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The metal enrichment of elliptical galaxies in hierarchical galaxy formation models

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ABSTRACT

We investigate the metal enrichment of elliptical galaxies in the framework of hierarchical models of galaxy formation. The semi-analytical model we use, which has been used to study the metal enrichment of the intracluster medium (ICM) by Nagashima et al., includes the effects of flows of gas and metals both into and out of galaxies and the processes of metal enrichment due to both type Ia and type II supernovae. We adopt a solar neighbourhood initial mass function (IMF) for star formation in discs, but consider models in which starbursts have either a solar neighbourhood IMF or a top-heavy IMF. We find that the α-element abundance in ellipticals is consistent with observed values only if the top-heavy IMF is used. This result is consistent with our previous study on the metal enrichment of the ICM. We also discuss the abundance ratio of α elements to iron as a function of velocity dispersion and metallicity. We find that models with a top-heavy IMF match the α/Fe ratios observed in typical L_* ellipticals, but none of the models reproduces the observed increase of α/Fe with velocity dispersion.

Key words: stars: luminosity function, mass function – galaxies: clusters: general – galaxies: formation – large-scale structure of Universe.

1 INTRODUCTION

The chemical abundances of elliptical galaxies have long been known to provide important constraints on theoretical models of their formation. The metallicities of the stellar populations in elliptical galaxies are estimated observationally from the strength of stellar absorption features in their integrated spectra. Such measurements indicated an increase of the overall metal abundance with galaxy luminosity and velocity dispersion (e.g. Faber 1973; Bender, Burstein & Faber 1993), and also an increase in the average Mg/Fe abundance ratio (e.g. O'Connell 1976; Worthey, Faber & Jesús González 1992; Jørgensen 1999), with the central regions of most bright ellipticals having above-solar total metallicities and Mg/Fe ratios (the so-called 'α-enhancement'). The detailed interpretation of line strengths in terms of chemical abundances is, however, complicated, due both to the non-solar abundance ratios and to the dependence of absorption-line strengths on both metallicity and age. Detailed stellar population synthesis models have been developed to relate measured absorption-line strengths to ages and metallicities; older models (e.g. Worthey 1994) assumed solar abundance ratios, but newer models (e.g. Trager et al. 2000b; Thomas, Maraston & Bender 2003) allow for non-solar ratios. None the less, there remain significant uncertainties in going from measured line strengths to abundances of different elements.

Most theoretical modelling of chemical abundances in ellipticals has been in the framework of the *monolithic collapse* or *single burst* model, in which all of the stars form at high redshift in a single burst of short duration, usually terminated by ejection of the remaining gas by a wind, following which the stars evolve passively (e.g. Larson 1975; Arimoto & Yoshii 1987). Subsequent works (e.g. Matteuccci 1994; Thomas, Greggio & Bender 1999) have shown that it is possible to explain the trends of both increasing total metallicity and increasing Mg/Fe ratio with galaxy mass within this framework, provided that the star formation time-scale of the initial burst (a free parameter) is chosen to have a suitable dependence on galaxy mass.

However, there is now overwhelming evidence that structure in the universe has been formed by hierarchical clustering of a dominant cold dark matter (CDM) component, and strong evidence that galaxy mergers played an important role in the formation of elliptical galaxies. Galaxy formation within this *hierarchical merger* framework has been studied extensively using semi-analytical models (e.g. White & Frenk 1991; Kauffmann, White & Guiderdoni 1993; Cole et al. 1994, 2000; Somerville & Primack 1999; Nagashima et al. 2001; Menci et al. 2002; Hatton et al. 2003). There have, however, been very few detailed studies of the chemical evolution of elliptical

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galaxies within this framework. Cole et al. (2000) and Nagashima & Yoshii (2004) computed the relation between total metallicity and luminosity for ellipticals, while Kauffmann & Charlot (1998) calculated the relation between Mg line strength and galaxy velocity dispersion, but these calculations all used the instantaneous recycling approximation for chemical evolution, with fixed solar abundance ratios built in. As a result, such models are unable to explain variations in abundance ratios such as Mg/Fe. Thomas (1999) and Thomas & Kauffmann (1999) calculated the separate evolution of [Fe/H] and [Mg/Fe], including both the prompt metal ejection by Type II supernovae (SNe II) and the long-delayed ejection by Type Ia supernovae (SNe Ia), based on star formation histories taken from a semi-analytical model. They found in their model that the average [Mg/Fe] actually decreased with increasing luminosity, in apparent conflict with observational data. However, they calculated chemical evolution using a *closed-box* model, which ignored the effects of galaxy mergers and the transport of metals into and out of galaxies by gas inflows and outflows, all of which form part of standard semi-analytical models.

In this paper we present the first calculations of chemical abundances in elliptical galaxies in a semi-analytical model which includes enrichment by both SNe Ia and SNe II within a fully consistent framework of hierarchical galaxy formation, i.e. including gas inflows and outflows and galaxy mergers. This enables us to investigate whether hierarchical merger models are able to reproduce the observed variations in the ratio, α/Fe, of α-elements to iron. We base our calculations on the semi-analytical model described in Baugh et al. (2005), which assumes that stars formed in bursts triggered by galaxy mergers have a top-heavy initial mass function (IMF), while stars formed quiescently in discs have a Kennicutt (1983) IMF, similar to the solar neighbourhood. The top-heavy IMF in bursts was introduced so that the model would fit the number counts of faint sub-mm galaxies. Nagashima et al. (2005) showed that this same model explained the observed abundances in the intracluster medium (ICM) in galaxy clusters, when enrichment by SNe Ia was included. In the present paper, we compare predictions from the same model with observed abundances of elliptical galaxies. Nagashima & Okamoto (2005) have already shown that a similar hierarchical model is able to explain the abundance patterns in disc galaxies like the Milky Way.

The general idea that some or all of the stars in elliptical galaxies may have formed with an IMF which was top-heavy relative to that in the solar neighbourhood is not a new one. Matteuccci (1994), Gibson & Matteucci (1997) and Thomas et al. (1999) all proposed a top-heavy IMF as one possible explanation for the abundance patterns observed in ellipticals. The model presented here is novel in that it is based within a fully consistent hierarchical framework, and in that the parameters of the top-heavy IMF and starbursts have been chosen in advance, independently of any metallicity constraints. We note that there is more direct evidence for a top-heavy IMF in bursts from observations of the starburst galaxy M82 (Tsuru et al. 1997; Smith & Gallagher 2001).

Thus, the purpose of this Letter is to investigate theoretical predictions for the metallicities of elliptical galaxies from the same hierarchical galaxy formation model as we used to study the enrichment of the ICM in Nagashima et al. (2005), and to make a preliminary comparison with observational data. In the next section we briefly summarize our model. We present the results from our model in Section 3 and our conclusions in Section 4. In the following, the cosmological parameters are fixed to be $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7, h \equiv H_0/100\,\mathrm{km\,s^{-1}\,Mpc^{-1}} = 0.7$, $\sigma_8 = 0.93$, and $\Omega_b = 0.04$.

2 MODEL

We adopt the same model as used in Nagashima et al. (2005), which is an extension of the GALFORM semi-analytical galaxy formation model (Cole et al. 2000; Baugh et al. 2005) to include both prompt metal enrichment by SNe II and delayed enrichment by SNe Ia. The model, which will be described in full in Lacey et al. (in preparation), includes the following physical processes: merging of dark haloes; radiative gas cooling; star formation; supernova (SN) feedback; mergers of galaxies due to dynamical friction; starbursts triggered by such mergers; and stellar population synthesis. It has been shown in our previous papers that this model reproduces both the observed sub-mm source counts, and the observed metal abundances and baryon fractions in the ICM, provided that a top-heavy IMF is adopted for starbursts. We assume a Kennicutt (1983) IMF for quiescent star formation in galaxy discs, which has slope $x = 0.4$ for $m < 1\,\mathrm{M_\odot}$ and $x = 1.5$ for $m > 1\,\mathrm{M_\odot}$. The top-heavy IMF has slope $x = 0$ between 0.15 and $120\,\mathrm{M_\odot}$ (where $x = 1.35$ for the Salpeter IMF).

As shown by Benson et al. (2003), the original GALFORM model (Cole et al. 2000), when used with currently estimated cosmlogical parameters, predicted an excessive number of very luminous galaxies at the present epoch. Nagashima et al. (2005) considered two alternative solutions to this problem: (a) a *superwind* model [similar to Benson et al. (2003)], in which SN feedback expels gas from haloes, the expelled gas later being recaptured once the halo grows up to a circular velocity $V_\mathrm{c} = V_\mathrm{recap} \equiv 600\ \mathrm{km\ s^{-1}}$; (b) a *conduction* model, in which the conductive heat flux from hot gas in the outer parts of massive haloes prevents gas from cooling in the centres of these haloes. Both models included a top-heavy IMF in bursts, and were consistent with metallicities in the ICM of clusters. We present results for both models in this paper. For comparison purposes, we also show results for a *superwind/Kennicutt* model, which is identical to our standard superwind model except that a Kennicutt IMF is used throughout.

We calculate the evolution of the abundances of different elements in the stars and gas using exactly the same prescription for chemical evolution as in Nagashima et al. (2005). The rates and chemical yields of SNe Ia and SNe II and gas restitution rates are computed consistently with the adopted IMFs based on Portinari, Chiosi & Bressan (1998) and Greggio & Renzini (1983). We compute a total metallicity [Z/H] and iron abundance [Fe/H] (both being expressed as logarithmic values relative to solar). For comparing with the observational data, we also compute an α-element abundance [α/H] which includes O, Mg and other elements which are assumed in observational analyses to vary in step with these – see Trager et al. (2000a) and Thomas et al. (2003) for details. The α-abundance is dominated in mass fraction by O. The α-elements dominate the total metallicity, so [Z/H] is close to [α/H].

For comparing with observational data, we also need to compute stellar velocity dispersions of elliptical galaxies in our model. We compute the radii of stellar spheroids formed in mergers using the method described in Cole et al. (2000), and we then compute the circular velocity V_{cS} at the half-mass radius of the spheroid including both its self-gravity and the gravity of its dark halo. We then estimate the 1D stellar velocity dispersion as $\sigma = V_{cS}/\sqrt{3}$.

3 RESULTS

Our predictions for the mean global stellar metallicities of ellipticals for the three different models we consider are shown in Figs 1 and 2. We select ellipticals in the model as galaxies with *B*-band bulge-to-total light ratios $(B/T)_B > 0.6$. The metallicities plotted for model galaxies are averages over all of the stars in the galaxy, weighted by the contribution of stars of different ages and metallicities to the V-band luminosity. This weighting is intended to mimic the measurement of metallicities from spectral features around 5000 Å.

We have compiled a set of observational data to compare with the models, by combining the samples of Trager et al. (2000a), Proctor & Sansom (2002), Proctor et al. (2004) and Thomas et al. (2005), and selecting ellipticals with measurement errors on [α/Fe] of less than 0.1 dex. This leaves us with about 140 ellipticals in a range of environments from groups to clusters, most of them with velocity dispersions in the range $100 \lesssim \sigma \lesssim 300\,\mathrm{km\,s^{-1}}$. (We note that a recent paper, Nelan et al. 2005, has reported very similar results to the above papers for much larger samples of 4097 red-sequence galaxies in 93 low-redshift galaxy clusters.) In the above papers, metallicities have been derived from measured absorption-line strengths (the Lick indices) using stellar population models, assuming that all of the stars in a galaxy have identical ages and metallicities. The metallicities and velocity dispersions have been estimated from spectra of the central regions of the galaxies. Since there are radial line-strength gradients in elliptical galaxies, the central values differ from the global average values. Based on the gradients measured by Wu et al. (2005), we estimate that the global total metallicities are typically lower by around 0.25 dex than the central values within 10 per cent of the effective radius. In contrast, the α/Fe ratio does not appear to show significant gradients (Mehlert et al. 2003). Therefore, in comparing observational data with models, we include downward shifts by 0.25 dex in the observed values of [α/H] and [Fe/H], to correct them to global values, but assume that the observed central values of [α/Fe] are equal to the global values.

The galaxies in the observational samples are selected in a heterogeneous way. In order to allow a fairer comparison between observations and models in Figs 1 and 2, we have plotted roughly the same number of model galaxies (∼140) as in the observational sample, randomly selected from a volume-limited model catalogue so as to match the distribution of velocity dispersion σ found in the observational sample. We note that the model reproduces the observed L_B–σ correlation, where L_B is the total B-band luminosity.

Fig. 1 shows [α/H], [Fe/H] and [α/Fe] plotted against velocity dispersion for the observational sample and for the three models we consider. The dashed boxes show the parameter region in which most of the observed elliptical galaxies are found, but in the panels showing the models, the boxes are plotted taking into account the

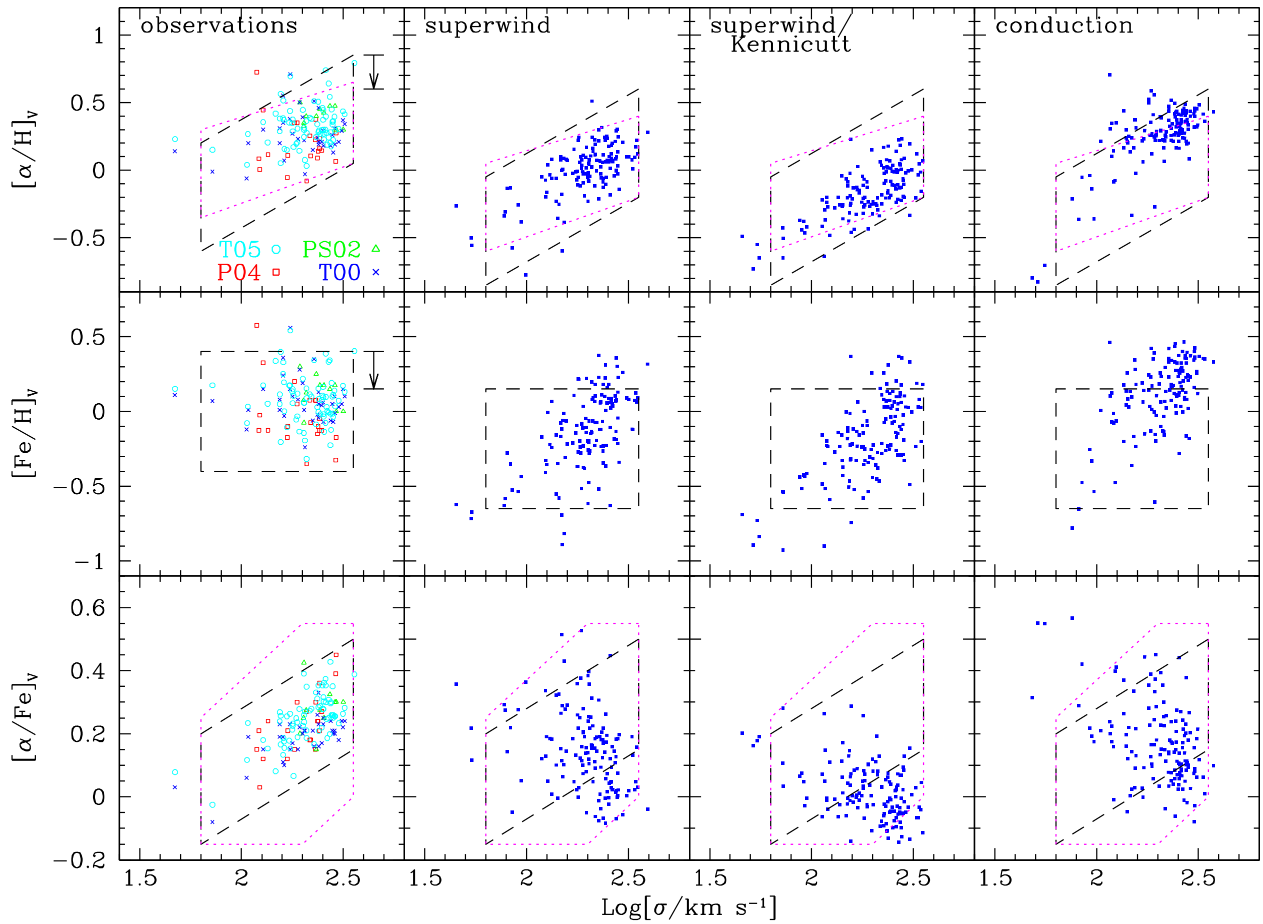

Figure 1. Abundances of α-elements, iron, and their ratio for stars in elliptical galaxies, plotted against velocity dispersion σ. Abundances are on a logarithmic scale, relative to solar. The left-hand column shows observational data (not corrected for metallicity gradients) as follows: Thomas et al. (2005, T05, *circles*), Proctor et al. (2004, P04, *squares*), Proctor & Sansom (2002, PS02, *triangles*), and Trager et al. (2000a, T00, *crosses*). The arrows show the estimated average corrections from central to global values, which are −0.25 dex for [α/H] and [Fe/H], and 0 for [α/Fe]. For reference, dashed boxes surrounding most of the observational data are repeated across each row of panels. In the right three columns, these boxes are shifted by the estimated central-to-global corrections. The other three columns show predictions for the three different models, as indicated. The model abundances are V-band luminosity-weighted averages for each galaxy. The dotted boxes indicate how the observational data shift if the correction to [α/Fe] proposed by Proctor et al. (2004) is adopted.

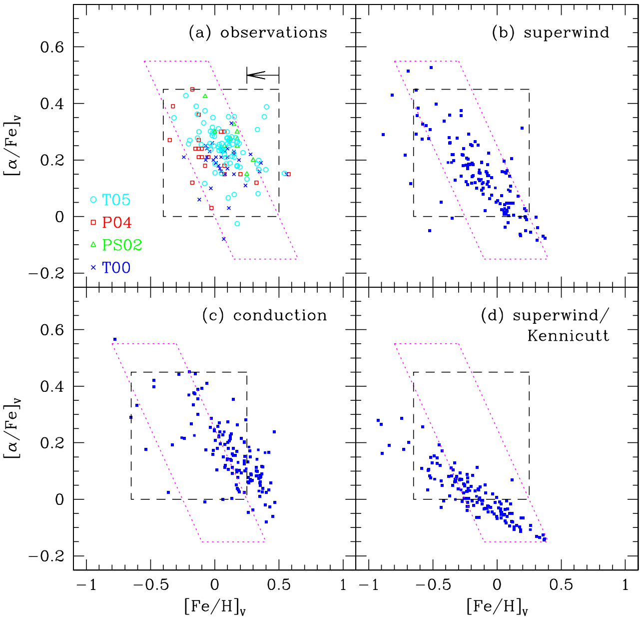

Figure 2. The α/Fe abundance ratio versus Fe-abundance for stars in elliptical galaxies. (a) Observational data, for the same galaxy samples as in Fig. 1. Panels (b), (c) and (d) show predictions for the three different models. For reference, dashed boxes surrounding most of the observational data are plotted in all panels. In the panels showing the models, these boxes are shifted by the estimated central-to-global correction for metallicity gradients. The dotted parallelogram indicates how the observational data shift if the correction to [α/Fe] proposed by Proctor et al. (2004) is adopted.

estimated correction from central to global metallicities. To allow a more quantitative comparison, we also give in Table 1 the median values and scatter for typical L_* ellipticals, with $\sigma \approx 200\,\mathrm{km\,s^{-1}}$. We note the following points.

(i) The observed ellipticals show a large scatter in both abundances ([α/H] and [Fe/H]) and in abundance ratios ([α/Fe]) at any value of σ, and this scatter is generally reproduced by the models.

(ii) All three models predict similar trends of increasing [α/H] with σ, which agree with the trend seen in the observations.

(iii) However, the overall normalization of [α/H] differs between the models. When we take metallicity gradients into account, the *superwind* model (with a top-heavy IMF in bursts) seems to be in best agreement with the observed [α/H] (see Table 1). The *superwind/Kennicutt* model, which assumes a solar neighbourhood IMF for all stars, but is otherwise identical to the *superwind* model, predicts [α/H] values that are too low by 0.2 dex. The *conduction* model, which also has a top-heavy IMF in bursts, but has less gas and

Table 1. Median of [α/H], [Fe/H] and [α/Fe] for galaxies with $150 \leqslant \sigma/\mathrm{km\,s^{-1}} \leqslant 250$. Values in the brackets represent the width between 25 and 75 per cent values of the distributions. For the observations, we show both the measured central values and the estimated global values. The model values are all global values.

model	[α/H]	[Fe/H]	[α/Fe]
observations (central)	0.29 (0.19)	0.06 (0.21)	0.23 (0.10)
observations (global)	0.04 (0.19)	−0.19 (0.21)	0.23 (0.10)
superwind	0.04 (0.17)	−0.18 (0.30)	0.21 (0.14)
superwind/Kennicutt	−0.16 (0.22)	−0.27 (0.32)	0.07 (0.10)
conduction	0.29 (0.16)	0.09 (0.28)	0.21 (0.16)

metals ejected from galaxies than in the *superwind* model, predicts [α/H] values too high by 0.2 dex.

(iv) The models all predict a trend of [Fe/H] increasing with σ, in disagreement with the observational data, which indicate a flat dependence.

(v) The *superwind* model predicts [Fe/H] for L_* galaxies in agreement with observations, when metallicity gradients are taken into account (see Table 1). The *superwind/Kennicutt* model predicts only slightly lower [Fe/H], showing that the top-heavy IMF in bursts affects the α-abundance more than the Fe-abundance. The *conduction* model predicts [Fe/H] too large by nearly 0.3 dex in L_* galaxies.

(vi) The trends for [α/Fe] versus σ reflect those for [α/H] and [Fe/H] separately. The observations indicate a trend of [α/Fe] increasing with σ, while the models all predict a trend in the opposite direction. Both the *superwind* and *conduction* models predict supersolar [α/Fe] values for L_* galaxies ($\sigma \approx 200\,\mathrm{km\,s^{-1}}$) which agree well with observations. However, none of the models matches the typical observed [α/Fe] values in high-luminosity ellipticals, with $\sigma \approx 300\,\mathrm{km\,s^{-1}}$.

The trend we find in our models of the typical [α/Fe] decreasing with increasing velocity dispersion or luminosity is similar to what was found by Thomas & Kauffmann (1999). However, although Thomas & Kauffmann based their calculations on star formation histories extracted from hierarchical models, they computed the chemical evolution treating each galaxy as a closed box, ignoring galaxy mergers and inflows and outflows of gas and metals. Our calculation does include all of these effects, so our result is a stronger one. We will compare our results with the closed box result in more detail in a future paper. In all three models presented here, ellipticals with $\sigma = 200$–$300\,\mathrm{km\,s^{-1}}$ had around 40 per cent of their star formation occurring in bursts, while the most recent burst typically happened 3–7 Gyr ago.

In Fig. 2 we plot the α/Fe ratio directly against the Fe abundance, for exactly the same samples of observed and model galaxies as shown in Fig. 1. We see that the observational data do not show any strong correlation of [α/Fe] with [Fe/H], but instead show a scatter of 0.4 dex in [α/Fe] at a given value of [Fe/H]. The models all show a trend of declining [α/Fe] with increasing [Fe/H], with varying amounts of scatter. Once we include the effect of metallicity gradients on the observational data, the *superwind* model seems to be the most consistent with observations, while the *superwind/Kennicutt* and *conduction* models predicts [α/Fe] values at a given [Fe/H] which are respectively too low or too high.

We note here that there is a systematic uncertainty in the [α/H] and [α/Fe] values obtained from observational data due to *template bias*. The stellar population models used to derive metallicities and ages from the observed integrated absorption-line strengths (Lick indices) are based on libraries of observed stellar spectra, in which some stars have non-solar α/Fe ratios. If no allowance is made for non-solar α/Fe in the template stellar spectra, then this can bias the determination of [α/Fe] and [α/H] from the integrated spectra of galaxies. However, different authors have made different corrections for this bias, and the issue is currently controversial. Thomas et al. (2003) include an internal correction within their models. Proctor et al. (2004) have instead proposed that the following correction should be applied to [α/Fe] values derived from integrated line strengths:

$$[\alpha/\mathrm{Fe}]_{\mathrm{final}} = -0.5[\mathrm{Fe/H}] + [\alpha/\mathrm{Fe}]_{\mathrm{raw}}, \tag{1}$$

where $[\alpha/\mathrm{Fe}]_{\mathrm{raw}}$ is the value derived using a stellar population model which ignores the template bias. A corresponding correction is applied to [α/H], but no correction is applied to [Fe/H]. Proctor et al. (2004) found that when this correction is applied to observational data, the [α/H]–σ relation becomes flatter but tighter, while the trend of [α/Fe] increasing with σ almost disappears. However, Thomas et al. (2005) have disputed the validity of this correction and the conclusions of Proctor et al. Since this correction is controversial, we have plotted all of the observational data in Figs 1 and 2 (including the data from Proctor & Sansom (2002) and Proctor et al. (2004)) *without* including this correction. However, to show what the effect of making this correction would be, we have plotted in both figures dotted boxes indicating where the observational points would shift to if the correction were applied. We see that the model predictions in fact agree better with the corrected than with the uncorrected data, especially for the *superwind* model.

4 CONCLUSIONS

We have investigated the metal enrichment of elliptical galaxies in the framework of hierarchical galaxy formation models, taking into account the effects of galaxy mergers and gas inflows and outflows, as well as the production of metals by both SNe Ia and SNe II. This is the first time this has been done using a semi-analytical model. Our model is the same as that which Nagashima et al. (2005) used to show that the metallicities of iron and α elements in the ICM are successfully reproduced only when a top-heavy IMF is adopted for starbursts. We find that all of the models that we consider predict correlations of the α-element abundance with stellar velocity dispersion σ with similar slopes to what is observed, but the model without a top-heavy IMF in bursts (the *superwind/Kennicutt* model) predicts α-element abundances which are somewhat too low. Of our two models which include a top-heavy IMF in bursts, the *superwind* model predicts α-element abundances which agree well with observations of bright ellipticals, while the *conduction* model (which has less ejection of gas and metals) predicts abundances which are too high.

Our models with a top-heavy IMF also predict [α/Fe] values in typical typical L_* ellipticals (with $\sigma \approx 200\,\mathrm{km\,s^{-1}}$) which are similar to observed values, while the model in which all stars form with an IMF like that in the solar neighbourhood predicts [α/Fe] values which are too low. However, none of the models reproduces the trend of [α/Fe] increasing with σ which is implied by most observational data.

We note, however, some caveats to our comparison of the models with observational data:

(i) the observed metallicities are for the central regions of galaxies, while the models predict global values;

(ii) there are uncertainties in the estimation of metallicities from stellar absorption line indices connected with the treatment of non-solar α/Fe abundance ratios;

(iii) the models used to estimate metallicities and ages from observed stellar absorption line indices may give biased results if a galaxy contains stars with a mixture of ages and metallicities, rather a single stellar population with a unique age and metallicity.

We plan to address these issues in a future paper, to allow a more detailed test of our models against observational data on ellipticals.

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