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Why Galaxies Care about AGB Stars. Modelling Galaxies.

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Abstract. The Thermally-Pulsating Asymptotic Giant Branch (TP-AGB) phase of stellar evolution has received attention only recently in galaxy evolution, but is now an important player in our understanding of how galaxies form and evolve. Because it is a short but very luminous phase, bright in the near-IR where dust effects are small, the TP-AGB phase is a powerful tracer of intermediate-age stars in galaxies up to high redshift. The spectral signature of TP-AGB stars as defined by population synthesis models has been detected by the *Spitzer Space Telescope* in high-redshift galaxies, whose spectra show an amazing similarity to spectra of local stellar populations. Even accounting for the high uncertainty affecting the theoretical modelling of this phase, stellar population models including the TP-AGB have leveraged a better determination of galaxy ages and hence stellar masses, fundamental quantities for studying galaxy formation and evolution. They have also improved the results of semi-analytic models, which can better reproduce colours and the K-band luminosity function of high-z galaxies.

1. Background: Stellar Population Models and Galaxy Evolution

Stellar population models are the tool to perform galaxy evolution studies, as they predict the integrated spectrophotometric properties of arbitrary populations of stars as a function of parameters such as age, chemical composition, star formation history, initial mass function, stellar mass, etc. Their usage is twofold: they allow the derivation of galaxy properties from data on observed galaxies, and they are the ingredients for calculating the predicted spectra of synthetic galaxies from galaxy formation models (see e.g. Baugh 2006). I will review results on both aspects, focusing on the role played by the Asymptotic Giant Branch (AGB) phase of stellar evolution – the protagonist of this meeting – on our understanding of galaxy evolution.

1.1. Model Basics

Stellar population models are calculated assuming (1) stellar evolution models which provide the energetics at given stellar mass; (2) stellar spectra for distributing the energetics at the various wavelengths; and (3) a numerical algorithm to calculate the integrated spectral energy distribution (SED). This approach – which is based on stellar evolution – is referred to as Evolutionary Population Synthesis (EPS), the foundations of which are due to the pioneering work by Tinsley (1972) and Renzini (1981).

Figure 1 illustrates the concept of EPS models and their development over the last three decades. The left-hand plot shows the theoretical HR diagram for a coeval population of stars with different initial masses, up to the tip of the Red Giant Branch (RGB).

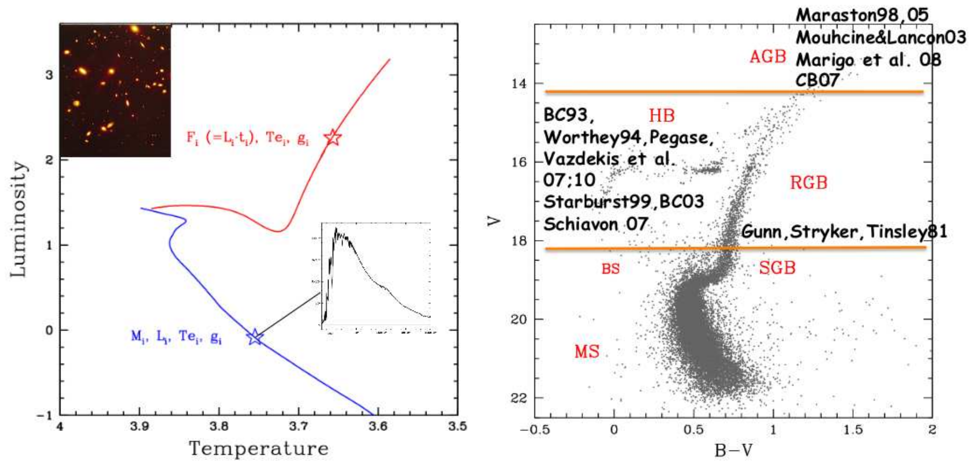

Figure 1. EPS model calculation and model evolution over years. *Left*: Theoretical HR diagram for a coeval population, with blue and red lines indicating stars on the Main Sequence (MS) and post-Main Sequence. The inserts show a galaxy cluster at redshift 0.6, and the spectrum of a MS star. The integrated spectrum is calculated by summing up the contribution by all mass bins, following different techniques (see text). *Right*: The evolution of EPS models with respect to the inclusion of stellar evolutionary phases. The TP-AGB has been added last to population synthesis.

The spectrum of the population is obtained by integrating the luminosity contribution from stars of different masses convolved with the assumed initial mass function (IMF).

The integral can be performed using mass as the evolutionary variable, as in the so-called isochrone synthesis (Bruzual & Charlot 1993). An alternative approach is based on Renzini's *fuel consumption theorem* (Renzini 1981), as in the models by Buzzoni (1989) and Maraston (1998, 2005, hereafter M98, M05), and also by Marigo & Girardi (2007) for constraining the contribution of the TP-AGB in their stellar models. In the Maraston models, the integration variable adopted in post-MS is the *fuel*, i.e. the product of luminosity and lifetime (Fig. 1, *left*). This approach turned out to be particularly useful for inserting a prescription for the TP-AGB in EPS models. The right-hand panel provides a historical overview over the evolution of these models, which could be viewed as the evolution in the number of major stellar phases that could be included in the synthesis. While at the end of the 1970's models could cover just the base of the RGB (Gunn et al. 1981), during the 1990's the availability of large grids of isochrones from the Padova group (Bertelli et al. 1994) allowed the inclusion of all stellar phases up to the end of the Early-Asymptotic Giant Branch (E-AGB; Worthey 1994; Bruzual & Charlot 1993; Vazdekis et al. 1996, 2010; Fioc & Rocca-Volmerange 1997; Leitherer et al. 1999; Schiavon 2007) or shortly after as in the models by Bruzual & Charlot (2003, hereafter BC03).

The TP-AGB was included in the Maraston models in a semi-empirical fashion, as described in the next Section. Marigo et al. (2008) extend the Padova isochrones with their models for the TP-AGB, after calibrating them with data as in the Maraston models. Mouhcine & Lançon (2003) present an implementation of TP-AGB based on their own stellar models. The reader is referred to the review by Lançon (this volume) for further details on models and comparison to star clusters.

1.2. TP-AGB in Integrated Models: a Semi-empirical Approach

The theoretical modelling of the TP-AGB presents several well-known but challenging aspects stemming from the pulsational regime, the double-shell burning, and especially the strong mass loss affecting this phase. Also complicated is the spectral modelling, especially during the carbon-rich phase. These issues have traditionally hampered the calculation of isochrones that could easily be implemented in population synthesis. In

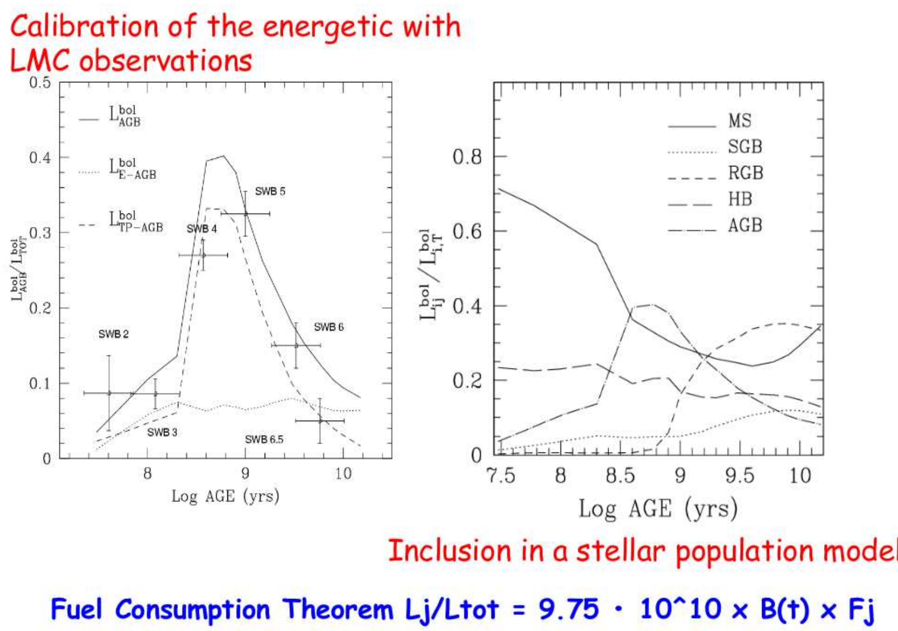

Figure 2. Modelling the TP-AGB with the fuel consumption theorem

order to overcome this situation and test the effect these luminous stars have on the integrated properties of galaxies, M98 attempted a semi-empirical approach. The theoretical energetics in the TP-AGB phase for stellar models of several initial masses were calibrated with the observed bolometric contribution by the TP-AGB in Magellanic Cloud (MC) globular clusters (GCs) from Frogel et al. (1990). Key to this calibration is the fuel consumption theorem (FCT; Renzini 1981, see Eq. in Figure 3), which expresses the bolometric luminosity of a post-MS phase J in terms of the *fuel* (i.e. equivalent masses of H and/or Helium) at disposal for core/shell burning to a star of mass equal to the turnoff mass M_{TO} at the given population age. Note that because the fuel is calibrated with observations, it automatically includes the (otherwise unknown) effect from mass-loss. The left-hand plot of Figure 2 shows the calibration of the bolometric contribution of the AGB phase to the total as a function of the age of the population, split into E-AGB and TP-AGB. This calibration shows a peak contribution by the TP-AGB phase in populations with ages $\sim 0.5 - 1$ Gyr, by up to 40% of the bolometric contribution. It is important to stress that stochastic fluctuations in the number of bright AGB stars per cluster, which are due to the shortness of the TP-AGB phase ($\sim 10^6$yr), were minimised by averaging the TP-AGB contributions in GCs of similar age (see M98 for details). Vertical error bars show the size of such stochastic fluctuations. Horizontal error bars represent the uncertainty in GC ages, which stem from the fact that tracks with and without overshooting fit the same turnoff with ages that differ by a few hundred million years (Girardi et al. 1995; Ferraro et al. 1995, 2004). Note also that the MC GCs are the most useful calibrators in this context as their metallicities and ages – unlike more distant star clusters or galaxies – can be derived independently of stellar population models.

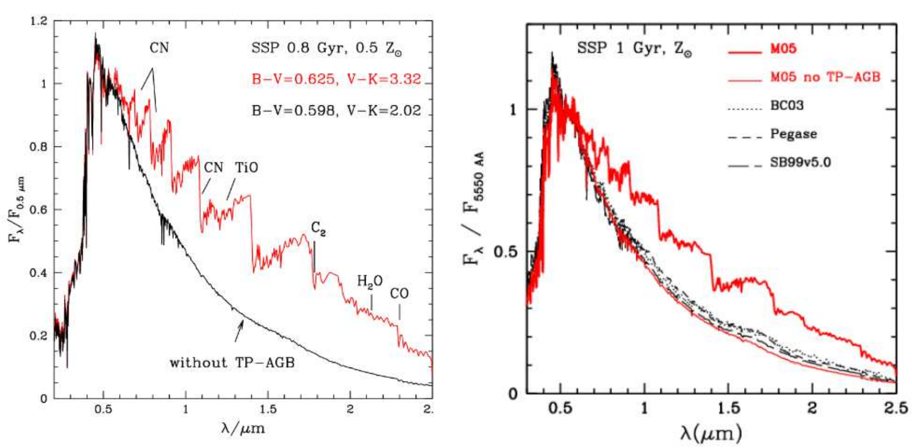

Figure 3. Effect of TP-AGB on the synthetic SED of population models

M05 – following the availability of empirical spectra of C-rich and O-rich TP-AGB stars from Lançon & Wood (2000) – extended the modelling of M98 by calculating the full SED of population models of various ages and metallicities, with the aim of studying high-redshift galaxies. Figure 3 (left) shows the effect of the TP-AGB on the integrated SED. The addition of luminous red stars increases the flux in the near-IR compared to a model including only the E-AGB, and the spectral absorptions typical of TP-AGB stars become apparent. The right-hand plot compares model SEDs from different authors, not including the TP-AGB or adopting different prescriptions (see M05 for details and references). This plot helps understanding discrepant results that are obtained on galaxies when different models, together with data extending to the near-IR rest-frame, are used to derive galaxy properties.

1.2.1. Caveats

There are a number of caveats intrinsic to the semi-empirical modelling, namely: the onset age, the energetics, stochastic fluctuations, and metallicity effects.

First, the age at which the TP-AGB is held to be relevant is calibrated with the ages of MC GCs, which depend on the tracks adopted to derive them and also on the fitting method. In the Maraston models the relevant age range is between 0.3 and 2 Gyr (Fig. 2), which stems from turnoff ages derived via classical (non overshooting) tracks. Recent work has confirmed this scale (Mucciarelli et al. 2006). Tracks with overshooting make the peak age older by some hundred million years (Girardi et al. 1995; Marigo et al. 2008). However, there is not yet universal agreement on the actual size of overshooting. Moreover, MC age fitting that includes post-MS stars and not only the turnoff, pushes the ages of some MC GCs to even older values (Kerber et al. 2007). This older age scale was used by Pessev et al. (2008) and Conroy & Gunn (2010) to argue that the Maraston models are mis-calibrated, but this – more than a conclusion – is a tautology as the calibration depends on the adopted age scale.

Stochastic fluctuations in the number of bright AGB stars affect the observed colours and magnitudes (see Lançon, this volume). M98 used a representative average cluster for each age bin (Fig. 2, details in M98) so that there is probably little doubt that the bolometric contribution of the TP-AGB can be up to 40 %, whereas the maximum age and the shape of the phase transition depends on the adopted age scale and on the age binning.

A further caveat regards the metallicity dependence of the energetics and stellar spectra. The Maraston models assume the theoretical scaling proposed by Renzini & Voli (1981) according to which a metal-rich population burns more TP-AGB fuel in form of oxygen-rich stars than in carbon stars. This trend of spectral type with metallicity is confirmed by modern models (e.g. Marigo et al. 1996), though the quantitative scaling may be different. On the other hand, the same empirical spectra are used, which involves the assumption that the main spectral features of the two types do not depend on the initial chemical composition. Lyubenova et al. (2010) cast some doubt on this assumption, as they find that the CO absorption measured in two MC GCs with ages around 1 Gyr is lower than predicted by the M05 models (while the integrated colours of the same objects perfectly agree). Their suggestion is that – due to the lower metallicity of the Magellanic Clouds with respect to our Galaxy and the stars observed by Lançon & Wood – the spectral absorptions cannot be adequately modelled. More data will be interesting, as the result is based on only two objects with the lowest S/N.

2. Why Real Galaxies Care about AGB Stars

The AGB phase is bright and well-populated in intermediate-age stellar populations for a short period of time. This makes it a powerful age indicator, and generally a useful tool to break the age/metallicity degeneracy, which plagues the analysis of galaxy spectra. The high-redshift Universe is the best target for several reasons: galaxies are younger and the age spread between different stellar generations is smaller than in local objects, both facts helping to enhance the signal of the AGB phase in the spectra. The M05 models were motivated by the launch of NASA's *Spitzer Space Telescope*, which could sample the galaxy rest-frame near-IR spectrum – which hosts the signature of red stars (cf. Fig. 3) – up to high redshift (Maraston 2005). A large number of papers have

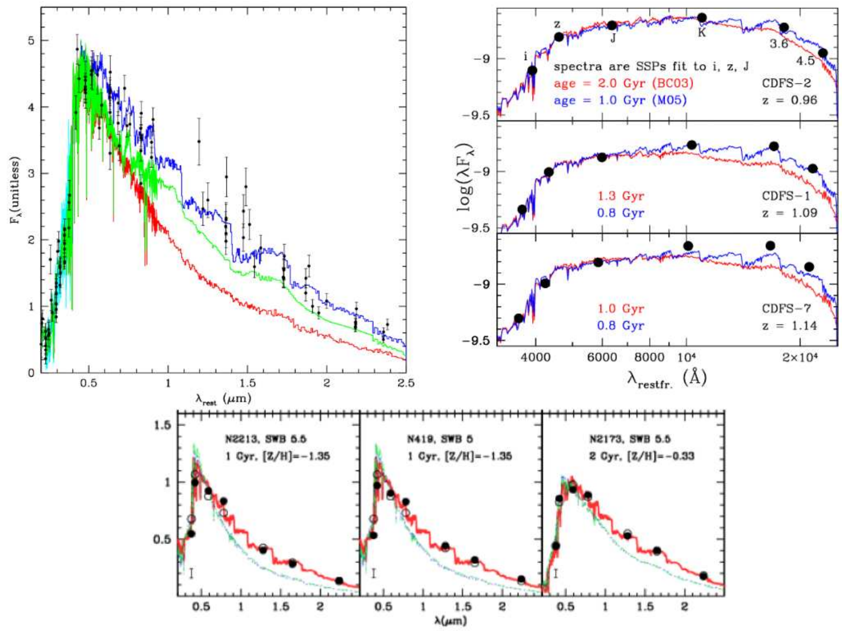

Figure 4. AGB stars are common inhabitants in high-redshift galaxies. *Upper left*: Stacked spectrum of $z \sim 2$ galaxies from Cimatti et al. (2008), compared to models by M05 (blue), BC03 (red) and Charlot & Bruzual (2007, *private communication*, green). *Upper right*: Data for field galaxies at redshift 1 fitted with M05 and BC03 models (red and blue lines, from van der Wel et al. 2006). *Bottom panel*: Large Magellanic Cloud GCs SED fit from M05.

been published on the topic. In the following we shall provide a brief snapshot of the importance of the TP-AGB in galaxies as a function of redshift.

2.1. AGB Stars: Common Inhabitants as a Function of Redshift

Figure 4 illustrates the effect of the TP-AGB on the fitting of observed galaxy spectrophotometry, for galaxies at various redshifts and for local MC GCs.

The right-hand plot shows the SED fit for galaxy data at redshift ~ 1 with M05 and BC03 models (blue and red lines, respectively). The SED fit is performed using just the three bands i, z, J, which sample the rest-frame spectrum up to $\sim$ 8000 Å. Longer wavelength data are added onto the best-fit model, without using them to further constrain the fit. The M05 models with their prescriptions for the TP-AGB phase fit the rest-frame near-IR much better, the other model lacking near-IR rest-frame flux. Note that the galaxy light-averaged ages obtained with the two models are different, namely the M05 models give younger ages. Finally, note that if one fits all six bands simultaneously, good solutions would be found for the BC03 models as well, which probably would yield older ages/higher metallicities/higher dust content, in essence all model ingredients that help to give a higher flux in the near-IR. One cannot avoid noting, however, that the TP-AGB solution fits the whole spectrophotometry well. The left-hand panel shows a similar SED fit for a galaxy stack at $z \sim 2$. Note the strong near-IR fluxes of these galaxies that are best fitted with models including a strong TP-

AGB. The figure also includes a comparison with the models by Charlot & Bruzual (*in preparation*) which adopt the Marigo et al. (2008) isochrones. Finally note the SED fits of MC GCs from M05. The similarity between the spectra of small, local objects, and distant, massive galaxies with similar ages is suggestive of an overall similarity in the stellar evolution of AGB stars born locally and in the distant Universe.

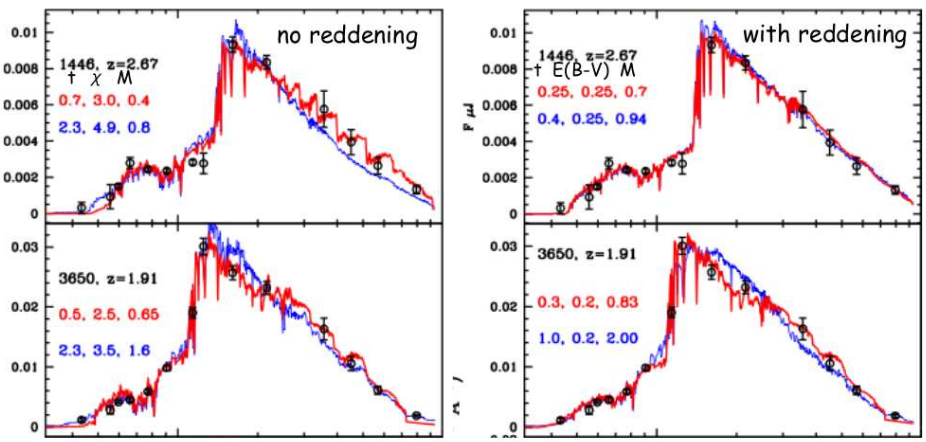

Figure 5. Effect of population models – M05 in red and BC03 in blue – on the physical properties derived for galaxies. *Left*: the SEDs of two galaxies on the assumption of no reddening; *right*: the same galaxies fitted with additional reddening. Labels indicate age, χ^2 and stellar mass on the left, and age, reddening $E(B-V)$ and stellar mass on the right. Note that these galaxies were pre-selected to be mostly passive and were found to be lacking dust re-emission; hence the fit with reddening is a formal, but probably not very realistic, solution. From Maraston et al. (2006)

We now illustrate why details of the TP-AGB modelling are critical for the derivation of galaxy properties. Figure 5 shows the SED fit of galaxies at redshift ~ 2 for the M05 (red) and the BC03 (blue) models. In the left-hand panel reddening was not included in the fit. Galaxy ages derived with the M05 models are lower, because the TP-AGB makes the galaxy red at a younger age, whereas the BC03 models require older ages with a pronounced RGB for matching the high near-IR fluxes, even if the fit is not equally good. The older ages explain the higher masses. The addition of reddening dilutes, but does not remove, the differences. Maraston et al. (2006) found that masses derived with M05 are on average $\sim$30 to 50 % lower than those derived with BC03, a figure that has been confirmed in several subsequent works. It is important to note that these galaxies have been found to have a negligible amount of dust. Hence, the solutions with reddening are statistically good, but perhaps not very realistic. Similar results can be found in the literature, leading to the following conclusions: models with TP-AGB give lower ages, lower stellar masses and lower dust content.

One may be tempted to conclude that a TP-AGB prescription as in M05 provides good fits to galaxies over a wide redshift range. This conclusion has been challenged by Kriek et al. (2010), who – based on their SED fit of colour-defined post-starburst galaxies with photometric redshifts over a broad redshift range (1 to 2.5) – conclude that M05 and Marigo et al. (2008) overestimate the TP-AGB contribution while the BC03 models work better. It is not easy to reconcile this result with others - for example Raichoor et al. (2011) just conclude the opposite, namely that M05 and Charlot & Bruzual 2007 *private communication* fit better than BC03 (see also the next Section).

Finally, worth mentioning in the high-redshift context is the result by Kelson & Holden (2010) who – extending the M05 models longward to the *K*-band – find that the contribution of AGB stars to dust re-emission is significant and affects the determination of galaxy star-formation rates from 24 μm data, lowering the high values sometimes derived for high-z galaxies, with obvious impact on our understanding of galaxy evolution.

2.2. Local Galaxies in Integrated Light

Several types of galaxies in the local Universe are known to host significant numbers of AGB stars, and this conference has an entire session devoted to resolved stellar populations in nearby systems. Here I will focus on results for the local Universe that are obtained in integrated light. For galaxies with star formation – or, more generally, with stellar populations with ages around 1 Gyr – the modelling of the TP-AGB should be relevant.

For spiral galaxies, MacArthur et al. (2010) find that the star formation histories derived from optical spectroscopy with the BC03 models give predicted near-IR colours that are too blue compared with the observed ones. The correct colours, matching the observations, are obtained with the M05 models because of their brighter TP-AGB. Eminian et al. (2008) analyse the near-IR colours of a sample of $\sim$ 6000 galaxies from SDSS and find that galaxies with higher star formation rates have bluer optical colours *and* redder near-IR colours, which are better explained with models including the TP-AGB phase such as M05 and CB07 rather than the BC03 ones. Both conclusions are at odds with the results by Kriek et al. (2010) mentioned above. From the spectroscopic side, Riffel et al. (2007, 2008) obtained the near-IR spectra of Seyfert/AGN-host galaxies and show that the spectral bumps in the near-IR can only be explained with the M05 models because they include empirical carbon- and oxygen-rich TP-AGB stars. The amount of TP-AGB fuel in the M05 model does not appear to be excessive. Similarly, Miner et al. (2011) measure C_2 and other spectral features in the near-IR spectra of the dwarf elliptical M 32 and the post-starburst galaxy NGC 5102, finding that ages obtained with the M05 models are consistent with ages derived from the optical spectra in the literature. Moreover, they find that decreasing the TP-AGB fuel as suggested by Kriek et al. (2010) breaks this agreement (J. Miner, *private communication*). TP-AGB stars even affect galaxy dynamics. Rothberg & Fischer (2010) show that the measurement of dynamical masses for merger remnants from CO absorptions is affected by the choice of stellar population models and find encouraging results using the M05 models. In years to come we shall see the full development of near-IR spectroscopy which will greatly improve our knowledge on these issues.

3. Why Semi-analytic Galaxies Care about AGB Stars

Recent works have shown that the TP-AGB prescriptions in stellar population models adopted in galaxy formation models influence the meaning of the comparison with observations. In Tonini et al. (2009, 2010) we calculate semi-analitic models (SAM) with different input stellar population models and compare them to data for high-z galaxies. Figure 6 shows that the observed-frame theoretical colour-magnitude diagram of semi-analytic galaxies at redshift 2 (small red and cyan points) is only able to match the observations (large black points) when the input stellar population model includes the TP-AGB phase (left-hand panel). This suggests that much of the well-known mismatch between high-z data and traditional semi-analytic models (SAMs; right-hand panel) may be due to a light deficit at given mass, rather than to a mass deficit.

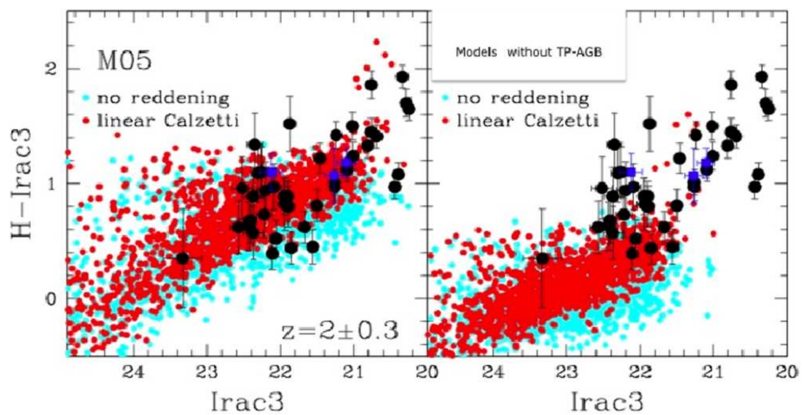

Figure 6. Observed-frame colour-magnitude diagram (corresponding to rest-frame K vs. V–K) of redshift 2 galaxies from semi-analytic models (small red and cyan points, from Tonini et al. 2010) compared to observations (large black circles).

Henriques et al. (2011) use several SAMs equipped with models with and without the TP-AGB phase to understand the discrepancy with the observed near-IR high-z galaxy luminosity function. Figure 7 shows that SAM models with the M05 models match the rest-frame near-IR luminosity function at high-redshift, where the discrepancy was pointed out. Finally, Fontanot & Monaco (2010) conclude that the observed colours of Extremely Red Objects can be better matched by SAM models including a bright TP-AGB.

4. Concluding Remarks

The recent inclusion of the TP-AGB in stellar population models has had a significant impact on our understanding of real galaxies as well as of synthetic galaxies from galaxy formation models. Galaxies do care about AGB stars! While the exact energetics for the TP-AGB may still be debatable, there is no doubt that several spectral features as well as the spectral continuum in the near-IR can be better explained with models including a substantial contribution (up to 40% of the bolometric contribution)

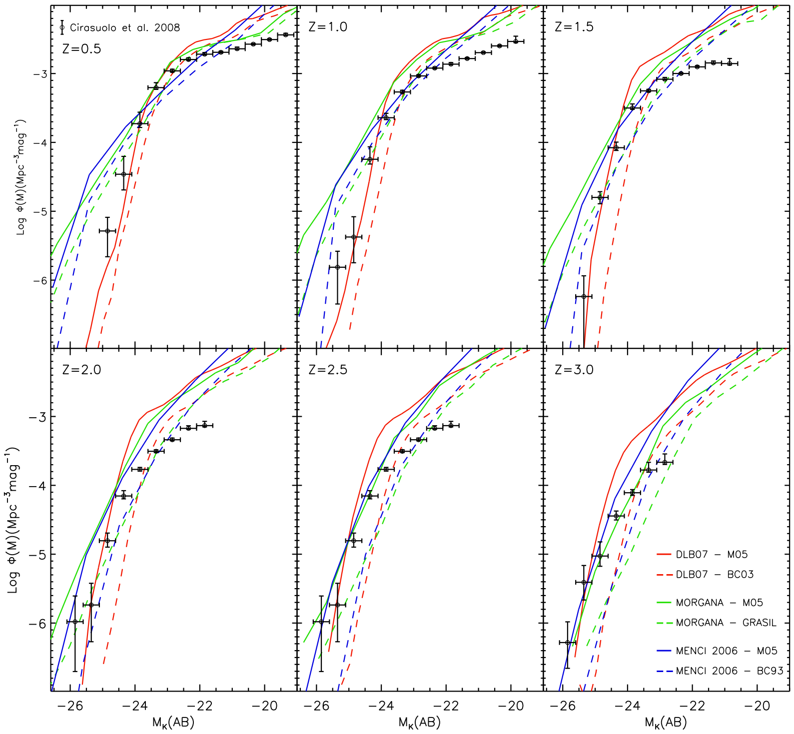

Figure 7. Rest-frame *K*-band luminosity function of galaxies as a function of redshift (filled points with errorbars, Cirasuolo et al. 2010) compared with the predictions of several semi-analytic models as a function of the TP-AGB modelling in the input stellar population model. Dashed lines refer to stellar population models with little TP-AGB, solid lines to M05 models.

from the TP-AGB. Once more it is clear how our understanding of the galaxy formation process in a cosmological sense depends on our understanding of stellar evolution.

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