On the stellar populations of massive galaxies

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\textbf{ABSTRACT}

In this Letter, we analyse the predicted physical properties of massive galaxies, in the framework of recent semi-analytic models of galaxy formation. All models considered account for winds driven by supernova explosions and suppression of gas condensation at the centre of relatively massive haloes by active galactic nuclei (AGN). We show that while these models successfully reproduce the old stellar populations observed for massive galaxies, they fail in reproducing their observed chemical abundances. This problem is alleviated but still present if AGN feedback is completely switched off. Moreover, in this case, model predictions fail in accounting for the old stellar ages of massive galaxies. We argue that the difficulty of semi-analytical models in simultaneously reproducing the observed ages and metallicities of massive galaxies signals a fundamental problem with the schemes that are currently adopted to model star formation, feedback and related recycling of gas and metals.

\textbf{Key words:} galaxies: abundancies – galaxies: ellipticals and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: stellar content.

\section{1 INTRODUCTION}

In the current standard picture for structure formation, galaxies originate from gas condensation within the potential wells of hierarchically formed dark matter haloes. The mass distribution of these haloes is well described by a power law, differing significantly from the typical shape of the observed galaxy mass function.

Stellar feedback is believed to play a crucial role at the low-mass regime (White & Frenk 1991; Benson et al. 2003). Observations suggest that galactic-scale outflows are ubiquitous in starburst galaxies at all cosmic epochs and that the outflowing material is multiphase (containing cold, warm and hot gas, dust and magnetized relativistic plasma; e.g. Heckman 2002; Weiner et al. 2009). Unfortunately, available observational measurements refer to material that is still relatively deep within the gravitational potential of the halo. Therefore, the estimated outflow rates are difficult to translate into rates at which mass, metals and energy escape from galaxies and are eventually transported into the intergalactic medium. The fate of the outflowing material will depend critically on a number of unknowns, as well as on its multiphase nature. Given the uncertainties, it is not clear how appropriate the different prescriptions adopted for treating galactic winds in galaxy formation models are.

At the massive end, feedback from active galactic nuclei (AGN) is believed to play a key role. X-ray observations show that AGN feedback should be responsible for the thermal structure of ‘cool cores’; only a modest amount of gas cools and forms stars at the centre of galaxy clusters, despite the short cooling time-scales inferred from the X-ray emission. Detailed recent studies have confirmed that brightest cluster galaxies (BCGs) are more likely to host a radio-loud AGN than other galaxies of similar stellar mass, and have shown that the ensemble-averaged power from radio galaxies is sufficient to offset the mean level of cooling (e.g. Best et al. 2007; McNamara & Nulsen 2007). Heating from a central AGN has become a crucial ingredient for galaxy formation models in order to reproduce the observed exponential cut-off at the bright end of the galaxy luminosity function, and the old stellar populations observed for massive galaxies (e.g. Croton et al. 2006; De Lucia et al. 2006). The details of the energy injection by the central engine and coupling with the surrounding hot gas are, however, still unclear. Therefore, the prescriptions adopted to model this process are very schematic and often not well grounded in observations.

\section{2 THE GALAXY FORMATION MODELS}

In this study, we take advantage of publicly available galaxy catalogues,\textsuperscript{1} constructed applying semi-analytic methods to high-resolution cosmological simulations. In particular, we use catalogues from the models by Bower et al. (2006, BOW06 hereafter), De Lucia & Blaizot (2007, hereafter DLB07) and Guo et al. (2011, These are available at the following webpage: http://www.mpa-garching.mpg.de/millennium/}

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hereafter GUO11) applied to the Millennium Simulation (Springel et al. 2005).

The first two models have been developed independently and differ in a number of details related to the merger tree construction and the prescriptions adopted for various physical processes considered. The GUO11 model is based on the DLB07 one, but it adopts a different (significantly more efficient) supernova (SN) feedback and an improved treatment for the evolution of satellite galaxies. All three models include prescriptions for SN-driven winds, follow the growth of supermassive black holes and include a phenomenological description of AGN feedback. All three models adopt an instantaneous recycling approximation and assume an efficient mixing of metals within the cold gaseous phase.

Using the public catalogues, we have selected all the galaxies in a subcube of the Millennium Simulation of 100 Mpc on a side. In addition, we have selected all the central galaxies of haloes more massive than \( M_{200} > 5 \times 10^{14} \, M_\odot \). We focus, in particular, on the stellar ages and metallicities of model galaxies. Unfortunately, the public catalogues do not provide consistent information: ages and metallicities are weighted by mass in the DLB07 and GUO11 models, while those from the BOW06 model are weighted by mass, luminosity, and V-band luminosity. Purple lines show the conditional distribution of stellar ages as a function of stellar mass from Gallazzi et al. (2005).

3 THE STELLAR POPULATIONS OF MODEL GALAXIES

The grey regions in Fig. 1 show the age–stellar mass relation for all model galaxies in the subvolume of the Millennium Simulation considered. Solid and dashed red lines show the median and the 16th and 84th percentiles of the distributions, while filled symbols show the location of central galaxies of haloes with \( M_{200} > 5 \times 10^{14} \, M_\odot \). As mentioned above, the stellar ages from the DLB07 and GUO11 models are weighted by mass, while those from the BOW06 model are weighted by V-band luminosity. The latter are more directly comparable to the observational measurements by Gallazzi et al. (2005), shown as purple lines. These are obtained adopting a Bayesian statistical approach to derive full likelihood distributions for ages and metallicities by comparing the observed spectra to a library of model star formation histories. The comparison is based on the strengths of spectral absorption features that depend weakly on the \([\alpha/Fe]\) ratio. Note that the distributions obtained for model galaxies are not convolved by observational uncertainties, which are relatively large particularly for older ages.

Model galaxies tend to be on average older than observational estimates, particularly for low-mass galaxies. This problem is in part due to the well-known excess of faint and passive model satellites (e.g. Wang et al. 2007; Weinmann et al. 2010, and references therein). It appears less severe when considering luminosity-weighted ages (see right-hand panel), but models still miss a population of very young low-mass galaxies. At the massive end, model galaxies are dominated by very old stellar populations so that differences between mass- and luminosity-weighted ages are small. In this mass range, model predictions are close to the upper limits of the observational estimates. Central galaxies of massive clusters have very old ages: in the DLB07 model, the median age is 11.8 Gyr with a scatter of only about 0.3 Gyr. For the same galaxies, the GUO11 model predicts somewhat younger mass-weighted ages (the median age is 11.4 Gyr) with a comparable scatter. This is likely due to the fact that, in this model, the hot reservoir associated with satellite galaxies is not stripped instantaneously. Cooling is allowed on these galaxies so that they are on average more gas rich than in a model with instantaneous stripping of hot gas. Their accretion on to the central galaxies triggers star formation episodes that slightly rejuvenate the stellar population of the remnant galaxies. For these galaxies, the median luminosity-weighted age from the BOW06 model is 11.2 Gyr, with a scatter of \( \sim 0.4 \) Gyr.

Fig. 2 shows model predictions and observational estimates for the stellar metallicity–mass relation, with lines and symbols having the same meaning as in Fig. 1. All models predict a relatively tight metallicity–mass relation with a steep slope and a pronounced turnover at the most massive end. Central galaxies of massive clusters have stellar metallicity of \( \sim 0.57 \, Z_\odot \) in the DLB07 model, with a scatter of \( \sim 0.04 \). Because of the more efficient SN feedback, the

\( ^2 M_{200} \) is the mass contained within the radius encompassing an average density of 200 times the critical cosmic density.

![Figure 1](https://academic.oup.com/mnrasl/article-abstract/426/1/L61/988614/1)
GUO11 model predicts a steeper metallicity–mass relation. For the central massive galaxies considered, this model predicts a median metallicity of $\sim 0.74 Z_\odot$, with a scatter of $\sim 0.08$. The luminosity-weighted metallicities from the BOW06 model are offset low with respect to predictions from other models, as expected. For the central galaxies of massive clusters, this model predicts a median metallicity of $\sim 0.43 Z_\odot$, with a scatter of $\sim 0.10$. Purple lines show measurements by Gallazzi et al. (2005). The typical uncertainty on stellar metallicity is $\sim 0.12$ dex, but there is a significant tail of galaxies with uncertainties of up to $\sim 0.25$ dex. Low-metallicity galaxies tend to be associated with larger uncertainties because of the weaker absorption lines.

**4 THE STELLAR POPULATIONS OF BCGs**

The models used in this study successfully reproduce the old stellar populations observed for massive galaxies. If any, model galaxies are too old with respect to data. All the three models considered, however, fail in reproducing the observed chemical abundances of massive galaxies: at the massive end, the predicted metallicity–mass relation turns over and is offset low with respect to the data. The problem appears to be more severe when considering the most massive galaxies at the centre of relatively massive haloes, but is not limited to them. This is due to the fact that many of the most massive satellites have been accreted recently from relatively massive haloes (De Lucia et al. 2012). Therefore, the same physical processes acting on today’s BCGs have played an important role during the lifetime of these galaxies.

From the observational viewpoint, while stellar populations in early-type galaxies have been extensively studied, very little is known about the stellar populations of BCGs. In a recent work, von der Linden et al. (2007) studied a sample of $\sim 600$ BCGs and contrasted their stellar populations with those of a ‘control sample’ of non-BCGs matched in stellar mass, redshift and colour. They found that the ages and the metallicities of BCGs are comparable to those typical of massive ellipticals, while the $\alpha$-enhancements are higher in BCGs. Loubser et al. (2009) analysed the stellar populations of $\sim 50$ nearby BCGs using long-slit spectroscopy. They found that most BCGs are very old, but some (generally associated with cooling flow clusters) show signatures of recent star formation. The metallicity and $\alpha$-enhancement distributions measured by Loubser et al. peak at values higher than those obtained for normal giant ellipticals. It is worth noting that these measurements apply to the central regions of BCGs: the inner 3 arcsec in the study by von der Linden et al. and one-eighth of the half-light radius in Loubser et al. However, the mean stellar population gradients of BCGs (null for $\alpha$-enhancements, almost null for age and negative for metallicity) are consistent with those of normal massive elliptical galaxies (Loubser & Sanchez-Blazquez 2012). Therefore, any attempt to correct for aperture effects would change the normalization but not the shape of the model mass–metallicity relation at the massive end, making the discrepancy shown in Fig. 2 robust and severe.

In models where cooling flows are suppressed at late times by AGN activity (like those considered here), the stars of massive central galaxies form early, in low-mass progenitors whose high star formation rates are fuelled by rapid cooling. Galaxies are then assembled relatively late, through the accretion of many smaller satellites, driven by the merging history of the parent halo. The metallicity–mass relation does not evolve significantly in the models, so that these late dry mergers tend to decrease their total stellar metallicity. Dry minor mergers would likely deposit metal-poor stars in the outer regions of the remnant, so they would not affect significantly the central stellar metallicity of BCGs. For the DLB07 model, we find that the stellar metallicity of the main progenitor of the BCGs at $z \sim 1$ is on average only about 3 per cent lower than its final value, so that even removing all stars accreted after $z \sim 1$ does not improve the disagreement with observational data. Therefore, in a scenario where the mass growth of the most massive galaxies is dominated by minor dry mergers, it appears difficult to reproduce simultaneously the observed mass–metallicity relation and the chemical abundances of the most massive galaxies.

It is interesting to analyse what happens when AGN feedback is switched off. To this aim, we have rerun the DLB07 model on all merger trees of haloes more massive than $5 \times 10^{14} M_\odot$. Fig. 3 shows the distribution of stellar masses, mass-weighted ages and stellar metallicities for all central galaxies of these haloes. Black unfilled histograms show results from the DLB07 model, while red hatched ones correspond to the same model but with no AGN feedback. As expected, galaxies become significantly more massive (by a factor of $\sim 6$) in a model with no AGN feedback. Gas cooling and, in minor part, accretion of other gas-rich satellites provide fresh

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Footnote 3: Around $-0.3$ dex per decade of variation in the radius.
material for late star formation, which makes the stellar population of these galaxies significantly younger (by $\sim 5$ Gyr). Since the material out of which new stars form is enriched by past generations of stars, the mean stellar metallicity increases, going from $\sim 0.6$ to $\sim 0.7 Z_\odot$. The increase is not large because the metallicity of the cooling gas is relatively low ($\sim 0.1$–$0.2 Z_\odot$, in agreement with observational measurements), and it is further diluted by metals being deposited through accreted galaxies. Interestingly, a recent study by McCarthy et al. (2010) shows that hydrodynamical simulations including AGN feedback provide central group galaxies that have too low metallicity with respect to observational data. They find, however, that when AGN feedback is switched off, the metal content of central galaxies increases dramatically, becoming even larger than observed.

5 DISCUSSION AND CONCLUSIONS

All recent models of galaxy formation combine a relatively strong SN feedback with a model for AGN feedback to suppress cooling at the centre of relatively massive haloes. The former is needed to bring the faint-end slope of the galaxy luminosity/mass function in agreement with the relatively shallow value measured. The latter affects significantly the number densities and stellar ages of the most massive galaxies. Our observational and physical understanding of both processes is rather poor so that both are described in galaxy formation models using quite schematic prescriptions.

We have shown that models fail dramatically in reproducing the observed stellar populations of galaxies. At the low-mass end, they tend to overpredict the fraction of passive galaxies and lack a population of very young galaxies that is observed. This is a well-known problem that plagues all recently published models as well as hydrodynamical simulations (Weinmann et al. 2012). In this Letter, we have shown that significant discrepancies are found also for the most massive galaxies, whose model stellar populations are very old but relatively metal poor.

As mentioned above, the modelling adopted for AGN feedback is quite simple and neglects some relevant aspects of AGN activity (e.g. a finite duty cycle, a better modelling of the interaction between the cooling gas and radio jets; see also Fontanot et al. 2011). Thus, there is room for residual star formation at late times in BCGs, which would increase the metallicity of their stellar population while decreasing their ages. However, we have shown that the stellar metallicities of the most massive galaxies would be too low with respect to data even in the case where AGN feedback is switched off. An improved treatment of the satellite evolution that allows residual star formation in satellite galaxies would help in increasing the stellar metallicity of massive galaxies. However, predictions from the GUO11 model (that uses such a scheme) are still off the observational measurements.

Uncertainties in the stellar yields can affect model stellar metallicities. However, the DLB07 and GUO11 models assume an already relatively large yield ($y = 0.03$), while the BOW06 model assumes $y = 0.02$ which is closer but still somewhat larger than a ‘standard’ value. In addition, one should consider that increasing the yield would increase not only the total amount of metals in the stars (and in the gas), but also the overall luminosities of model galaxies (because of the strong dependence of cooling rates on metallicity). A variable initial mass function (IMF) could also affect the total metal content of the most massive galaxies if these formed earlier than their lower mass counterparts, from material with different physical properties. For example, hydrodynamical simulations by Smith & Sigurdsson (2007) show that above a critical metallicity of about $10^{-3} Z_\odot$ clouds can fragment to form low-mass stars, while for gas of lower metallicities stars form following a more top-heavy IMF. This critical metallicity value, however, is well below that of observed galaxies. Finally, our chemical enrichment scheme is rather crude, neglecting the mass-dependent lifetimes of stars, the influence of inefficient mixing and metal loading. All these processes can affect the distribution of metals in different baryonic components.

To illustrate the importance of SN feedback, we show in Fig. 3 predictions from a model with AGN feedback but an alternative SN feedback model (that adopted in De Lucia et al. 2004, based on energy conservation arguments — purple cross-hatched histograms). As explained in DLB07, this model results in less efficient outflows and therefore longer star formation histories and higher stellar metallicities. However, it also overpredicts the overall luminosities of model galaxies. This example highlights the sensitivity of metallicity on the details of SN feedback models. Therefore, requiring a model to predict at the same time the correct number densities, ages and metallicities of galaxies provides strong constraints on the
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