Session II

Spectral Evolution Models

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Population Synthesis: Challenges for the Next Decade

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Abstract. In this paper I present a brief summary of recent advances in the fields of stellar evolution, stellar model atmospheres, and stellar spectral libraries, which allow us to build more realistic stellar population synthesis models than those available up to now. Applications of these models to problems of current interest are discussed. Problems that need to be understood and data sets that need to be collected in order to solve issues present in these models are listed.

Keywords. galaxies: stellar content; galaxies: spectral evolution; stars: evolution.

1. Introduction

In the last few years we have seen considerable progress in the quality and extent of data sets used as ingredients in population synthesis models. Stellar evolution models with updated input physics for stars up to $15 M_\odot$ have been computed by Bertelli *et al.* (2008). Marigo & Girardi (2007), and Marigo *et al.* (2008) provide a semi-empirical prescription to follow the evolution of TP-AGB stars that includes several important theoretical improvements over previous calculations. The Marigo & Girardi (2007) prescription has been calibrated using carbon star luminosity functions in the Magellanic Clouds and TP-AGB lifetimes (star counts) in Magellanic Cloud clusters. Bertelli *et al.* (2008) use different TP-AGB tracks, also based on the Marigo & Girardi (2007) prescription, but extrapolated to different chemical compositions of the stellar envelope. As pointed out by Bertelli *et al.* (2008), their sets of TP-AGB tracks are uncalibrated, since no attempt was made to reproduce the available observations.

Numerous stellar spectral libraries are available and ready to use for population synthesis models. On the theoretical side, spectral libraries of theoretical model atmospheres by Lanz & Hubeny (2003), Martins *et al.* (2005), Rodríguez-Merino *et al.* (2005), Coelho *et al.* (2007), Lanz & Hubeny (2007), and Aringer *et al.* (2009), represent important improvements over the Westera *et al.* (2002) BaSeL 3.1 atlas, both in spectral resolution and coverage of physical parameters. Similarly, the IndoUS (Valdes *et al.* 2004), Miles (Sánchez-Blázquez *et al.* 2006), and HNGSL (Heap *et al.* 2006) libraries provide high quality empirical spectra with excellent coverage of parameter space in the optical range (the HNGSL covers down to 2000Å) for stars of different metallicities not far from $Z_\odot$, increasing the number of available spectra by a factor of roughly 20 with respect to the Stelib library (Le Borgne *et al.* 2003) used in BC03. IR spectra of unprecedented quality are contained in the IRTF library (Rayner *et al.* 2009). The compilation of IR spectra by Lançon & Mouhcine (2002) is particularly useful for upper-AGB stars. See Figs. 5, 6, and 9 for illustration.

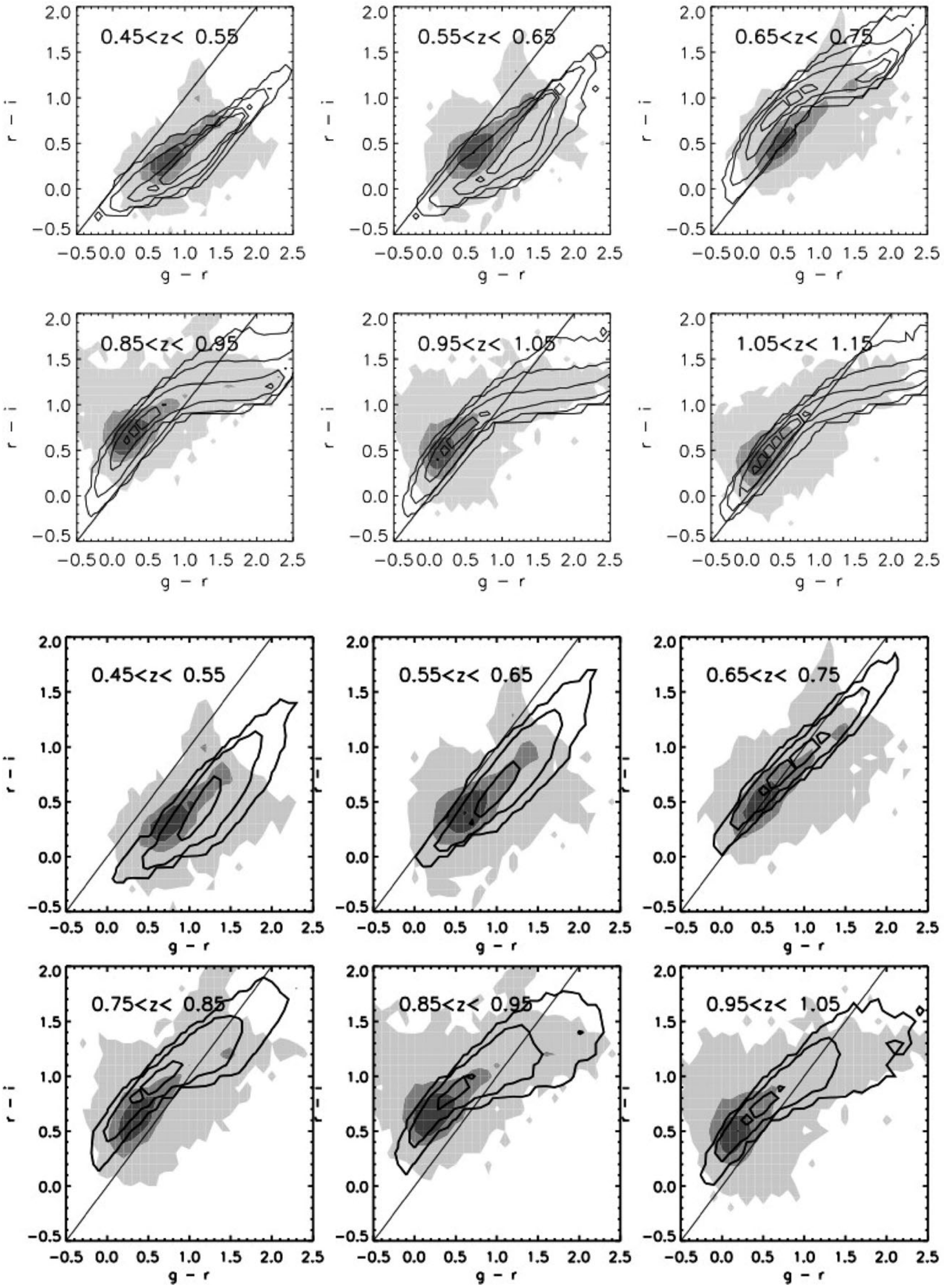

Figure 1. Overlap between the loci in color-color space of data and models for the Walcher *et al.* (2008) sample. The observed data are in grey shading, while model galaxies are shown as solid contours. The two top rows are reproduced from Walcher *et al.* (2008) and correspond to the CB07 models. The model distributions shown in the two bottom rows were kindly computed by J. Walcher using the CB10 models. The improvement introduced by the more complete stellar libraries used in the CB10 models clearly shows at $0.55 < z < 0.75$.

2. Model Improvements

2.1. *CB10 & CB07 models*

Using these new ingredients, Charlot & Bruzual (2010) (hereafter CB10) have built a series of population synthesis models that overcome many of the problems present in previous generations of models, e.g. Bruzual & Charlot (2003) (hereafter BC03). In the rest of this paper I will describe some results from the CB10 models built using the Bertelli *et al.* (2008) evolutionary tracks, the Marigo & Girardi (2007) TP-AGB prescription, and the Miles (Sánchez-Blázquez *et al.* 2006) stellar library, complemented at the hot effective temperature end by theoretical model atmospheres from Lanz & Hubeny (2003), Martins *et al.* (2005), Rodríguez-Merino *et al.* (2005), and Lanz & Hubeny (2007), and at the cool end by the IRTF library (Rayner *et al.* 2009), and the Aringer *et al.* (2009) models.

A preliminary version of the CB10 models was distributed on demand by Charlot & Bruzual (2007) (hereafter CB07). The CB07 models are similar to the BC03 models, except for the use of the Marigo & Girardi (2007) prescription to describe the TP-AGB evolution.

2.2. *Photometric properties of large samples of galaxies*

In their study of the photometric properties of a large sample of galaxies, Walcher *et al.* (2008) find that the observed and modeled colors of their galaxies do cover the same loci in parameter space for most values of the redshift. However, for redshift from 0.6 to 0.7, the distribution of the model galaxies deviate from the observed distribution in the color system that they use. This can be seen clearly in the corresponding frames in the two top rows of Fig. 1, reproduced from Walcher *et al.* (2008). A similar effect is also seen in data accumulated for use in the DEEP2 survey, according to a private communication by S. Salim to Walcher *et al.* (2008). At redshift 0.7, the models are bluer than the data in $g - r$, and redder than the data in $r - i$. In their study, Walcher *et al.* (2008) use the CB07 models. Walcher *et al.* (2008) could track this problem as due to an excess of flux in the U band of the CB07 models when compared with observed galaxies for 10 Myr populations.

J. Walcher kindly computed the color distributions in Walcher *et al.* (2008) using the CB10 models. The results presented in the two bottom rows of Fig. 1 show excellent agreement between models and observations at all values of the redshift. The excess flux in the U band present in previous models for 10 Myr populations reported by Walcher *et al.* (2008) and other authors (see Fig. 2), is now understood as being due to a lack of intermediate effective temperature main sequence stars in the Stelib and Miles libraries. These stars were assigned the spectra of hotter stars, producing this excess flux. When these libraries are supplemented with the theoretical model atmospheres atlas mentioned above, a good match with the observations is obtained. This result indicates clearly the importance of using stellar spectral libraries that include all spectral types required by the synthesis model.

2.3. *Number of He$^+$ ionizing photons*

The inclusion in the population synthesis models of the Lanz & Hubeny (2003, 2007) model atmospheres for O- and B-type stars, respectively, allows the computation of a realistic value for the number of He$^+$ ionizing photons in young populations for all metallicities, down to $Z = 0$. The Westera *et al.* (2002) stellar atmospheres predict unrealistically low figures for this number, because, as shown in Fig. 3, these models do not extend to low enough wavelengths in the EUV end.

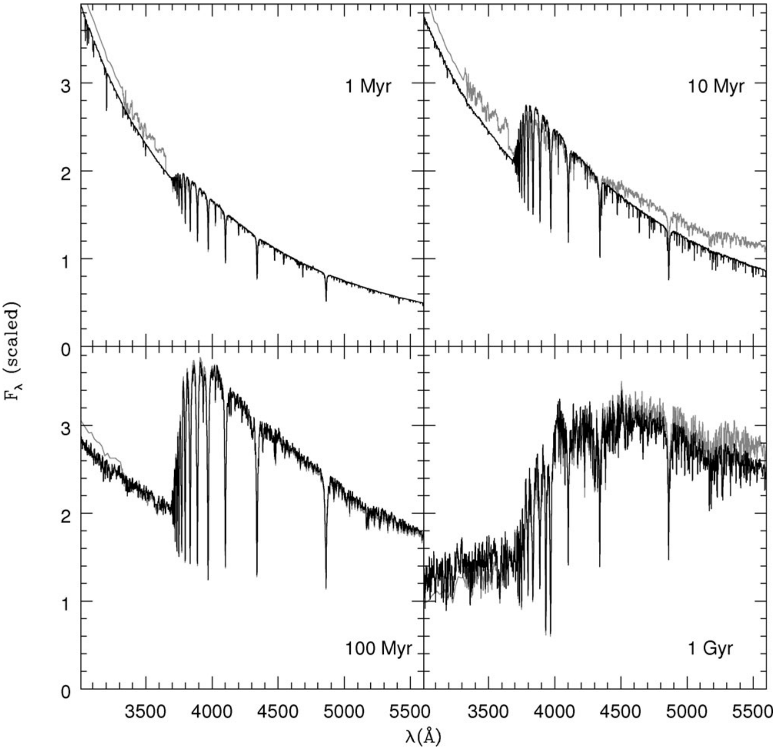

Figure 2. Spectral energy distribution in the 3000-5500 Å range for a $Z = Z_\odot$ simple stellar population at the age indicated inside each frame. The black line corresponds to the CB10 model and the gray line to the CB07 model. The stellar libraries used in each of these models are indicated in the text. The excess U flux noticed by Walcher *et al.* (2008) in the CB07 model at 10 Myr is clearly seen in this figure, as well as an excess around 5000 Å.

2.4. *UV spectral indices of integrated stellar populations*

Synthesis models built with the Lanz & Hubeny (2003, 2007), Martins *et al.* (2005), Rodríguez-Merino *et al.* (2005), and Heap *et al.* (2006) stellar spectral libraries, allow to study in detail the behavior in time of UV line strength indices defined by, e.g., Fanelli *et al.* (1998), revisited by Chavez *et al.* (2009), and Maraston *et al.* (2009). Fig. 4 shows the behavior in time of four of the line strength indices defined by Fanelli *et al.* (1998) for a solar metallicity CB10 simple stellar population. Bruzual (2007b) has shown that most of the Fanelli *et al.* (1998) indices computed from models behave as the values measured in globular clusters. The exceptions are the Mg indices which are stronger in the clusters than in the models. This may be an indication of the relevance of α-enhancement in globular clusters, detected in the UV range. More detailed modeling and more abundant and higher quality data are required to derive firmer conclusions. For more details see Bruzual (2007b) and CB10.

2.5. *IR stellar spectra*

Figs. 5 and 6 compare spectral energy distributions of M- and C-type stars observed by Lançon & Mouhcine (2002) with IRTF (Rayner *et al.* 2009) and Aringer *et al.* (2009) spectra. The agreement seen in the shape of these spectra is remarkable. Both the IRTF and the Aringer *et al.* (2009) spectra improve on the wavelength coverage and the

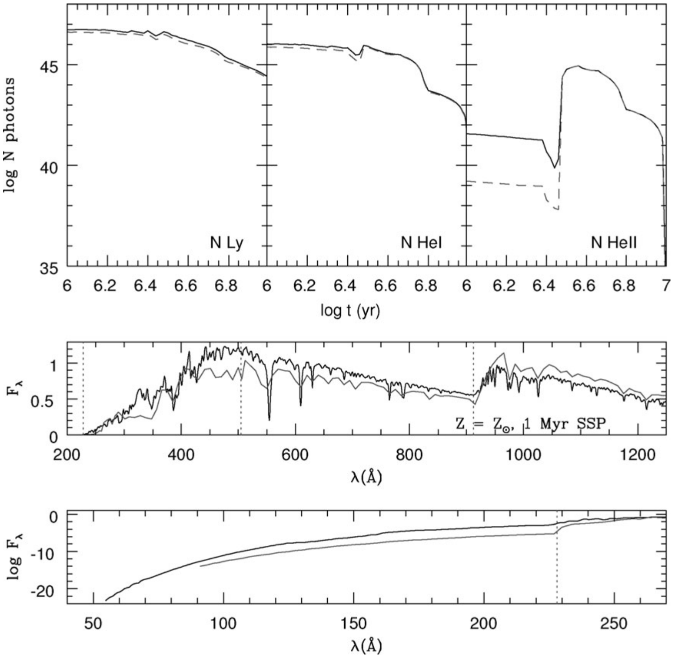

Figure 3. *Topframe*: Number of Ly, HeI, and HeII ionizing photons as a function of time for a $Z = Z_\odot$ simple stellar population of total mass = 1 $M_\odot$. *Middleframe*: Spectral energy distribution in the EUV range at age = 1 Myr. The dotted vertical lines denote the three ionization edges. *Bottomframe*: Detail of the spectral energy distribution at the shortest wavelengths available. In all the frames the black lines represent the CB10 model. The gray lines correspond to models computed using the Westera *et al.* (2002) stellar atmospheres and the same evolutionary tracks as in the CB10 models.

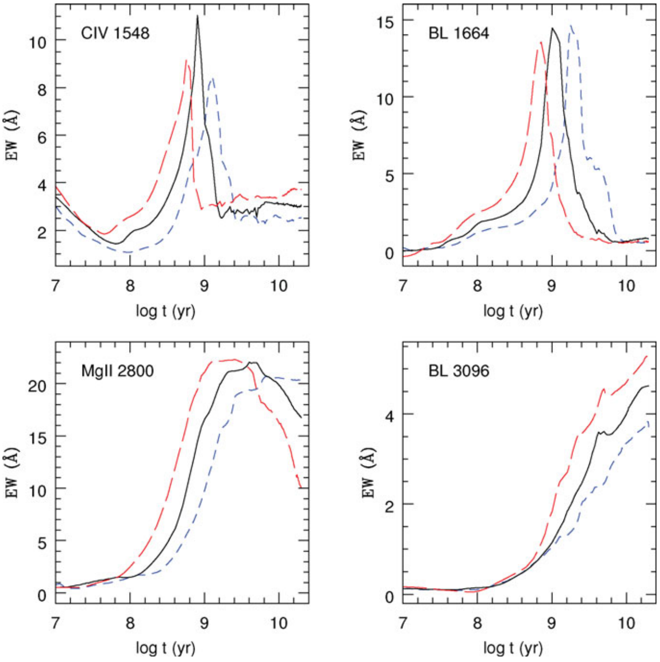

Figure 4. Behavior in time of four of the UV spectral indices defined by Fanelli *et al.* (1998) measured in CB10 models for $Z = Z_\odot$ (solid line), $Z = 2.4 \times Z_\odot$ (long dashed line), and $Z = 0.5 \times Z_\odot$ (short dashed line). The name of the index is indicated inside each frame.

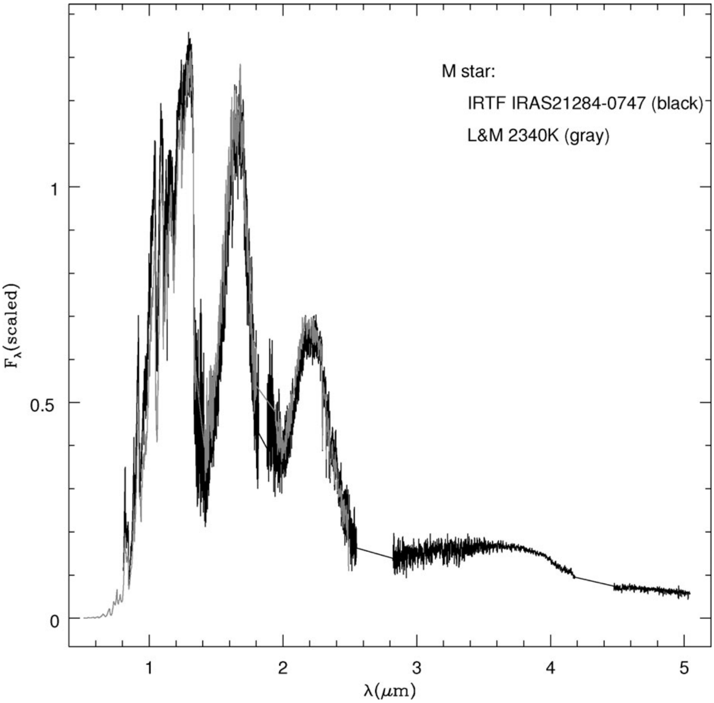

Figure 5. Comparison of the Lançon & Mouhcine (2002) observed spectral energy distribution for an M type star of T_{eff} = 2340K (gray line) and an IRTF (Rayner *et al.* 2009) library spectrum for the source indicated inside the frame (black line).

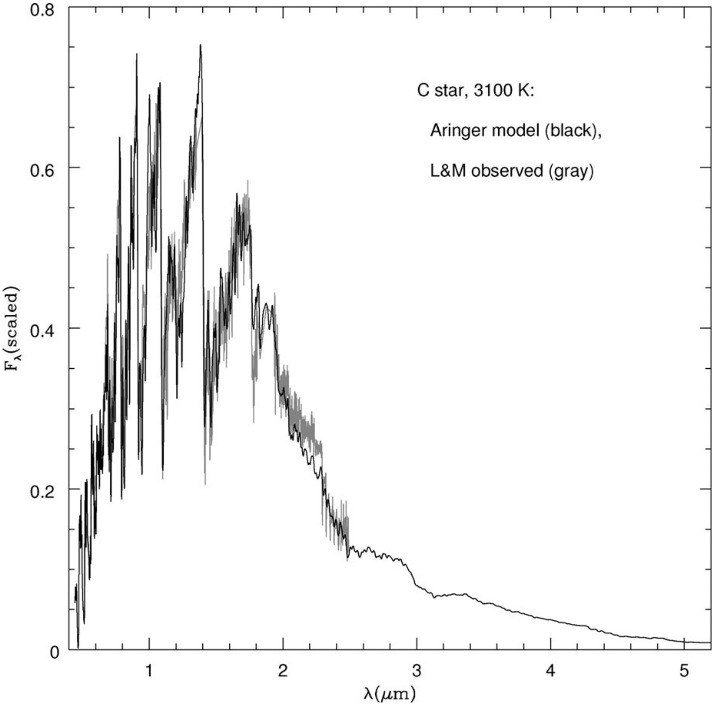

Figure 6. Comparison of the Lançon & Mouhcine (2002) observed spectral energy distribution for a C star of $T_{eff} = 3000$K (gray line) and a model spectrum by Aringer *et al.* (2009) for the same temperature (black line).

signal-to-noise ratio with respect to the Lançon & Mouhcine (2002) observations, which translates into a higher quality of the synthesis model predictions in the NIR range.

2.6. *The mass of galaxies determined from their sed's*

Population synthesis models are frequently used to estimate properties of stellar populations, such as the age and mass of the stars dominating the emitted light. Bruzual (2007a) has shown that the mass estimates of star clusters and galaxies with dominant stellar populations in the age range ≈1 Gyr depend critically on the treatment of TP-AGB stars in population synthesis models. According to Bruzual (2007a), TP-AGB stars dominate the K-band luminosity in SSPs of age ≈1 Gyr, and models computed following the prescription by Marigo & Girardi (2007) have brighter K-band magnitudes and redder near-IR colors than other models.

When considering the plots of fraction of light vs. redshift in Fig. 7 and 8, it becomes clear why the physics of TP-AGB stars dominates so strongly the determination of the total mass contained in the stellar populations of galaxies. When examining the light emitted in the rest frame by galaxies in the redshift range from $z = 3$ to $z = 8$, the CB10 and CB07 models predict that for all metallicities (Fig. 8) the contribution of TP-AGB stars in the K-band is close to 60%, about a factor of two higher than the 40% seen in the BC03 models. The mass that we assign to these galaxies is inversely proportional to the galaxy luminosity. The brighter the model galaxy, the lower the mass in stars needed to produce a given galaxy luminosity. Masses derived from the CB07 and CB10 models are half the masses implied by the BC03 models. More realistic galaxy mass estimates are thus obtained for distant galaxies using the Marigo & Girardi (2007) TP-AGB evolutionary prescription than with previous schemes. Uncertainties in the physical properties that we assign to TP-AGB stars (e.g. stellar temperature, luminosity, mass loss rate, effects of dust and super wind on the stellar spectrum, etc.) have a direct influence in the mass that we assign to galaxies in this redshift range.

3. The future

Progress in the field of stellar population synthesis in the next decade will certainly depend on how much time and effort is dedicated to fundamental observations and basic theory. It is fair to say that the answers to distant galaxy problems will come from understanding nearby stars. So far, we have collected more photons from distant galaxies than from nearby stars. Population synthesis models can get better only if the ingredients that go into them get better. Most of the current uncertainties in these models come from uncertainties in our understanding of critical stages in evolutionary tracks, and from missing either observed or theoretical spectra of stars in relevant evolutionary phases.

3.1. *Basic things that we do not know well enough*

The following list is most likely incomplete. Many of the points listed here have been treated in one or more talks or posters in this conference, which are included in this volume.

- Distance to star clusters needed for calibration of stellar evolution models to a higher precision than at present. These errors translate into errors in the age of galaxies or other stellar populations dated using synthesis models.
- Physical properties of more stars distributed all over the HR diagram: mass, Teff, radius, chemical abundance, chemical anomalies.
- Complete stellar spectral libraries that fill the current gaps (TP-AGB, EHB, Blue stragglers, etc.) in as wide a wavelength range as possible and with a good flux calibration.

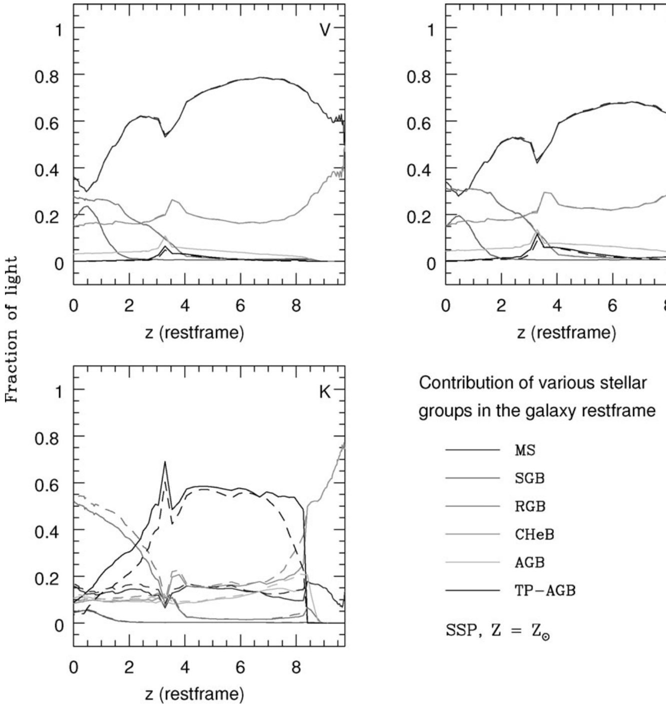

Figure 7. Fraction of light contributed by stars in different evolutionary phases as a function of redshift in the rest frame of the galaxy in the V, R, and K-bands for the CB10 $Z = Z_{\odot}$ SSP model. The solid lines correspond to the calibrated TP-AGB according to Marigo & Girardi (2007), whereas the dashed lines use the uncalibrated TP-AGB of Bertelli *et al.* (2008).

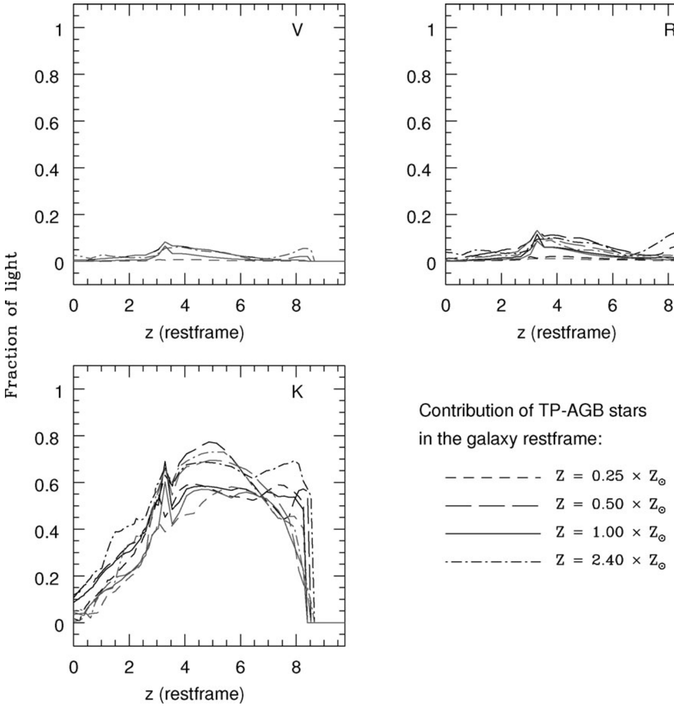

Figure 8. Fraction of light contributed by TP-AGB stars in stellar populations of different metallicities as a function of redshift in the rest frame of the galaxy in the V, R, and K-bands for the CB10 SSP models. $Z = 0.25 \times Z_{\odot}$ (short dashed line), $Z = 0.5 \times Z_{\odot}$ (long dashed line), $Z = Z_{\odot}$ (solid line), and $Z = 2.4 \times Z_{\odot}$ (dot dashed line). The black lines correspond to the calibrated TP-AGB according to Marigo & Girardi (2007), whereas the gray lines use the uncalibrated TP-AGB of Bertelli *et al.* (2008).

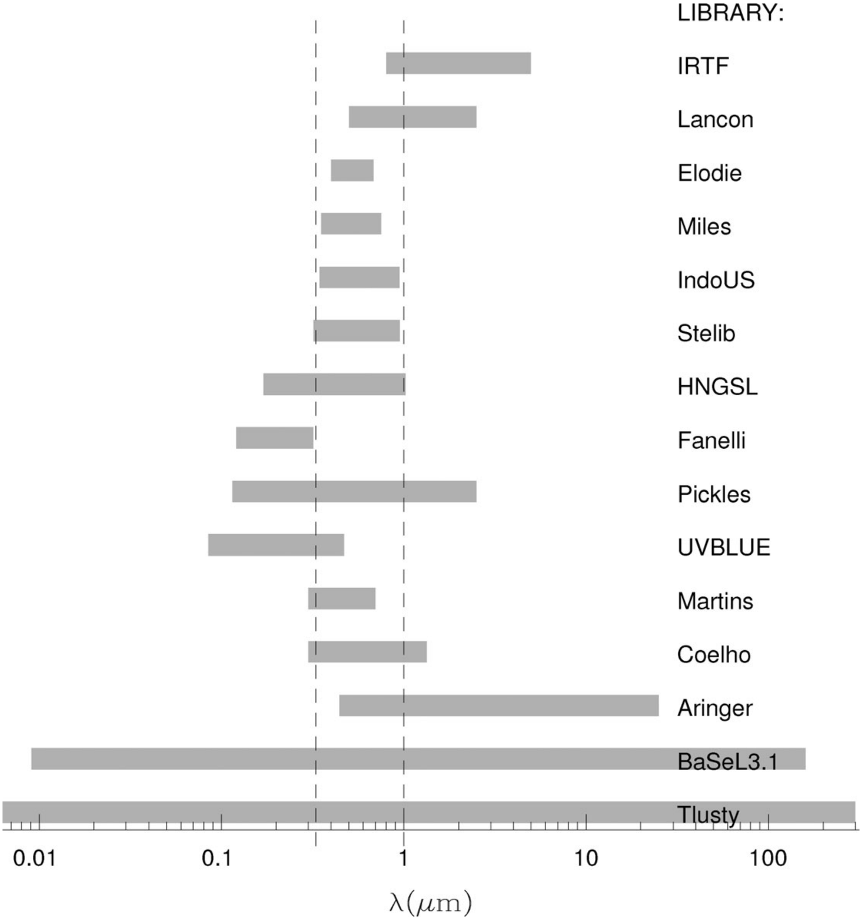

Figure 9. Wavelength range covered by most spectral libraries commonly used in population synthesis models. The Tlusty models are the models computed by Lanz & Hubeny (2003, 2007).

Fig. 9 shows in a pictorial manner the wavelength coverage of most of the spectral libraries available in the literature and in common usage in population synthesis models today.

- Model stellar atmospheres that can be used instead of the observed spectra mentioned in the previous point, including complete line lists and the right geometry and kinematics. These libraries should be studied in detail and calibrated against the observations as was done by Westera *et al.* (2002) for the BaSeL 3.1 data set.
- Evolutionary tracks or evolutionary prescription for EHB stars: frequency of these stars, their lifetimes, dependence of these quantities on metallicity.
- The role of mass loss and rotation in stellar evolution and in the spectrophotometric properties of stars subject to different amounts of mass loss and rotation.
- Effects of dust on the spectra of individual stars. Interplay between mass loss and dust content.
- Origin and role of blue stragglers in stellar evolution and their relevance in the integrated properties of star clusters and galaxies.
- The role of binaries in the evolution of stellar populations of various ages and metallicities, and in different environments (stellar density).

- Do light/heavy element ratios vary from star to star or galaxy to galaxy in a way that we can understand? Are models with flexible chemistry which vary individual element abundance a la Worthey (Dotter *et al.* 2007, Lee *et al.* 2009) really necessary?
- Is the IMF universal?

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