
\[ X_{\text{Fe,ICM}}(z) = \frac{F_{\text{ICM,0.3R}_{\text{vir}}}}{\rho_{\text{ICM}}(z)}. \]

In Fig. 1, we show the observed and predicted evolution of the Fe abundance in the ICM, calculated with the two different MR01 (left-hand panel) and MVP06 (right-hand panel) formulations for the Type Ia SN rate. In Fig. 1, the observational values for the Fe abundances are from Balestra et al. (2007), rescaled by a factor of 1.5 owing to the meteoritic value by Anders & Grevesse (1989). The Fe enrichment of the ICM at redshift \( z > 0.5 \) can be explained as due entirely to the galactic winds in ellipticals. We account for the longer delay times of the Fe abundance profile \( z > 0.5 \) by a typical elliptical and a typical S0, respectively, the comoving density of the Fe in the ICM is
\[ \rho_{\text{ICM,0.3R}_{\text{vir}}} \simeq 0.2 \times 10^{-7} \text{ M}_\odot \text{ Mpc}^{-3}. \]
At this point, we can calculate the Fe abundance in the ICM as a function of redshift, as
\[ X_{\text{Fe,ICM}}(z) = \frac{F_{\text{ICM,0.3R}_{\text{vir}}}}{\rho_{\text{ICM,0.3R}_{\text{vir}}}}. \]

2 Assuming for the ICM Fe abundance profile the one found by De Grandi et al. (2004) for cool core clusters, which represent at least 2/3 of local clusters, we compute that the Fe mass within \( 0.3R_{\text{vir}} \) is 60 per cent of the total. However, we stress that in this paper we are mainly interested in reproducing the trend of the Fe abundance in the ICM with redshift, rather than the exact value of the total Fe ICM abundance.
pressure stripping is more efficient as a gas ejection mechanism than galactic winds in the redshift interval between 1 and 0, with mass-loss rate values between 0.4 and $\sim 10 M_\odot$ yr$^{-1}$, consistent with our estimates.

### 3.2 The evolution of the Type Ia SN rate in clusters

In Fig. 2, we show the predicted evolution of the Type Ia SN rate density ($\rho_{SNR}$) $\rho_{SNR,i}$, expressed in $\delta^{-1}$ Mpc$^{-3}$ yr$^{-1}$, with $\delta$ being the cluster baryon overdensity with respect to the field (Loewenstein 2006), in the case of the two Type Ia SN formulations described in Section 2.1. In this case, we show the predicted Type Ia SN rates for three types of galaxies, i.e. E, S0 and spirals (Sp). For spiral galaxies, we use the model described in Calura & Matteucci (2006b), i.e. the two-infall model with a Salpeter IMF. For E, S0 and Sp galaxies, the cluster Ia SNRD is given by

$$\rho_{SNR,i}(z) = \rho_B(z) \frac{R_{SN,i}}{100} \frac{L_B}{10^{10}} f_\delta \delta^{-1}. \quad (9)$$

(see Calura & Matteucci 2006b), where $k = E, S0, Sp$, and $\rho_B(z)$ is the field $B$-band LD. For the total field LD, we assume a local value of $\rho_B(0) = 1.3 \times 10^3 L_\odot$ Mpc$^{-3}$ and we assume a redshift dependency $\rho_B(z) = \rho_B(0) (1 + z)^{1.9}$ (Dahlen et al. 2004). $R_{SN,i}$ and $f_\delta$ are the Type Ia SN rate (expressed in SNu$^3$) and the morphological fraction for the galaxy of the $k$th morphological type, respectively. In Fig. 2, the predicted SN rates are compared with the observations by Gal-Yam, Maoz & Sharon (2002) and Sharon et al. (2007). Here, the transformation from the Type Ia SN rate expressed in SNu, $R_{SN,i}$, as presented in table 7 of Gal-Yam et al. (2002) and table 5 of Sharon et al. (2007), to $\rho_{SNR,i}$ is performed according to

$$\rho_{SNR,i} = \rho_B \frac{R_{SN,i}}{100} \frac{L_B}{10^{10}} \delta^{-1}. \quad (10)$$

In both panels of Fig. 2, we note that at redshift $z < 1.5$, the cluster SNRD is dominated by S0 galaxies.

With both MR01 and MVP06 formulations, the predicted total cluster Ia SNRs are in very good agreement with the available observations. As can be seen in Fig. 2, the main differences in the Type Ia SNR predicted in the MR01 and MVP06 formulations concern the earliest phases of galactic evolution, i.e. at redshifts $z < 0.5$. In both panels of Fig. 2, we note that at redshift $z < 1.5$, the cluster SNRD is dominated by S0 galaxies.

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In principle, observations of Type Ia SNR as a function of the morphological type at these redshifts could allow us to disentangle between these two formulations. A discussion of the Type Ia SN rate in clusters adopting the Mannucci et al. (2005) formulation can be found in Scannapieco & Bildsten (2005).

4 CONCLUSIONS

In this Letter we have studied the evolution of the Fe content of clusters of galaxies, using chemical evolution models for galaxies of different morphological types. We have assumed that the Fe ICM enrichment is due to elliptical galaxies, ejecting their gas via galactic winds, and to S0 galaxies, which lose their ISM by means of external mechanisms, such as ram pressure stripping and viscous stripping (Boselli & Gavazzi 2006). Our results indicate that the ICM Fe abundance observed at \( z > 0.5 \) can be explained thanks to the Fe-rich gas ejected by cluster ellipticals through SN-driven galactic winds. The increase of the ICM Fe abundance as observed by Balestra et al. (2007) at \( 0 \leq z \leq 0.5 \) can be explained by stripping of Fe-rich ISM from the progenitors of S0 galaxies in this redshift interval. For S0, we predict a stripping rate of \( \sim 2 \text{M}_\odot \text{yr}^{-1} \), consistent with the ram pressure stripping rates achieved in numerical simulations (Schindler et al. 2005). The observed \( X_{\text{Fe, ICM}} \) are well reproduced assuming \( E+S0 \) cluster fractions of \( 0.81-0.96 \), in excellent agreement with the available observations for the central regions of galaxy clusters. Beside the observed evolution of \( X_{\text{Fe, ICM}} \), our picture is consistent with the observed evolution of the Type Ia SN rate density in clusters. We model the cluster Type Ia SN rate according to two different scenarios of SNe Ia progenitors, by adopting the MR01 and MVP06 formulations, and we compare our predictions with the available observations. In both scenarios, the cluster Type Ia SN rate is reproduced with very good accuracy. However, the present data do not allow us to establish which is the best scenario for Type Ia SN rate in clusters adopting the Mannucci et al. (2005) formulation.

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