Mon. Not. R. Astron. Soc. **000**, 1–9 (2009) Printed 9 September 2010 (MN LaTeX style file v2.2)

arXiv:1009.1392v1 [astro-ph.CO] 7 Sep 2010

The effect of TP-AGB stars on the evolution of the rest-frame near-infrared galaxy luminosity function

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Submitted to MNRAS

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, that 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 UKIDSS 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 ($\sim$1 Gyr) to contain a well-developed TP-AGB phase which makes them redder without the need of changing their mass or age.

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 too short merging timescales and inefficient 'radio-mode' AGN 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 – galaxies: formation – galaxies: evolution – stars: AGB

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 et al. 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.

In order to obtain the spectral energy distribution (SED), or specific broad-band luminosities, of a

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model galaxy of given mass and star formation history, evolutionary populations synthesis (EPS) models (e.g. Tinsley 1972, Bruzual A. 1983, Buzzoni 1989, Bruzual A. & Charlot 1993, Worthey 1994, Vazdekis et al. 1996, Fioc & Rocca-Volmerange 1997, Maraston 1998, Leitherer et al. 1999, Bruzual & Charlot 2003, Thomas et al. 2003, Maraston 2005 (M05), Conroy et al. 2009) are adopted. By relying on stellar evolution theory and model atmosphere calculations or empirical libraries, EPS models provide the expected spectral energy distribution 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 on the final result in terms of stellar evolution are the properties of the simple stellar population 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, 2010; Fontanot & Monaco 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 $\sim 6000\AA$, peaking around the J, H, K bands (M05) and a recent study has highlighted their importance also long-ward 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 (Marigo & Girardi 2007; Bruzual 2007).

The galaxy formation models we use in this study do not include, in their standard stellar populations, 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, Marigo & Girardi 2007, Bruzual 2007, Eminian et al. 2008, Conroy et al. 2009) the inclusion of TP-AGB stars provides an enhancement of the near-infrared 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 a 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 effect of TP-AGB stars was not taken into account.

The first test of this kind is performed in Tonini et al. (2009, 2010). They run the GALICS semi-analytic model (Hatton et al. 2003) using M05 as input EPS and show 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 luminosity function at high-redshift, namely the 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 et al. 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 (De Lucia & Blaizot 2007; Monaco et al. 2007; Menci et al. 2006) outputs are produced using, respectively Bruzual & Charlot (2003), Silva et al. (1998) and Bruzual A. & Charlot (1993), and M05.

This paper is organized as follows. In Section 2, we briefly describe the semi-analytic models used in this study, and we 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-infrared luminosity function 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 halos in terms of their merger history (the so-called merger trees). The evolution of the baryonic component hosted by these halos 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 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); 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 Super-Massive Black-Holes (SMBHs) at the center 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 fueled by merger driven instabilities, it is the dominant channel in terms of black hole 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 SMBH growth 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. 2010b 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 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 over-prediction 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 halos 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 onto 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 re-

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[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.

sults based on N-body-simulations (Boylan-Kolchin et al. 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 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 over-estimating the number density of bright K-band objects at later times (see Section 4).

2.3 Implementation of the M05 models

As recalled in the Introduction, 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 $Z_\odot$, 1/2 $Z_\odot$, $Z_\odot$ 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) for MORGANA[2] and the Munich model, and a Salpeter (1955) 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 colors, especially at $z > 2$ (Fontanot et al. 2009). 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.

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-infrared galaxy luminosity function (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).

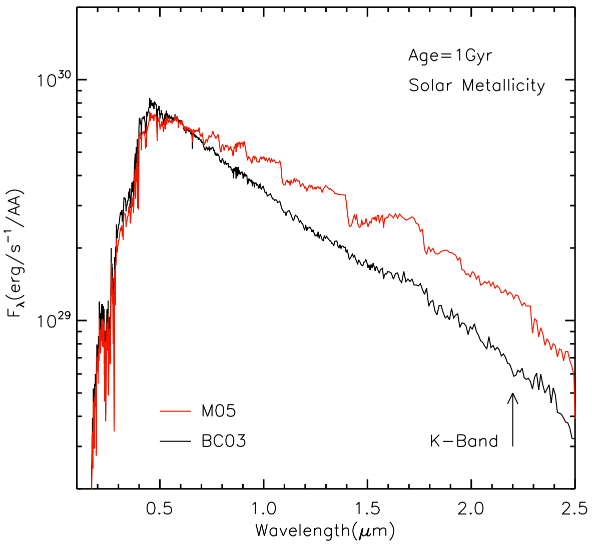

Figure 1. A simple stellar population spectral energy distribution from M05 is compared with the equivalent predictions from models used in semi-analytic models (here Bruzual & Charlot (2003) as an illustrative example). The plot refers to a 1 Gyr old population with solar metallicity. The TP-AGB stellar phase in the M05 models is significant between 0.2 and 1 Gyr. For similar plots and discussion see M05.

This paper uses a data set from the Ultra Deep Survey (UDS), the deepest survey from the UKIRT Infra-Red Deep Sky Survey (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 $\approx$ 50,000 objects over an area of 0.7 square degrees, with high completeness down to $K \leqslant 23$. Cirasuolo et al. (2010) find that the space density of the most massive galaxies at high redshifts (above 2) is under-predicted by semi-analytic models, in other words the theoretical luminosity function lacks the brightest sources in the near-IR.

Tonini et al. (2009, 2010); 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-infrared. For the luminosity function 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 spectral energy distribution (SED) for a population with 1 Gyr of age and solar metallicity, using M05 and 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.

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, photomet-

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

ric 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 model results and data, one should consider that model 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 high signal-to-noise. 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 (PSF) corrections to total magnitudes (Cirasuolo et al. 2010). Nevertheless, both aspects can influence the evolution of the bright end of the luminosity function.

4 RESULTS

Fig. 2 compares the evolution of the K-band luminosity function from redshift 3 to redshift 0.5 for the semi-analytic models with the Cirasuolo et al. (2010) data (shown as open black circles). 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 mags) from the brightest objects ($M_K \leqslant -24$) which for $z \geqslant 2$ 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 luminosity function 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 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 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 over-estimation 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 follows the bright tail in every redshift bin (z=0.5 to z=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 over-predict 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 emphasised by both stellar population models in our study.

In order to clarify the different results obtained with the three semi-analytic models, we show in Fig. 3 the model mass-weighted ages as a function of redshift for all galaxies brighter than M_K=-24. At early times (z≈2.5), the impact of the TP-AGB phase is larger, which stems from the mean ages around 1 Gyr of galaxies in the three models. As we move towards lower redshifts a bimodality emerges in the Munich model, with the bright-end of the K-band luminosity function being build up by a combination of young

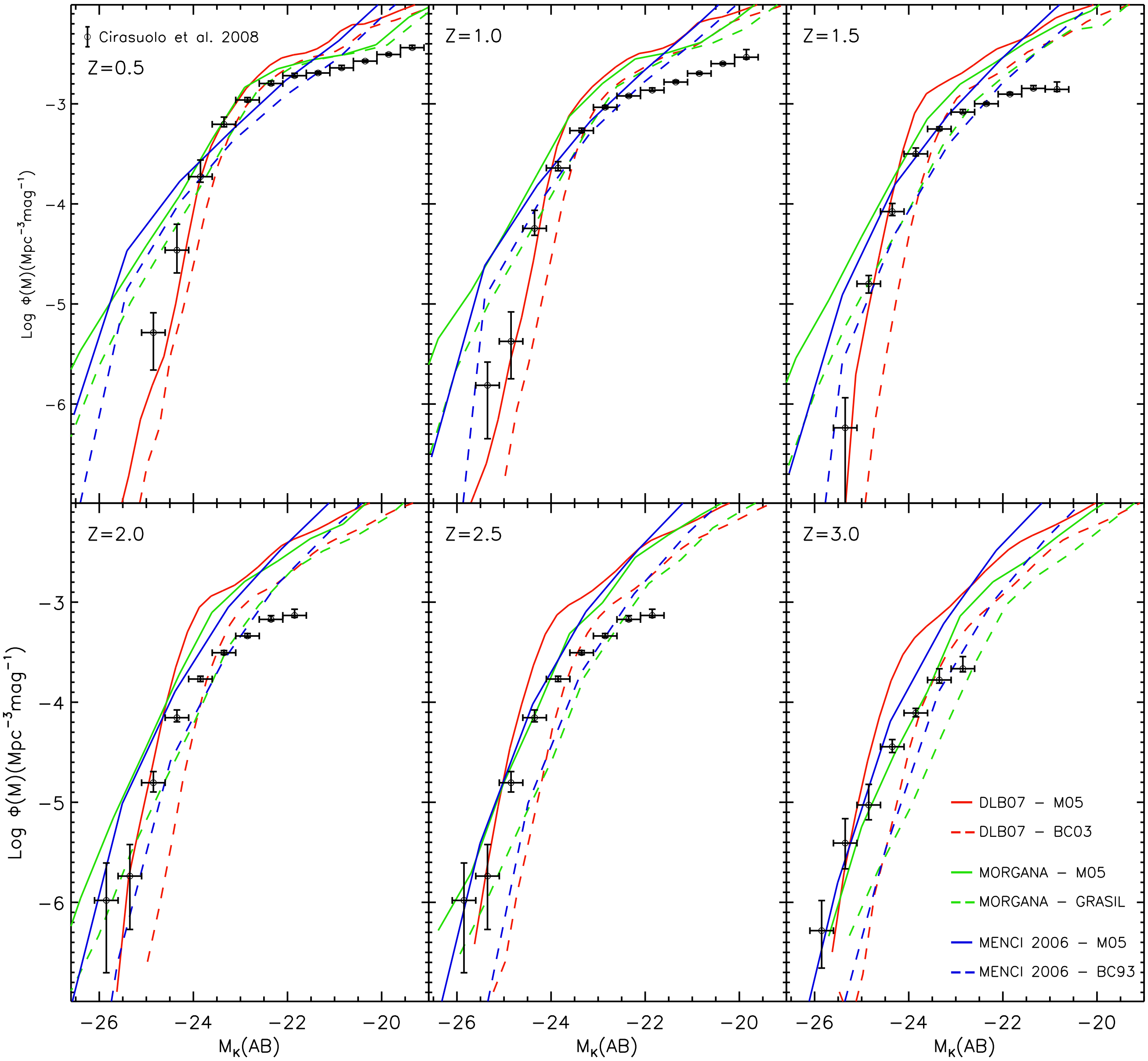

Figure 2. The evolution of the K-band luminosity function from z=3.0 to z=0.5. The original predictions from three different semi-analytic models are shown as dashed lines and their version with the M05 as solid lines. Red lines refer to De Lucia & Blaizot (2007), green to Monaco et al. (2007) and blue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

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 it is weaker and the oldest population is ∼ 1 Gyr younger than its counter part in the Munich model. On the other hand, MORGANA shows considerably younger ages, centered at ∼2.5 Gyr, with only a very week peak at ∼ 4 Gyr. Despite the difference in the age distribution at z=0.5, 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 modeling of "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.

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. 4, 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

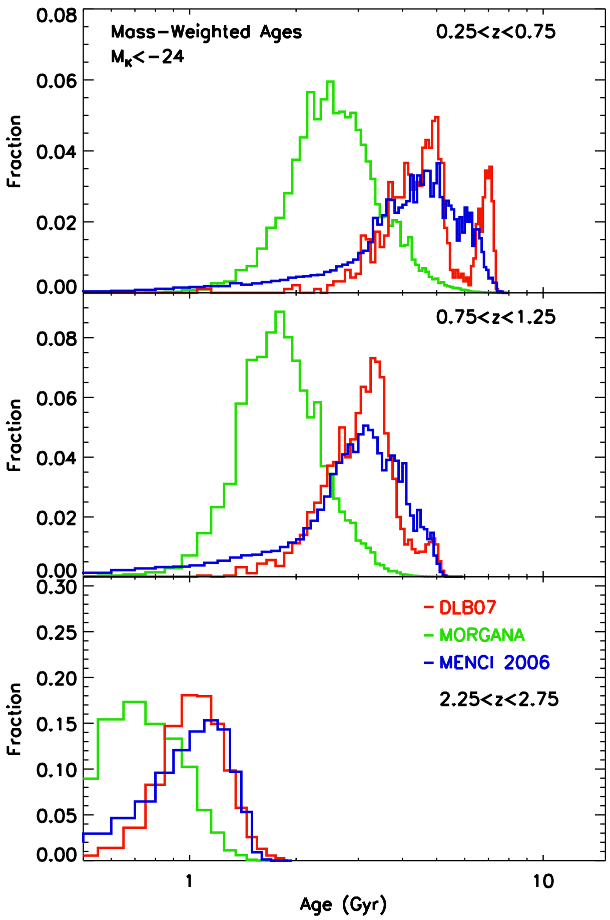

Figure 3. The mass-weighted age distribution of galaxies with $M_K < -24$ in the three semi-analytic models used in our study. In the three panels, the solid red line represents De Lucia & Blaizot (2007), the solid green line shows MORGANA predictions and the solid blue line gives the ages in Menci et al. (2006). From top to bottom, the panels show respectively galaxies ages at z=0.5, z=1.0 and z=2.5.

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. 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 luminosity function, the faint end remains problematic. The luminosity (as well as the stellar mass) function for faint objects ($-22 \leqslant M_K \leqslant -24$) is known to be much higher than measured (Fontana et al. 2006; Weinmann et al. 2006; Henriques et al. 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. 2010). 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.

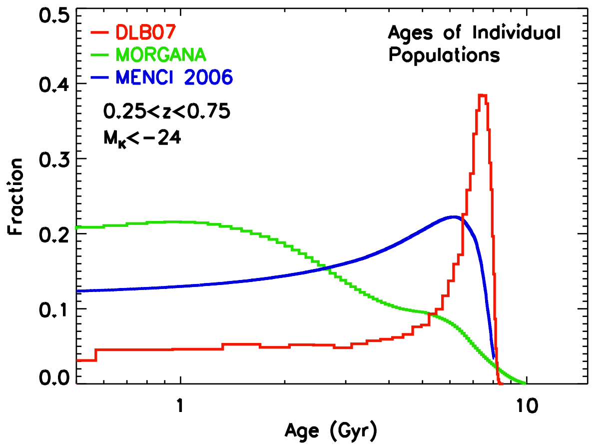

Figure 4. The ages of the individual populations present in semi-analytic galaxies with $M_K < -24$. The solid red line represents De Lucia & Blaizot (2007), the solid green line shows MORGANA predictions and the solid blue line gives Menci et al. (2006) ages at z=0.5.

5 SUMMARY

The main objective of this work is to re-address the fundamental question of matching the observed rest-frame K-band luminosity function 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 ($\sim 2-3$), and the failure has been attributed to an insufficient mass build-up at early epochs.

However, the galaxy luminosity function 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 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 Gyrs), 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

De Lucia & Blaizot (2007), MORGANA (Monaco et al. 2007) and Menci et al. (2006) and we 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 mags 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 $\mathrm{M}_K < -24$ now match very well.

This result is strongly suggestive that the models at redshift $2 - 3$ 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 timescales 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 luminosity function 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 luminosity function 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; Henriques & Thomas 2010; Fontanot et al. 2009b; Guo et al. 2010) 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 infra-red). Therefore, we should now be able to constrain galaxy formation models with better accuracy and disentangle between different theoretical approaches.

ACKNOWLEDGEMENTS

This project is supported by the Marie Curie Excellence Team Grant MEXT-CT-2006-042754 "UniMass" of the Training and Mobility of Researchers programme financed by the European Community. PM and FF acknowledge support by the ASI/COFIS grant. FF acknowledges the support of an INAF-OATs fellowship granted on 'Basic Research' funds. GDL acknowledges financial support from the European Research Council under the European Communitys Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement n. 202781.

The authors thank Emanuele Daddi for helpful comments. PM and FF thank Laura Silva for useful discussions. BH, CM and CT thanks Edd Edmondson for a computer network that always works. BH thanks Peter Thomas for his guidance and constant support.

REFERENCES

Baugh C. M., 2006, Reports on Progress in Physics, 69, 3101

Bower R. G., Vernon I., Goldstein M., Benson A. J., Lacey C. G., Baugh C. M., Cole S., Frenk C. S., . 2010, ArXiv e-prints

Boylan-Kolchin M., Ma C.-P., Quataert E., 2008, MNRAS, 383, 93

Bruzual G., 2007, ASPCS, 374, 303

Bruzual G., Charlot S., 2003, MNRAS, 344, 1000

Bruzual A. G., 1983, ApJ, 273, 105

Bruzual A. G., Charlot S., 1993, ApJ, 405, 538

Buzzoni A., 1989, ApJ Supp., 71, 817

Chabrier G., 2003, PASP, 115, 763

Chandrasekhar S., 1943, ApJ, 97, 255

Cimatti A., Cassata P., Pozzetti L., Kurk J., Mignoli M., Renzini A., Daddi E., Bolzonella M., Brusa M., Rodighiero G., Dickinson M., Franceschini A., Zamorani G., Berta S., Rosati P., Halliday C., 2008, Astronomy and Astrophysics Supplement Series, 482, 21

Cimatti A., Daddi E., Renzini A., Cassata P., Vanzella E., Pozzetti L., Cristiani S., Fontana A., Rodighiero G., Mignoli M., Zamorani G., 2004, Nat., 430, 184

Cirasuolo M., McLure R. J., Dunlop J. S., Almaini O., Foucaud S., Simpson C., 2010, MNRAS, 401, 1166

Conroy C., Gunn J. E., White M., 2009, ApJ, 699, 486

Croton D. J., Springel V., White S. D. M., De Lucia G., Frenk C. S., Gao L., Jenkins A., Kauffmann G., Navarro J. F., Yoshida N., 2006, MNRAS, 365, 11

De Lucia G., Blaizot J., 2007, MNRAS, 375, 2

De Lucia G., Boylan-Kolchin M., Benson A. J., Fontanot F., Monaco P., 2010, ArXiv e-prints

De Lucia G., Kauffmann G., Springel V., White S. D. M., Lanzoni B., Stoehr F., Tormen G., Yoshida N., 2004, MNRAS, 348, 333

Eminian C., Kauffmann G., Charlot S., Wild V., Bruzual G., Rettura A., Loveday J., 2008, MNRAS, 384, 930

Fioc M., Rocca-Volmerange B., 1997, Astronomy and Astrophysics Supplement Series, 326, 950

Fontana A., Salimbeni S., Grazian A., et al., 2006, Astronomy and Astrophysics Supplement Series, 459, 745

Fontanot F., De Lucia G., Monaco P., Somerville R. S., Santini P., 2009, MNRAS, 397, 1776

Fontanot F., Monaco P., 2010, MNRAS, pp 473–+

Fontanot F., Monaco P., Cristiani S., Tozzi P., 2006, MNRAS, 373, 1173

Fontanot F., Pasquali A., De Lucia G., van den Bosch F. C., Somerville R. S., Kang X., 2010, ArXiv e-prints

Fontanot F., Somerville R. S., Silva L., Monaco P., Skibba R., 2009, MNRAS, 392, 553

Gao L., White S. D. M., Jenkins A., Stoehr F., Springel V., 2004, MNRAS, 355, 819

Guo Q., White S., Boylan-Kolchin M., De Lucia G., Kauffmann G., Lemson G., Li C., Springel V., Weinmann S., 2010, ArXiv e-prints

Hatton S., Devriendt J. E. G., Ninin S., Bouchet F. R., Guiderdoni B., Vibert D., 2003, MNRAS, 343, 75

Henriques B. M., Bertone S., Thomas P. A., 2008, MNRAS, 383, 1649

Henriques B. M. B., Thomas P. A., 2010, MNRAS, 403, 768

Henriques B. M. B., Thomas P. A., Oliver S., Roseboom I., 2009, MNRAS, 396, 535

Iben Jr. I., Renzini A., 1983, ARA&A, 21, 271

Kampakoglou M., Trotta R., Silk J., 2008, MNRAS, 384, 1414

Kelson D. D., Holden B. P., 2010, ApJ, 713, L28

Kimm T., Somerville R. S., Yi S. K., van den Bosch F. C., Salim S., Fontanot F., Monaco P., Mo H., Pasquali A., Rich R. M., Yang X., 2009, MNRAS, 394, 1131

Kitzbichler M. G., White S. D. M., 2007, MNRAS, 376, 2

Lauer T. R., Faber S. M., Richstone D., Gebhardt K., Tremaine S., Postman M., Dressler A., Aller M. C., Filippenko A. V., Green R., Ho L. C., Kormendy J., Magorrian J., Pinkney J., 2007, ApJ, 662, 808

Leitherer C., Schaerer D., Goldader J. D., González Delgado R. M., Robert C., Kune D. F., de Mello D. F., Devost D., Heckman T. M., 1999, ApJ Supp., 123, 3

Lo Faro B., Monaco P., Vanzella E., Fontanot F., Silva L., Cristiani S., 2009, MNRAS, 399, 827

Lu Y., Mo H. J., Weinberg M. D., Katz N. S., 2010, ArXiv e-prints

Maraston C., 1998, MNRAS, 300, 872

Maraston C., 2005, MNRAS, 362, 799

Maraston C., Bastian N., Saglia R. P., Kissler-Patig M., Schweizer F., Goudfrooij P., 2004, Astronomy and Astrophysics Supplement Series, 416, 467

Maraston C., Daddi E., Renzini A., Cimatti A., Dickinson M., Papovich C., Pasquali A., Pirzkal N., 2006, ApJ, 652, 85

Maraston C., Kissler-Patig M., Brodie J. P., Barmby P., Huchra J. P., 2001, Astronomy and Astrophysics Supplement Series, 370, 176

Marigo P., Girardi L., 2007, Astronomy and Astrophysics Supplement Series, 469, 239

Marigo P., Girardi L., Bressan A., Groenewegen M. A. T., Silva L., Granato G. L., 2008, Astronomy and Astrophysics Supplement Series, 482, 883

Menci N., Cavaliere A., Fontana A., Giallongo E., Poli F., 2002, ApJ, 575, 18

Menci N., Fontana A., Giallongo E., Grazian A., Salimbeni S., 2006, ApJ, 647, 753

Monaco P., Fontanot F., Taffoni G., 2007, MNRAS, 375, 1189

Monaco P., Murante G., Borgani S., Fontanot F., 2006, ApJ, 652, L89

Monaco P., Theuns T., Taffoni G., Governato F., Quinn T., Stadel J., 2002, ApJ, 564, 8

Pozzetti L., Cimatti A., Zamorani G., Daddi E., Menci N., Fontana A., Renzini A., Mignoli M., Poli F., Saracco P., Broadhurst T., Cristiani S., D'Odorico S., Giallongo E., Gilmozzi R., 2003, Astronomy and Astrophysics Supplement Series, 402, 837

Salpeter E. E., 1955, ApJ, 121, 161

Silva L., Granato G. L., Bressan A., Danese L., 1998, ApJ, 509, 103

Somerville R. S., Hopkins P. F., Cox T. J., Robertson B. E., Hernquist L., 2008, MNRAS, 391, 481

Springel V., White S. D. M., Jenkins A., et al., 2005, Nat., 435, 629

Taffoni G., Mayer L., Colpi M., Governato F., 2003, MNRAS, 341, 434

Thomas D., Maraston C., Bender R., 2003, MNRAS, 339, 897

Tinsley B. M., 1972, ApJ, 178, 319

Tonini C., Maraston C., Devriendt J., Thomas D., Silk J., 2009, MNRAS, 396, L36

Tonini C., Maraston C., Thomas D., Devriendt J., Silk J., 2010, MNRAS, 403, 1749

van der Wel A., Franx M., Wuyts S., van Dokkum P. G., Huang J., Rix H., Illingworth G. D., 2006, ApJ, 652, 97

Vazdekis A., Casuso E., Peletier R. F., Beckman J. E., 1996, ApJ Supp., 106, 307

von der Linden A., Best P. N., Kauffmann G., White S. D. M., 2007, MNRAS, 379, 867

Wang J., De Lucia G., Kitzbichler M. G., White S. D. M., 2008, MNRAS, 384, 1301

Weinmann S. M., van den Bosch F. C., Yang X., Mo H. J., Croton D. J., Moore B., 2006, MNRAS, 372, 1161

Worthey G., 1994, ApJ Supp., 95, 107