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The effect of thermally pulsating asymptotic giant branch stars on the evolution of the rest-frame near-infrared galaxy luminosity function

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ABSTRACT

We address the fundamental question of matching the rest-frame K-band luminosity function (LF) of galaxies over the Hubble time using semi-analytic models after modification of the stellar population modelling. We include the Maraston evolutionary synthesis models, which feature a higher contribution by the thermally pulsating asymptotic giant branch (TP-AGB) stellar phase, into three different semi-analytic models, namely the De Lucia and Blaizot version of the Munich model, MORGANA and the Menci model. We leave all other input physics and parameters unchanged. We find that the modification of the stellar population emission can solve the mismatch between models and the observed rest-frame K-band luminosity from the brightest galaxies derived from UKIRT Infrared Deep Sky Survey data at high redshift. For all explored semi-analytic models, this holds at the redshifts – between 2 and 3 – where the discrepancy was recently pointed out. The reason for the success is that at these cosmic epochs the model galaxies have the right age (∼1 Gyr) to contain a well-developed TP-AGB phase, which makes them redder without the need of changing their mass or age. We have also computed a version of the Munich model using the Charlot and Bruzual models that adopt the Marigo TP-AGB prescription and find the same result as that with the Maraston models. At the same time, the known overestimation of the faint end is enhanced in the K band when including the TP-AGB contribution. At lower redshifts ($z < 2$) some of the explored models deviate from the data. This is due to short merging time-scales and inefficient 'radio-mode' active galactic nucleus feedback. Our results show that a strong evolution in mass predicted by hierarchical models is compatible with no evolution on the bright end of the K-band LF from $z = 3$ to the local universe. This means that, at high redshifts and contrary to what is commonly accepted, K-band emission is not necessarily a good tracer of galaxy mass.

Key words: methods: numerical – methods: statistical – stars: AGB and post-AGB – galaxies: evolution – galaxies: formation.

1 INTRODUCTION

Models for the formation and evolution of galaxies in a cold dark matter universe (e.g. the so-called semi-analytic models) predict the intrinsic properties of galaxies, such as ages, metallicities, stellar masses, star formation rates, etc., after having tuned a number of free parameters that make up for the poorly known aspects of baryonic physics (see Baugh 2006, for an extensive review). The comparison between models and observations helps constraining these parameters, and robust statistical tools have been recently used to achieve this goal (Kampakoglou, Trotta & Silk 2008; Henriques et al. 2009; Henriques & Thomas 2010; Bower et al. 2010; Lu et al. 2010).

The results of these comparisons are very sensitive to the spectro-modelling of the stellar component. Either for extracting galaxy properties such as mass, age, star formation rate from data, and compare them to the intrinsic quantities of the semi-analytic models, or for calculating the spectra of semi-analytic galaxies and compare it with the observed light, the details on how the stellar modelling is performed influence the final result.

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In order to obtain the spectral energy distribution (SED), or specific broad-band luminosities, of a model galaxy of given mass and star formation history, evolutionary population synthesis (EPS) models (e.g. Tinsley 1972; Bruzual 1983; Buzzoni 1989; Bruzual & Charlot 1993; Worthey 1994; Vazdekis et al. 1996; Fioc & Rocca-Volmerange 1997; Maraston 1998; Leitherer et al. 1999; Bruzual & Charlot 2003; Thomas, Maraston & Bender 2003; Maraston 2005, hereafter M05; Conroy, Gunn & White 2009) are adopted. By relying on stellar evolution theory and model atmosphere calculations or empirical libraries, EPS models provide the expected SED of a galaxy of given mass and star formation history.

In galaxy formation models, the unit single-burst EPS models or simple stellar populations (SSPs) are used to model coeval stars with a homogeneous metallicity, after adopting an initial mass function (IMF). The total stellar emission from the synthetic galaxy composite population is then obtained by combining SSPs. Hence, what matters in the final result in terms of stellar evolution are the properties of the SSP models.

It is clear then that this modelling is a crucial aspect of galaxy formation and evolution theory. Uncertainties in the conversion between masses/ages and light can create artificial discrepancies, which in turn could drive into difficult attempts to modify the parametrization of the complicated physics of gas cooling, star formation or feedback to account for this mismatch. The approach we take in this paper, following our previous work (Tonini et al. 2009; Fontanot & Monaco 2010; Tonini et al. 2010), is to check the impact of modifying the input stellar population model in galaxy formation models following recent progress in the literature.

At present, the highest source of discrepancy between different SSP models is the treatment of the thermally pulsating asymptotic giant branch (TP-AGB) phase (Maraston 1998; M05; Marigo et al. 2008; Conroy et al. 2009). The TP-AGB phase is the last luminous phase in the Hertzsprung–Russel diagram before intermediate-mass stars evolve to their final destiny as planetary nebulae and white dwarfs. TP-AGB stars are very luminous and cool. Their emission affects the integrated model spectra at wavelengths larger than ∼6000 Å, peaking around the J, H, K bands (M05), and a recent study has highlighted their importance also longward the rest frame K (Kelson & Holden 2010). Due to difficulties in the stellar modelling of this phase, which in turn are due to mass-loss and the pulsating regime (see Iben & Renzini 1983, for a review), generally stellar tracks did not include the full TP-AGB, so did not stellar population models based on these tracks (see M05 for discussion). Maraston (1998) and M05 include the TP-AGB semi-empirically calibrating the theoretical energetics with Magellanic Cloud clusters, an approach now adopted for including the TP-AGB phase in isochrones (Charlot & Bruzual, in preparation; Marigo & Girardi 2007).

The galaxy formation models we use in this study, in their standard stellar populations, either neglect or do not include a full contribution from the TP-AGB stellar phase. As pointed out by several papers (Maraston 1998; Maraston et al. 2001; Maraston et al. 2004; M05; Maraston et al. 2006; van der Wel et al. 2006; Charlot & Bruzual, in preparation; Marigo & Girardi 2007; Eminian et al. 2008; Conroy et al. 2009), the inclusion of TP-AGB stars provides an enhancement of the near-infrared (near-IR) emission of galaxies dominated by ∼1 Gyr old populations. To test the influence of this inclusion on model predictions, one needs to consider a statistically significant sample of model galaxies, covering both a wide range of K-band luminosities and redshifts. This test is particularly important when the photometric properties of high-z (i.e. $2 < z < 3$) galaxies are considered, since we expect them to be dominated by young stellar populations.

Semi-analytical techniques represent an obvious tool to perform such test. Predictions from these models have already been compared with the evolution of the observed K-band luminosity function (LF; Pozzetti et al. 2003; Cimatti et al. 2004; Kitzbichler & White 2007; Cirasuolo et al. 2010). These works consistently found the lack of bright sources at high redshift. This apparent mismatch is being referred to as one of the strongest discrepancies between models and data (in particular in connection with the evolution of the stellar mass function; see Fontanot et al. 2009b for a critical review of the latter issue). However, these comparisons involved spectro-photometric codes based on stellar tracks where the full effect of TP-AGB stars was not taken into account.

The first test of this kind was performed by Tonini et al. (2009, 2010). They ran the GALICS semi-analytic model (Hatton et al. 2003) using M05 as input EPS and showed that the optical-to-near-IR colours of z∼2 galaxies can be matched by this type of models, with the original GALICS, which was based on a pre-TP-AGB EPS, failing to match the observations by a large margin. Moreover, Fontanot & Monaco (2010) introduced the M05 stellar populations in MORGANA obtaining a good match on the number density of extremely red objects (EROs) at high redshift.

Here we investigate whether the inclusion of the TP-AGB phase has also an impact on the inability of semi-analytic models to match the galaxy rest-frame K-band LF at high redshift, namely the UKIRT Infrared Deep Sky Survey (UKIDSS) data from Cirasuolo et al. (2010). This homogeneous data set covers an ideal redshift range ($0 < z < 3$) for this test.

To perform this analysis, we use three different semi-analytic models of galaxy formation: the De Lucia & Blaizot (2007) version of the Munich model, MORGANA (Monaco, Fontanot & Taffoni 2007) and the Menci et al. (2006) semi-analytic model. We compare the predictions obtained for the properties of the galaxy population using both stellar populations with and without a full treatment of the TP-AGB phase. For the three models (Menci et al. 2006; De Lucia & Blaizot 2007; Monaco et al. 2007), outputs are produced using, respectively, Bruzual & Charlot (2003), Silva et al. (1998) and Bruzual & Charlot (1993) and M05. Note that, despite including the contribution from TP-AGB stars in their model, Bruzual & Charlot (2003) only partially account for the emission during this stellar phase, meaning that 1 Gyr old populations are roughly only half as bright in the K band when compared to more recent treatments (Charlot & Bruzual, in preparation).

This paper is organized as follows. In Section 2, we briefly describe the semi-analytic models used in this study and explain how the M05 EPS is implemented in each galaxy formation model. In Section 3, we describe the data used for comparison and clarify where the impact of the M05 models is expected to be found. Section 4 presents the results for the evolution of the rest-frame near-IR LF, and in Section 5 we summarize our conclusions.

2 THE SEMI-ANALYTIC MODELS

A clear advantage of the work presented in this paper is the use of three semi-analytic models developed by independent groups and implementing different techniques for the description of the physics controlling galaxy formation and evolution. This allows us not only to assess the impact of the TP-AGB phase, but also to understand the interplay between the new ingredient and the other assumptions regarding galaxy physics on the light of the same stellar evolution background. In particular, we consider the De Lucia &

Blaizot (2007) version of the Munich model, MORGANA (originally described in Monaco et al. 2007 and updated by Lo Faro et al. 2009) and the Menci et al. (2006) model.

The backbone for all models is a description of the redshift evolution of the mass and number density of dark matter haloes in terms of their merger history (the so-called merger trees). The evolution of the baryonic component hosted by these haloes is then followed by means of an approximated set of simplified formulae, aimed at describing the physical processes acting on the gas (such as gas cooling, star formation and feedback) in terms of the physical properties of each model galaxy and/or its components (i.e. the stellar, hot and cold gas content and distribution). These analytical *recipes* include a set of parameters which are usually calibrated against a well-defined subset of low-redshift observations.

The three models adopt different techniques to describe the dark matter merger trees[1] and slightly different cosmologies. However, we do not expect these to have a significant effect on our conclusions (see e.g. Wang et al. 2008).

On the other hand, the different star formation histories and the corresponding distribution of ages and the mass build-up in the models do matter. In the following, we will briefly account for differences between the models, focusing in particular on the active galactic nucleus (AGN) feedback and the merging time-scales, the processes most relevant for the evolution of the bright end of the K-band LF. For more details on the treatment of these physical processes in the different models, we refer the reader to the original papers and to De Lucia et al. (2010), and to Fontanot et al. (2009b) for recent comparisons.

2.1 AGN feedback

The recipe adopted to describe AGN feedback is of crucial importance, since it largely determines the stellar population properties of the most massive galaxies, whose evolution is the focus of our paper. Recent studies (e.g. Croton et al. 2006) assume that the growth of supermassive black holes (SMBHs) at the centre of model galaxies follows two channels: a 'bright mode' (or 'quasar mode') and a 'radio mode', related to the efficient production of radio jets. The 'quasar mode' is fuelled by merger-driven instabilities, it is the dominant channel in terms of the black hole's growth and can be effective in producing feedback at early times (where merging rates are high). The 'radio mode' is less important in terms of the growth of the SMBH but is responsible for star formation quenching at low redshift.

The details of the implementations of the two modes differ between the models considered in this study (see e.g. Fontanot et al. 2011 for a detailed discussion about MORGANA and De Lucia & Blaizot 2007). While the net effect of the 'quasar-mode' is quite similar between the various models, even if the implementations are slightly different, it is the 'radio mode' to be mostly responsible for differences in the galaxy stellar populations towards low redshift.

In the Munich model, the 'radio-mode' feedback is the result of quiescent gas accretion from a static hot halo (Croton et al. 2006), with no triggering mechanism required. In MORGANA, the 'radio mode' is due to the accretion (at very low rates) of the cold gas from a reservoir surrounding the central SMBH (see Fontanot et al. 2006 for more details). Note that some amount of star formation is required to destabilize the gas in the reservoir. Hence, star formation is not completely quenched. This residual star formation causes galaxies to have colours that are too blue at low redshift with respect to both observations and other models (Kimm et al. 2009) and contributes to an excessive build-up of massive objects at later times. Finally, the Menci et al. (2006) model does not include 'radio-mode' feedback. For this reason, at low redshift, massive objects always have ongoing star formation, which causes an excessive mass build-up in these objects. Relevant to our work is that this results in an overprediction of the bright tail of the K-band LF, as we will show in Section 4.

2.2 Merging times

Dark matter substructures and their clustering have relevant consequences on the evolution of galaxies. Gravitational processes such as dynamical friction and tidal stripping affect the morphology, the stellar and the gaseous content of galaxies. Two-body mergers are even more extreme processes, leading to the formation of a new object, whose final properties depend on the properties of the progenitors.

In the Munich model, dark matter substructures in the N-body simulation are explicitly tracked down until tidal truncation and stripping reduce their mass below the resolution limit of the simulation (De Lucia et al. 2004; Gao et al. 2004). In Menci et al. (2006) dark matter is followed using a Press–Schechter formalism and satellite haloes are partially disrupted as the density in their outer parts becomes lower than the density of the host halo within the pericentre of its orbit (see Menci et al. 2002 for details). After this point the merging time of the satellite in both models is computed using the classical Chandrasekhar (1943) dynamical friction approximation. It is worth stressing that the De Lucia & Blaizot (2007) model includes an additional parameter in this formula, effectively doubling the expected merging times. This value was introduced to reduce the slight excess of bright galaxies that would be produced otherwise. MORGANA does not track explicitly dark matter substructures and assumes that satellite galaxies merge on to central galaxies after a dynamical friction time-scale which is computed using analytic formulae proposed by Taffoni et al. (2003).

De Lucia et al. (2010) compare different approximations for the dynamical friction merging time-scales used in semi-analytics. They find that while the De Lucia & Blaizot (2007) recipe is in good agreement with some recent results based on N-body-simulations (Boylan-Kolchin, Ma & Quataert 2008), the Taffoni et al. (2003) formulae predict significantly shorter merging times. Note that the same is true for Menci et al. (2006) with merging times two times shorter than those in De Lucia & Blaizot (2007).

Despite the overall agreement between different models in terms of the mass build-up found by Fontanot et al. (2009b), it can be seen that MORGANA shows an excessive build-up of massive galaxies at late times. We expect Menci et al. (2006) to show a similar behaviour. This is due to the combined effect from the enhanced merger activity and the ongoing star formation due to inefficient AGN feedback at low redshift. This will affect our results with both models overestimating the number density of bright K-band objects at later times (see Section 4).

[1] The Munich model uses merger trees extracted from a direct N-body simulation of a cosmological volume (the Millennium Simulation; Springel et al. 2005), MORGANA uses the Lagrangian semi-analytic code PINOCCHIO (Monaco et al. 2002) and Menci et al. (2006) uses Monte Carlo realizations of merger trees based on the halo-merging probability given by the extended Press–Schechter formalism.

2.3 Implementation of the M05 models

As recalled in Section 1, the spectra of galaxies in semi-analytic models are obtained by means of spectro-photometric population synthesis models. The implementation of the M05 models is straightforward in these semi-analytics. We use SSPs corresponding to four metallicities, 1/20, 1/2, 1 and 2 $Z_{\odot}$, which despite not being exactly the same as for the stellar populations previously used (since the input stellar tracks of the M05 models are different; see M05 for details), cover a similar range and are as coarse. Therefore, this difference has no impact on our predictions. The same IMF that was previously adopted in the various semi-analytic models is retained, namely the Chabrier (2003) IMF for MORGANA[2] and the Munich model and the Salpeter (1955) IMF for Menci et al. (2006).

The predicted luminosities are then corrected for dust extinction. For all models we keep these prescriptions unchanged. The different treatment of dust extinction has non-negligible effects on the predicted magnitudes and colours, especially at $z > 2$ (Fontanot et al. 2009a). However, since the rest-frame K-band emission is relatively insensitive to dust attenuation, we do not expect these differences to substantially affect our results.

Finally, it is worth stressing that we keep all other assumptions and parameters of the semi-analytic models as in their original formulation. Therefore, we can highlight any modification due just to the change in the stellar population libraries.

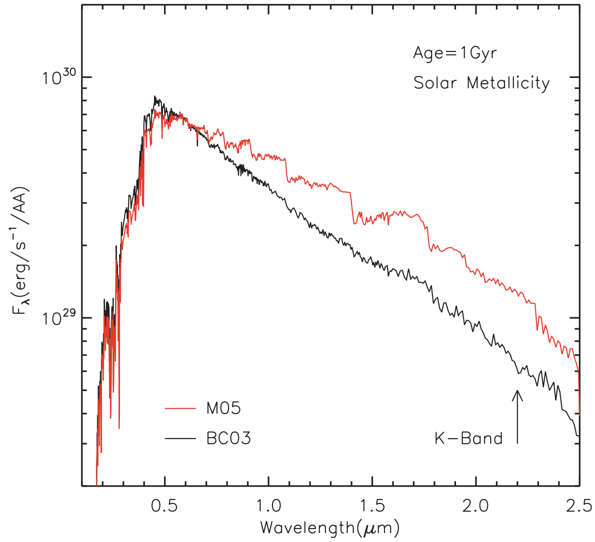

Figure 1. An SSP SED from M05 is compared with the equivalent predictions from models used in semi-analytic models (here Bruzual & Charlot 2003 as an illustrative example). The plot refers to a 1-Gyr-old population with solar metallicity. The full treatment of the TP-AGB stellar phase in the M05 models gives significant emission for populations between 0.2 and 1 Gyr. For similar plots and discussion see M05.

3 A CHALLENGING ISSUE: THE OBSERVED REST-FRAME *K*-BAND LUMINOSITY FUNCTION AT HIGH REDSHIFT

In this paper, we focus on a well-documented discrepancy between semi-analytic models and observations, the inability of the models in matching the observed redshift evolution of the rest-frame near-IR galaxy LF (Pozzetti et al. 2003; Cimatti et al. 2004; Kitzbichler & White 2007). This has recently been confirmed over a wide redshift range (Cirasuolo et al. 2010). This paper uses a data set from the Ultra Deep Survey (UDS), the deepest survey from the UKIDSS, containing imaging in the J and K bands, with deep multi-wavelength coverage in $BVRi'z'$ filters in most of the field. The sample contains ≈50 000 objects over an area of 0.7 deg^2, with high completeness down to $K \leq 23$. Cirasuolo et al. (2010) find that the space density of the most massive galaxies at high redshifts (above 2) is underpredicted by semi-analytic models; in other words, the theoretical LF lacks the brightest source in the near-IR.

Tonini et al. (2009, 2010) and Fontanot & Monaco (2010) showed that the number of bright K-band objects at high redshift in semi-analytic models can be increased by including the M05 models with their treatment of the TP-AGB phase of stellar evolution. We briefly recall here the origin of such an effect. The M05 models predict that young populations have a significant contribution to the near-IR. For the LF analysis, the differences are expected to be more significant at high redshift where a larger fraction of the galaxy population contains young stars. In Fig. 1, we plot the SED for a population with 1 Gyr of age and solar metallicity using M05 and an illustrative example of the stellar populations previously implemented in semi-analytic models (see M05 for similar plots and discussion). In the K band, the M05 model predicts more than twice the emission, hence affects the prediction of semi-analytic galaxies at high redshift.

[2] Note that the M05 stellar populations were implemented in MORGANA by Fontanot & Monaco (2010).

In concluding this section, some words of caution must be given on the data/model comparison. In Cirasuolo et al. (2010), the galaxies have photometric redshifts, which were obtained by fitting empirical as well as synthetic templates from Bruzual & Charlot (2003). For consistency, photometric redshifts and rest-frame magnitudes should have been derived for the data using the same stellar populations that we are implementing in the semi-analytic models, but these data are not available to us. However, we emphasize that the differences that arise from using the M05 models to convert from mass to light (or light to mass) are considerably larger than the ones originated from the determination of photometric redshifts (e.g. Maraston et al. 2006). The subsequent conversion from observed to rest-frame magnitudes is more difficult to track, as the different theoretical templates usually give different fitted ages depending on the properties of each galaxy (e.g. Maraston et al. 2006; Cimatti et al. 2008). However, this will produce differences between derived $k + e$ corrections that are not systematic and therefore should not alter our conclusions.

Finally, when comparing the model's results and data, one should consider that the model's magnitudes are 'total', while observational measurements are usually based on 'aperture' magnitudes. At redshift zero, a significant fraction of light might be missed for large objects that exceed the available aperture diameter (e.g. Lauer et al. 2007; von der Linden et al. 2007). At the higher redshifts studied here, despite galaxies being smaller than the maximum available apertures, there can still be an issue of missing light when small apertures are used to ensure a high signal-to-noise ratio. Moreover, the situation can be complicated by limited instrumental resolution that might blend together objects in crowded regions. The first problem is minimized in the data we use by applying point-spread function corrections to total magnitudes (Cirasuolo et al. 2010). Nevertheless, both aspects can influence the evolution of the bright end of the LF.

4 RESULTS

4.1 The *K*-band luminosity function

Fig. 2 compares the evolution of the *K*-band LF from redshift 3 to redshift 0.5 for the semi-analytic models with the Cirasuolo et al. (2010) data (shown as open black circles). The De Lucia & Blaizot (2007) models are shown in red, MORGANA in green and Menci et al. (2006) in blue. Original model versions are shown as dashed lines and the M05 versions as solid lines.

The three galaxy formation models in the M05 versions show an enhanced *K*-band emission (between 0.25 and 0.5 mag) from the brightest objects ($M_K \leq -24$), which for $z \geq 2$ brings the models into agreement with data. The original versions of the models predict that only old populations provide substantial *K*-band emission. For this reason, the bright end of the *K*-band LF could only be built up at lower redshifts when old populations become dominant in massive galaxies. The TP-AGB phase gives a simple and straightforward way to solve the problem with the observed evolution of the *K* band.

The agreement between the semi-analytic plus M05 models for bright *K*-band objects and observations at high redshift is remarkable. In principle, effects from the age/metallicity degeneracy could produce an artificial agreement between the data and model. For example, a luminous *K* band can originate from very metal-rich populations or from much older populations than those dominated by the TP-AGB emission. However, the wide redshift range that is spanned by these observations and the trend of the observed *K*-band LF with redshift allows us to exclude such effects acting at all redshifts. This is particularly the case at high redshift, where the time elapsed since the big bang is short enough such that this age degeneracy cannot enter the game.

These results suggest that if masses and ages were estimated from observational data using M05 these would be in agreement with model predictions. The conversion to photometric properties was fully responsible for the disagreement with observations that

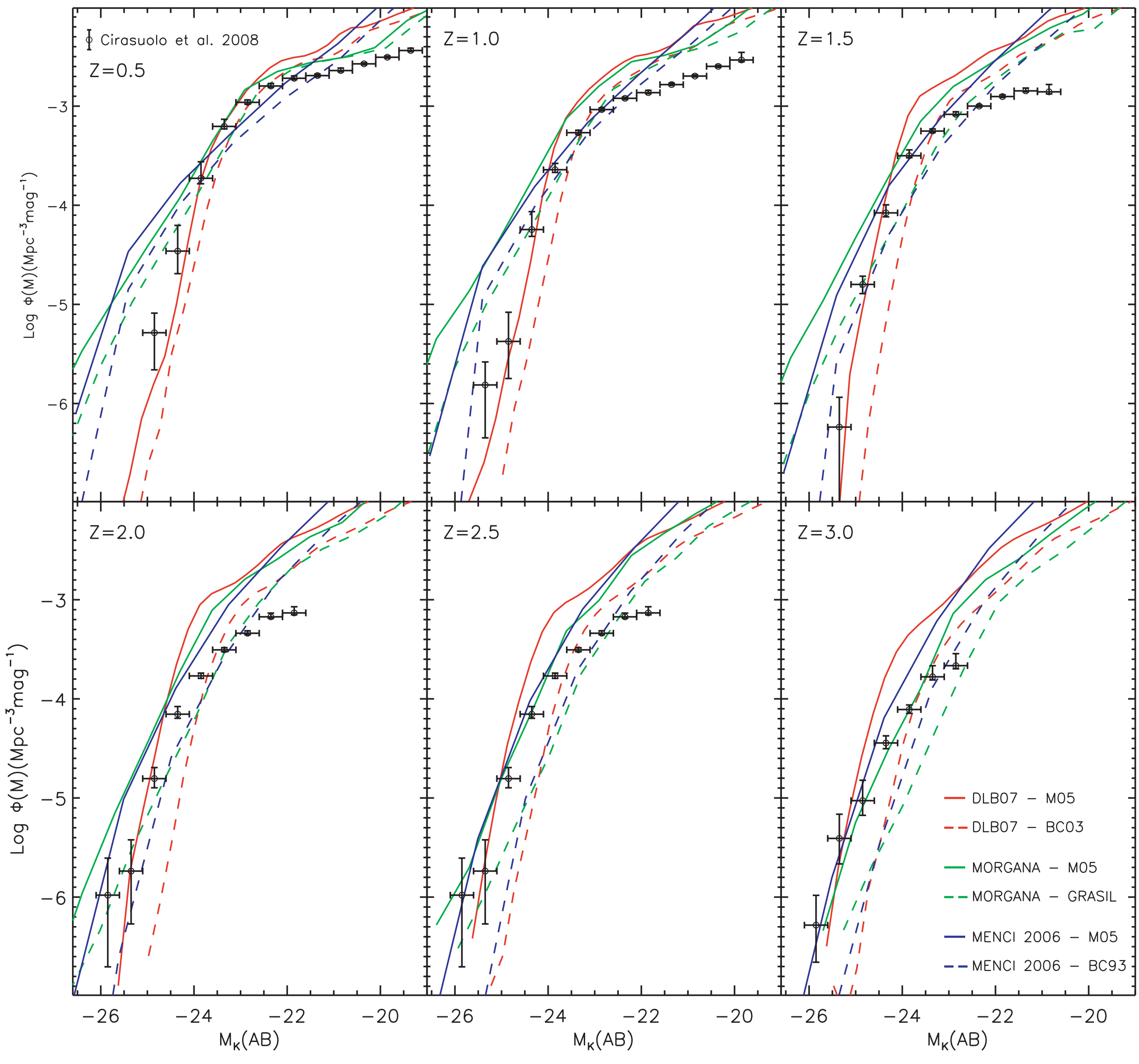

Figure 2. The evolution of the *K*-band LF from $z = 3.0$ to 0.5. The original predictions from three different semi-analytic models are shown as dashed lines and their version with the M05 as solid lines. Red lines refer to De Lucia & Blaizot (2007), green to Monaco et al. (2007) and blue to Menci et al. (2006). Data from Cirasuolo et al. (2010) are shown as black opened circles and the solid line.

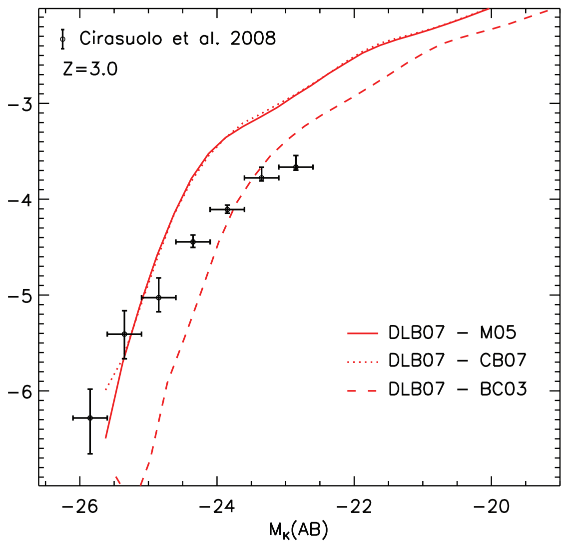

Figure 3. The K-band LF for the Munich model at z = 3.0. The solid, dotted and dashed red lines represent, respectively, runs using the M05, Charlot & Bruzual (in preparation) and Bruzual & Charlot (2003) stellar populations.

was pointed out by Cirasuolo et al. (2010) and previously found by other authors (Pozzetti et al. 2003; Cimatti et al. 2004; Kitzbichler & White 2007). This result has important implications for the observational determinations of stellar masses and ages from photometric data, in particular for galaxies at high redshift. Significant K-band emission can be produced by young populations at high redshift through the TP-AGB stellar phase. Without considering it, large K-band emission can only originate at older ages, which results in a systematic overestimation of stellar masses derived from emission in this band (e.g. Maraston et al. 2006).

Interesting differences among the models emerge at low redshifts. The De Lucia & Blaizot (2007) model plus M05 follow the bright tail in every redshift bin (z = 0.5–3.0). At redshift 1 the better match between data and the models implies a certain fraction of 1 Gyr population in these galaxies, a prediction that could be tested by acquiring rest-frame near-IR spectra.

For MORGANA and Menci et al. (2006), the inclusion of the M05 models worsens an existing discrepancy at lower redshift $z <=1.5$, namely that the models overpredict the number density of massive galaxies. This discrepancy is emphasized with M05 because existing ∼1 Gyr populations have a higher flux. However, the excess is present for both versions of each model; hence, it is primarily caused by mass growth rather than age. In both models, this is caused by a combination of enhanced merging times and inefficient AGN feedback at low redshift (see Section 2).

The dynamical friction merging times in Menci et al. (2006) and MORGANA are shorter than what is expected from the numerical analysis of Boylan-Kolchin et al. (2008), as pointed out by De Lucia et al. (2010). Moreover, both models have AGN-feedback implementations that are inefficient in shutting down star formation in massive objects at later times. In the Menci et al. (2006) model, this is caused by the absence of 'radio-mode' AGN feedback. In MORGANA, some amount of star formation is required to destabilize the reservoir of gas and trigger this feedback mode. This results in galaxy optical colours that are too blue (as pointed out by Kimm et al. 2009, for MORGANA) and in an excess of massive galaxies as emphasized by both stellar population models in our study.

In Fig. 3, we plot the K-band LF at redshift 3.0 for the Munich model using the original Bruzual & Charlot (2003) stellar populations (red dashed line), the M05 (solid red line) and the Charlot & Bruzual (in preparation, dotted red lines) models. The similarity between the M05 and Charlot & Bruzual (in preparation) results shows that the different treatment of the TP-AGB phase (respectively Maraston 1998; Marigo et al. 2008) has a minor impact on our conclusions.

4.2 The ages of the galaxy populations

In order to clarify the different results obtained with the three semi-analytic models, we show in Fig. 4 the mass-weighted and K-band light-weighted ages (left-hand and right-hand panels, respectively) for galaxies brighter than $M_K = -24$, as a function of redshift. The mass-weighted ages illustrate the relative contribution of galaxies with different ages to the total mass budget (with red, green and blue lines representing the Munich, MORGANA and the Menci et al. 2006 models, respectively). At early times ($z \approx 2.5$, bottom left-hand panel), the impact of the TP-AGB phase is larger, because the mean galaxy ages in the three models are around 1 Gyr. As we move towards lower redshifts (middle and top left-hand panels), a bimodality emerges in the Munich model, with the bright end of the K-band LF being built up by a combination of young and old populations (with the latter, maintained by the 'radio-mode' AGN feedback, growing in importance as we move to lower redshifts). This bimodality is also present in Menci et al. (2006), but is weaker and the oldest population is ∼1 Gyr younger than in the Munich model. On the other hand, MORGANA shows considerably younger ages, centred at ∼2.5 Gyr, with only a very weak peak at ∼4 Gyr. Despite the difference in the age distribution at $z = 0.5$ (top left-hand panel), the ongoing star formation produces the same mass excess in both MORGANA and Menci et al. (2006) (resulting in a similar over-estimation of the number density of bright K-band objects). The Menci et al. (2006) model has a smaller fraction of younger ages. This is due to the assumed modelling of the 'quasar-mode' feedback combined with the absence of 'radio-mode'. At very high redshift ($z > 3$) star formation is high in the progenitors of massive galaxies due to merger induced starbursts. At low redshifts only a fraction of these galaxies have their star formation quenched. On the other hand, MORGANA has continuous on-going star formation but always at a moderate level, being self-regulated by the 'radio-mode' feedback.

The mass-weighted age distribution of the models helped us understanding the results on the K-band LF and display the backbone of the models. We now consider a light-weighted age distribution, which emphasises how the different input stellar population models can force such distributions to different age domains. We consider K-band light-weighted ages, because they emphasize the distinction between the model ingredients. For technical reasons, we cannot easily compute light-weighted ages in the MORGANA model. We therefore limit this test to the two other models. In the three right-hand panels of Fig. 4, red lines represent results from the Munich model, while blue lines give ages for Menci et al. (2006). Solid lines represent versions that include the TP-AGB phase with the M05 and dotted lines represent the original stellar populations.

The strongest difference between the two model renditions is displayed by the Munich model because of the age bimodality mentioned above. Focusing on redshifts 1 and 0.5, the difference between light- and mass-weighted ages is smaller for M05 than for BC03 (solid versus dotted lines), because the young populations coloured with the M05 get enough K-band light such that the mass-weighted histogram's relative weights are maintained. In the case of the version with BC03, instead, the K-band light only comes from

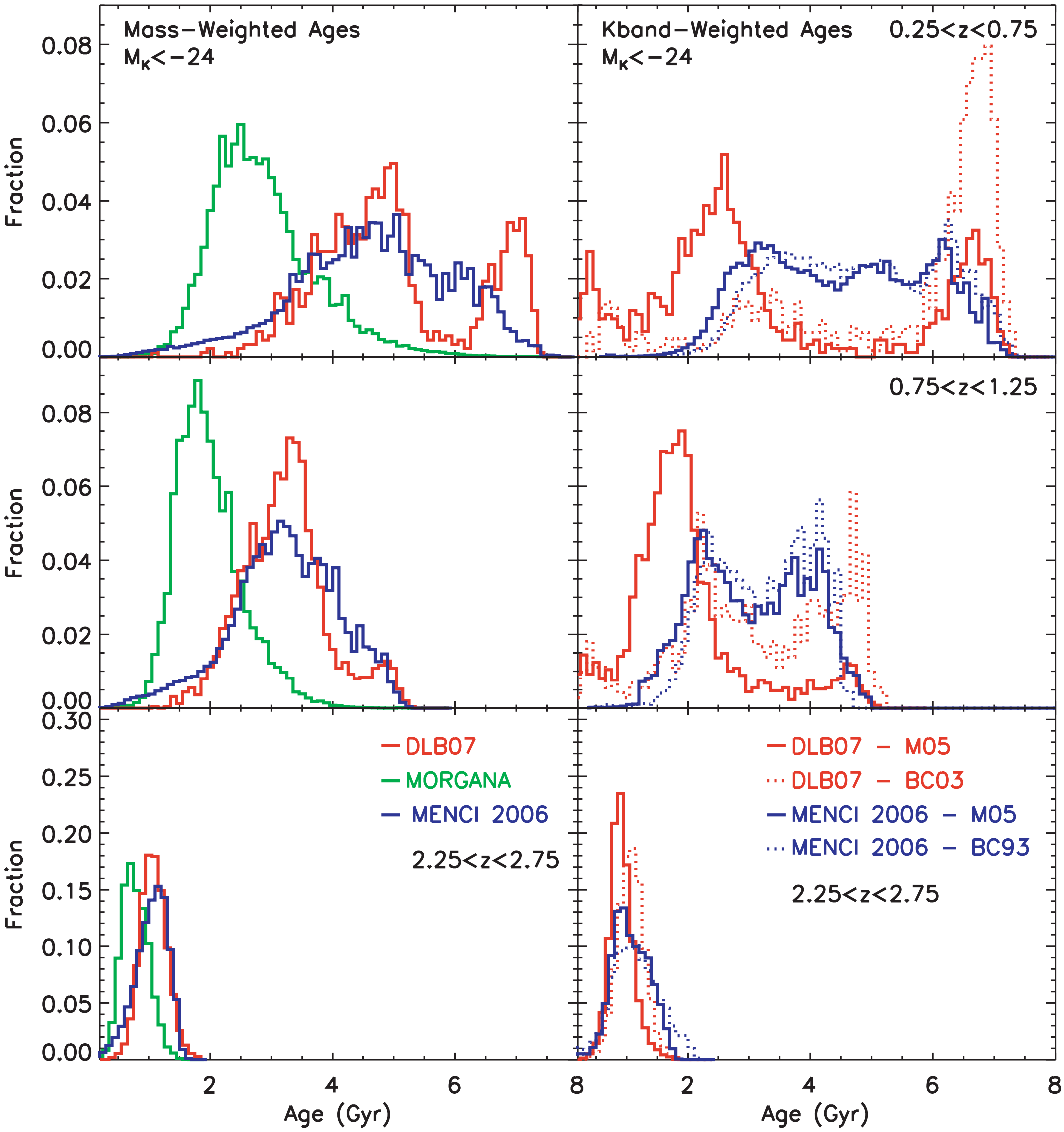

Figure 4. The mass-weighted (left-hand panel) and K-band light-weighted (right-hand panel) age distributions of model galaxies with $M_K < -24$. Red, green and blue colours refer to De Lucia & Blaizot (2007), MORGANA and Menci et al. (2006), respectively. Solid lines represent model versions with M05, whereas dotted lines refer to the original stellar populations. From top to bottom, panels refer to redshift $z = 0.5$, 1.0 and 2.5.

old populations, and as a result the weight of the bimodality (K-band light weighted) is distorted, with a much higher fraction of populations getting old ages. The behaviour is diluted for the Menci et al. (2006) models because galaxy ages do not show a clear bimodality between young and old ages. Therefore, mass-weighted and K-band light-weighted age distributions are similar, and the results for the different stellar population models are similar as well.

It should be noted that the mass-weighted age is an average over the individual populations that compose the theoretical galaxies. This implies that individual ages can extend down to much lower values. This can be seen in Fig. 5, where we show the ages of the individual populations for galaxies with $M_K < -24$ at $z = 0.5$ in the three semi-analytic models. The 1-Gyr-old populations present in the three models explain the impact of the TP-AGB phase even at this redshift. It can also be seen that MORGANA exhibits the larger fraction of young stars, since the 'radio-mode' feedback is regulated by star formation. The Menci et al. (2006) ages are considerably older due to the impact of the 'quasar-mode' feedback at early times. However, as it starts being ineffective at lower redshifts, a considerable fraction of younger populations emerge.

Despite the significant improvement obtained in matching the evolution of the bright end of the K-band LF, the faint end remains problematic. The luminosity (as well as the stellar mass) function for faint objects ($-22 \leq M_K \leq -24$) is known to be much higher than measured (Fontana et al. 2006; Weinmann et al. 2006; Henriques, Bertone & Thomas 2008; Fontanot et al. 2009b), and the inclusion of the M05 models worsens the case. This excess can be removed in different ways at redshift zero by using a more up-to-date cosmology (Somerville et al. 2008) or combining the disruption of stellar material from satellites during mergers (Monaco et al. 2006; Henriques et al. 2008; Somerville et al. 2008) with more efficient supernova feedback (Henriques & Thomas 2010; Guo et al. 2011). Nevertheless, the comparison presented in our work for high redshift (as already shown by Fontanot et al. 2009b) shows that for the early phases of galaxy evolution this might be a problem, even considering problems of incompleteness with the high-redshift data.

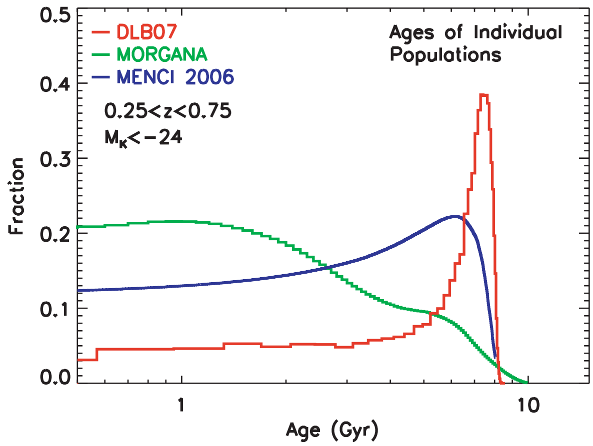

Figure 5. The ages of the individual populations present in semi-analytic galaxies with $M_K < -24$. The solid red line represents De Lucia & Blaizot (2007), the solid green line shows MORGANA predictions and the solid blue line gives the Menci et al. (2006) ages at $z = 0.5$.

5 SUMMARY

The main objective of this work is to re-address the fundamental question of matching the observed rest-frame K-band LF of galaxies over the Hubble time using semi-analytic models. In the literature (Pozzetti et al. 2003; Cimatti et al. 2004; Kitzbichler & White 2007; Cirasuolo et al. 2010), it has been pointed out that semi-analytic models underestimate the rest-frame K-band galaxy luminosity of the brightest objects at high redshift (∼2–3), and the failure has been attributed to an insufficient mass build-up at early epochs.

However, the galaxy LF does not only depend on the mass build-up, but also on the light emitted per unit mass. Hence, in order to pin down the origin of the mismatch, we improve upon the rest-frame K-band emission from the model galaxies. We use the M05 stellar population models, which include the full treatment of the emission from the cool and luminous TP-AGB phase. The contribution of this phase of stellar evolution in the M05 models is important at intermediate ages (between 0.2 and 2 Gyr), which are expected to be predominant at $2 < z < 3$. The relevance of this ingredient has been recently shown for the semi-analytic model GALICS in Tonini et al. (2009, 2010), where the observed near-IR colours of redshift 2 galaxies could only be matched by the model inclusive of the TP-AGB emission. Similarly, Fontanot & Monaco (2010) showed that the inclusion of this stellar phase in MORGANA increases significantly the number density of EROs at high redshift.

We consider several semi-analytic models, namely the De Lucia & Blaizot (2007), MORGANA (Monaco et al. 2007) and Menci et al. (2006) models and implement the M05 stellar population models, keeping all other ingredients and assumptions unchanged.

We find that the semi-analytic models with the M05 models exhibit a brighter K-band LF by as much as 0.5 mag at the highest redshift bins. This is precisely the offset that was plaguing the comparison with the UKIDSS data for the brightest objects in Cirasuolo et al. (2010). Models and data at high redshift and for $M_K < -24$ now match very well. This result is confirmed when using the Charlot & Bruzual (in preparation) models as an input for the Munich model. This confirms that different modelling of the TP-AGB phase has a minor impact on our conclusions.

This result is strongly suggestive that the models at redshifts 2–3 do not underestimate mass; rather they did require a proper conversion between mass and light. Moreover, we show that a strong evolution in mass predicted by hierarchical models is compatible with no evolution on the bright end of the K-band LF from $z = 3$ to the local universe. This means that, at high redshifts and contrary to what is commonly accepted, K-band emission is not necessarily a good tracer of galaxy mass.

At lower redshift, the details of the implementation of AGN feedback and merging time-scales produce differences between the various semi-analytic models that are not altered by the inclusion of the M05 models. In particular, MORGANA and Menci et al. (2006) exhibit a K-band LF bright tail that is higher than the data, which is due to an excessive mass build-up connected to the lack of an efficient quenching of low-z cooling flows via ‘radio-mode’ feedback.

Similarly, the faint end of the galaxy LF remains substantially overestimated by the models at all redshifts. This is a well-documented problem (Fontana et al. 2006; Weinmann et al. 2006; Henriques et al. 2008; Fontanot et al. 2009b; Henriques & Thomas 2010; Guo et al. 2011) that we plan to study in future work.

In recent years, our understanding of the various phases of stellar evolution has improved. Moreover, we now have high-quality observational data covering a wide spectral range (including the rest-frame near-IR). Therefore, we should now be able to constrain galaxy formation models with better accuracy and disentangle between different theoretical approaches.

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