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MODELING STELLAR POPULATIONS NEAR AND FAR

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RESUMEN

Presento un resumen de la situación actual de la determinación de la masa de galaxias basada en el uso de modelos de síntesis de poblaciones estelares a edades en las cuales la estrellas de la TP-AGB dominan el cercano IR (≈1 Gyr). Las estimaciones de masa de galaxias con población estelar dominante cercanas a esta edad dependen críticamente en el tratamiento dado a estas estrellas en los modelos de síntesis de poblaciones. Presento algunos resultados preliminares de Charlot, S., & Bruzual, G. (2011, in preparation) y una lista de puntos que requieren pronta revisión para avanzar en el campo de la síntesis de poblaciones estelares.

ABSTRACT

I summarize the current status of the determinations of galaxy masses based on population synthesis models at ages at which the TP-AGB stars dominate the NIR luminosity (≈1 Gyr). Mass estimates of galaxies with dominant stellar populations in this age range thus depend critically on the treatment of TP-AGB stars in population synthesis models. Here I present some preliminary results from Charlot, S., & Bruzual, G. (2011, in preparation) and a list of weak points in the modeling of stellar populations that hopefully will be improved in the near future.

Key Words: galaxies: evolution — Galaxy: stellar content — stars: AGB and post-AGB

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.

Numerous stellar spectral libraries are available and ready to use for population synthesis models (cf. Figure 10). 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 2000 Å) 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.

Using these new ingredients, Charlot & Bruzual (2011, hereafter CB11) have built a series of population synthesis models that overcome many of the problems present in previous generations of models, Bruzual & Charlot (e.g., 2003, hereafter BC03). The CB11 models are built using the Bertelli et al. (2008) evolutionary tracks, the Marigo & Girardi (2007) and Girardi et al. (2010, private communication) TP-AGB prescriptions, 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),

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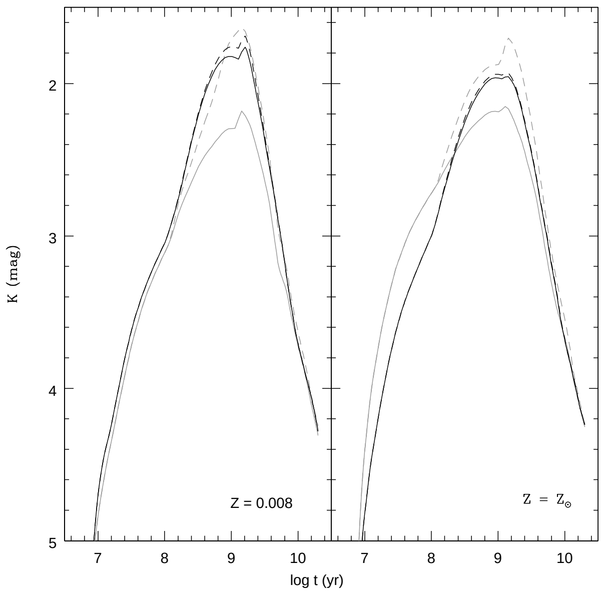

Fig. 1. Behavior of the absolute K magnitude for various models for $Z = 0.008$ (left frame) and $Z_\odot$ (right frame). The black solid line corresponds to a CB11 model which includes the effects of mass loss on the spectral distribution of TP-AGB stars. The black dashed line corresponds to the same model, but ignoring the effects of mass loss on the spectral distribution of TP-AGB stars (see text). The gray solid line corresponds to the BC03 model and the gray dashed line to the CB07 model. To build these models I have assumed the Chabrier (2003) IMF and an exponentially decaying star formation rate with $\tau = 1$ Gyr.

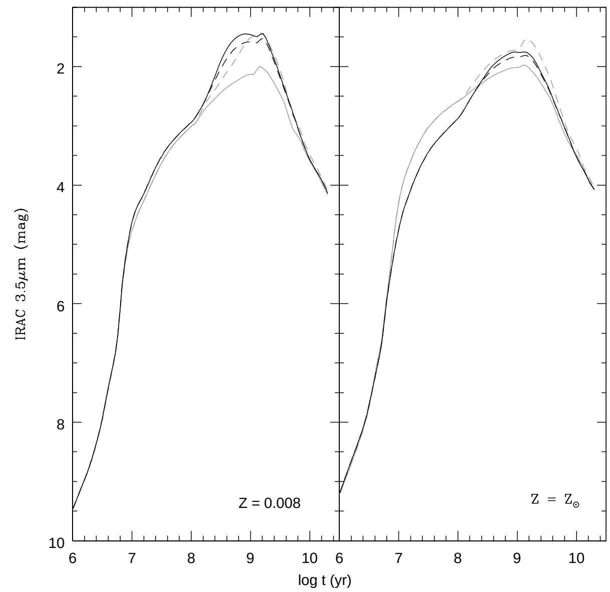

Fig. 2. Behavior of the absolute $IRAC$ 3.5μm magnitude for various models for $Z = 0.008$ (left frame) and $Z_\odot$ (right frame). The black solid line corresponds to a CB11 model which includes the effects of mass loss on the spectral distribution of TP-AGB stars. The black dashed line corresponds to the same model, but ignoring the effects of mass loss on the spectral distribution of TP-AGB stars (see text). The gray solid line corresponds to the BC03 model and the gray dashed line to the CB07 model. To build these models I have assumed the Chabrier (2003) IMF and an exponentially decaying star formation rate with $\tau = 1$ Gyr.

and the Aringer et al. (2009) models. A preliminary version of the CB11 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.

The reader is referred to the paper by Bruzual (2009) for a comparison of the CB11 models with older models. In the rest of this paper I will describe some results from the CB11 models specific to the determination of the mass of galaxies.

2. THE MASS OF GALAXIES

The estimates of the age and mass of the stellar population present in a galaxy depend critically on the ingredients of the stellar population model used to fit the galaxy spectrum. In particular, the treatment of the thermally pulsing asymptotic giant branch (TP-AGB) phase of stellar evolution is the major source of uncertainty in the determination of the spectroscopic age and mass of high-z ($1.4 < z < 2.7$) galaxies. The mid-UV spectra of these galaxies indicate ages in the range from 0.2–2 Gyr, at which the contribution of TP-AGB stars in the rest-frame near-IR sampled by the *Spitzer Space Telescope* is expected to be at maximum. TP-AGB stars dominate the K-band luminosity in simple stellar populations of age ≈1 Gyr. Mass estimates of galaxies with dominant stellar populations in this age range thus depend critically on the treatment of TP-AGB stars in population synthesis models. See Bruzual (2007) for more details.

2.1. *TP-AGB Stars*

The CB11 models are formally identical to the BC03 models, but include several important improvements. CB11 use the tracks up to 15 $M_\odot$ from the models with updated input physics by Bertelli et al. (2008). For stars more massive than 15 $M_\odot$, in the range from 20 to 120 $M_\odot$, CB11 use the so-called Padova 1994 tracks. In the CB11 models the TP-AGB evolution of low- and intermediate-mass

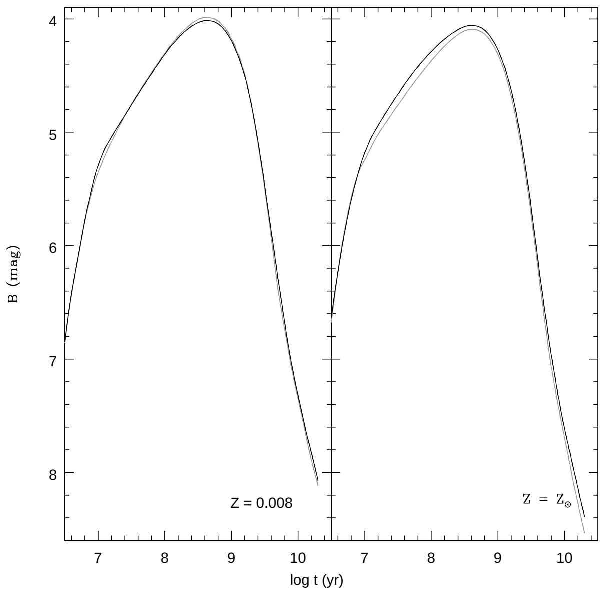

Fig. 3. Behavior of the absolute B magnitude for various models for $Z = 0.008$ (left frame) and $Z_\odot$ (right frame). The black solid line corresponds to a CB11 model which includes the effects of mass loss on the spectral distribution of TP-AGB stars. The black dashed line corresponds to the same model, but ignoring the effects of mass loss on the spectral distribution of TP-AGB stars (see text). The gray solid line corresponds to the BC03 model and the gray dashed line to the CB07 model. To build these models I have assumed the Chabrier (2003) IMF and an exponentially decaying star formation rate with $\tau = 1$ Gyr.

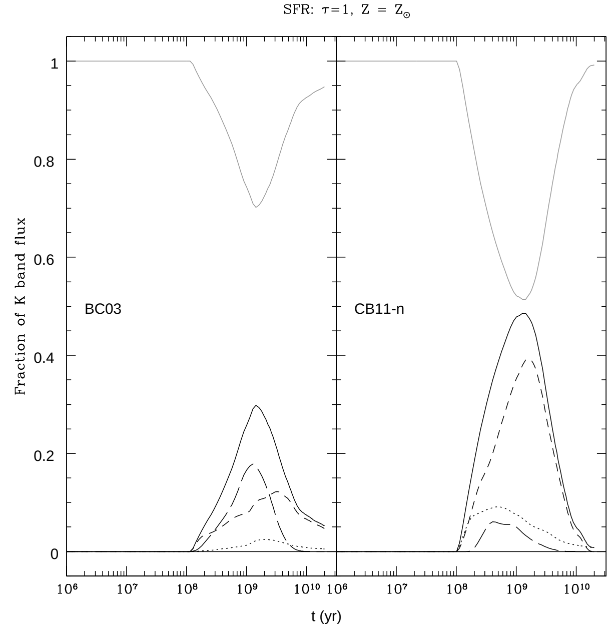

Fig. 4. Fraction of light contributed by TP-AGB stars and the "rest" of the stars (gray line) in the K-band as a function of time for the BC03 and the CB11 models. The contribution of all, the O-rich, the C-rich, and the Super Wind (SW) phase TP-AGB stars is shown as black solid, short dashed, long dashed, and dotted lines, respectively. To build these models I have assumed the Chabrier (2003) IMF, an exponentially decaying star formation rate with $\tau = 1$ Gyr, and $Z = Z_\odot$.

stars is followed according to the prescription of Girardi et al. (2010, private communication). This semi-empirical prescription includes several important theoretical improvements over previous calculations, and it has been calibrated using carbon star luminosity functions in the Magellanic Clouds and TP-AGB lifetimes (star counts) in Magellanic Cloud clusters. While the tracks used in CB11 account for 15 evolutionary stages in the TP-AGB (six in the O-rich phase, six in the C-rich phase, and three in the super wind phase), the BC03 models include only 1 evolutionary stage at each of these phases. The resulting CB11 isochrones are thus based on internally consistent sets of tracks, which naturally obey the fuel consumption theorem, and provide other quantities necessary for a consistent modeling of galaxies, such as chemical yields and remnant masses (Marigo et al. 2008).

The spectral energy distributions used by CB11 for the TP-AGB stars include emission from the dusty envelopes surrounding these stars undergoing mass loss. See González-Lópezlira et al. (2010) for details on the calculation of the stellar models.

In what follows I show some results from the CB11 models. All the models shown in this paper were computed for the Chabrier (2003) IMF, and an exponentially decaying star formation rate with e-folding time $\tau = 1$ Gyr.

Figures 1 to 3 show the galaxy luminosity in the K, $IRAC{-}3.5\mu$m, and B bands as a function of time for the $Z = 0.008$ and $Z_\odot$ BC03, CB07, and CB11 models. For the latter, the effect of including or not the emission of the dusty envelopes is shown. In the IR bands the CB07 and CB11 models are considerably brighter than the BC03 models because of the improved treatment of TP-AGB stars in the more recent models compared to BC03. This brightening overcomes the effect of the dusty envelopes.

Figures 4 and 5 show the fraction of light contributed by TP-AGB stars and the "rest" of the stars (i.e., everything else) in the K band as a function of time for the BC03 and CB11 models, with $Z = 0.008$ and $Z_\odot$, respectively. The CB11 models include the emission from the dusty envelopes of the TP-AGB

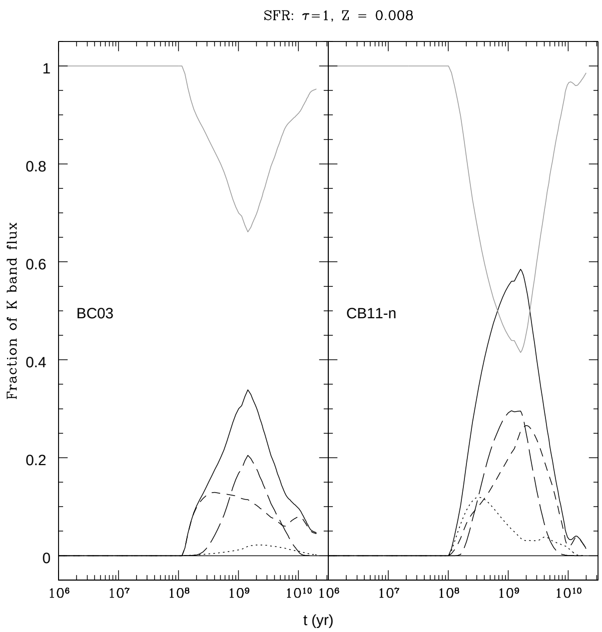

Fig. 5. Fraction of light contributed by TP-AGB stars and the "rest" of the stars (gray line) in the K-band as a function of time for the BC03 and the CB11 models. The contribution of all, the O-rich, the C-rich, and the Super Wind (SW) phase TP-AGB stars is shown as black solid, short dashed, long dashed, and dotted lines, respectively. To build these models I have assumed the Chabrier (2003) IMF, an exponentially decaying star formation rate with $\tau = 1$ Gyr, and $Z = 0.008$.

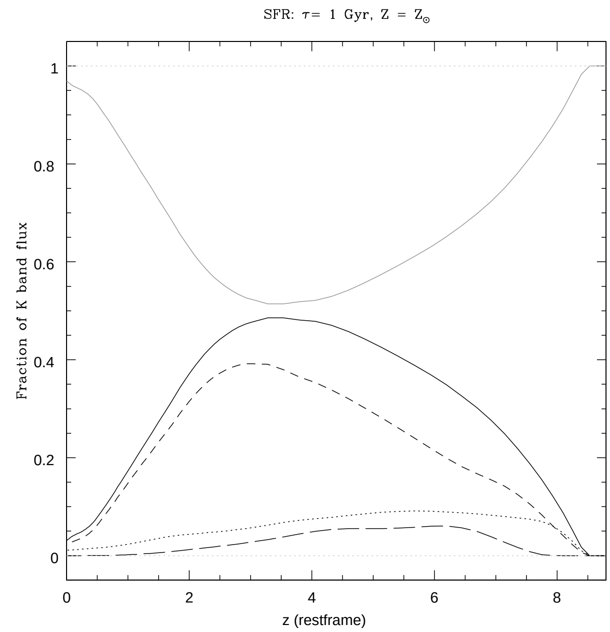

Fig. 6. Fraction of light contributed by TP-AGB stars and the "rest" of the stars (gray line) in the K-band as a function of redshift in the rest frame of the galaxy for a CB11 model built for the Chabrier (2003) IMF, an exponentially decaying star formation rate with $\tau = 1$ Gyr, and $Z = Z_\odot$. The contribution of all, the O-rich, the C-rich, and the Super Wind (SW) phase TP-AGB stars is shown as black solid, short dashed, long dashed, and dotted lines, respectively.

stars. Depending on the stellar metallicity, the contribution of the TP-AGB stars in the K-band reaches about 60% in the CB11 model, close to a factor of two more than in the BC03 model. In the CB11 models for $Z = Z_\odot$ the TP-AGB contribution is dominated by the O-rich stars. In the $Z = 0.008$ model the O-rich and C-rich stars contribute about equally. The stars in the SW phase never dominate the emission in the K band.

It is more interesting to plot the contribution of TP-AGB stars as a function of redshift z in the restframe of the galaxy instead of galaxy age. Figures 6 and 7 show that, as indicated above, these stars dominate the NIR in a wide redshift range, and 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 restframe by galaxies in the redshift range from $z = 3$ to $z = 8$, close to 60% of the light in the K-band comes from the TP-AGB stars. Thus, uncertainties in the physical properties that we assign to these stars have a direct influence in the mass that we attribute to galaxies in this redshift range.

Figures 8 and 9 show that 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.

In general, at ages around and above 1 Gyr, the galaxy masses derived from the CB07 and CB11 models are considerably lower than the BC03 masses. At early ages the galaxy masses determined from the $Z = Z_\odot$ CB11 model are up to 50% larger than the BC03 masses because the CB11 model is fainter than the BC03 model at these ages (cf. Figure 2). This is a consequence of the different chemical composition of the stellar models for $Z = Z_\odot$ in the Bertelli et al. (2008) and the Padova 1994 data sets. This effect is not seen in the $Z = 0.008$ case.

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

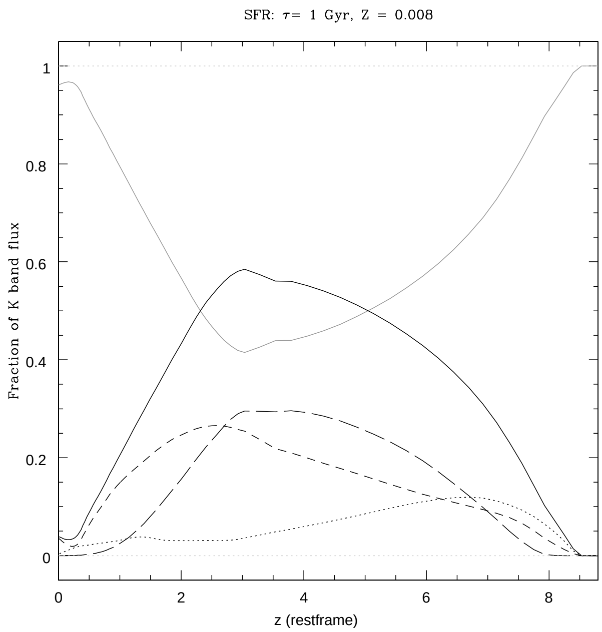

Fig. 7. Fraction of light contributed by TP-AGB stars and the "rest" of the stars (gray line) in the K-band as a function of redshift in the rest frame of the galaxy for a CB11 model built for the Chabrier (2003) IMF, an exponentially decaying star formation rate with $\tau = 1$ Gyr, and $Z = 0.008$. The contribution of all, the O-rich, the C-rich, and the Super Wind (SW) phase TP-AGB stars is shown as black solid, short dashed, long dashed, and dotted lines, respectively.

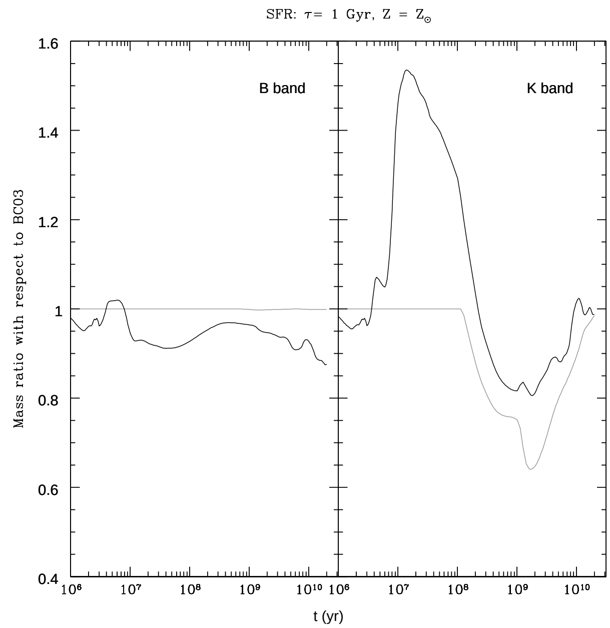

Fig. 8. Ratio of the stellar mass determined from the CB11 and CB07 models with respect to the BC03 model for a given B-band (left frame) and K-band (right frame) galaxy luminosity as a function of time. The black solid line represents the CB11/BC03 ratio. The gray solid line corresponds to the CB07/BC03 ratio. All models used in this figure were built for the Chabrier (2003) IMF, an exponentially decaying star formation rate with $\tau = 1$ Gyr, and $Z = Z_{\odot}$.

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*

• 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 10 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.

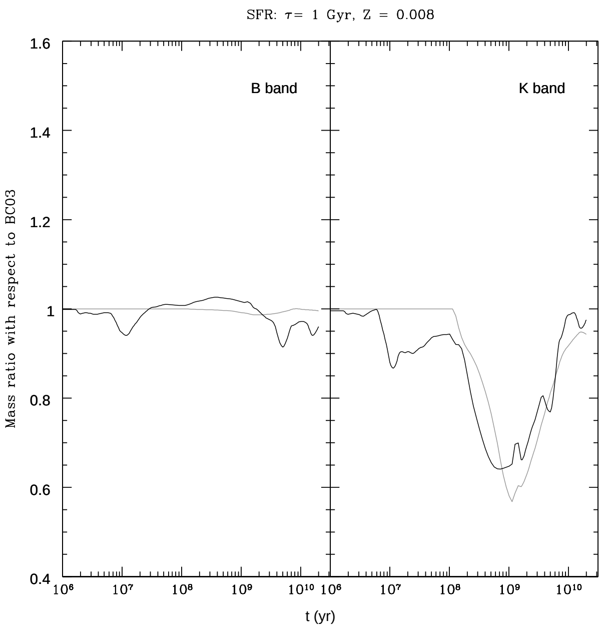

Fig. 9. Same as Figure 8 but for the $Z = 0.008$ BC03, CB07, and CB11 models.

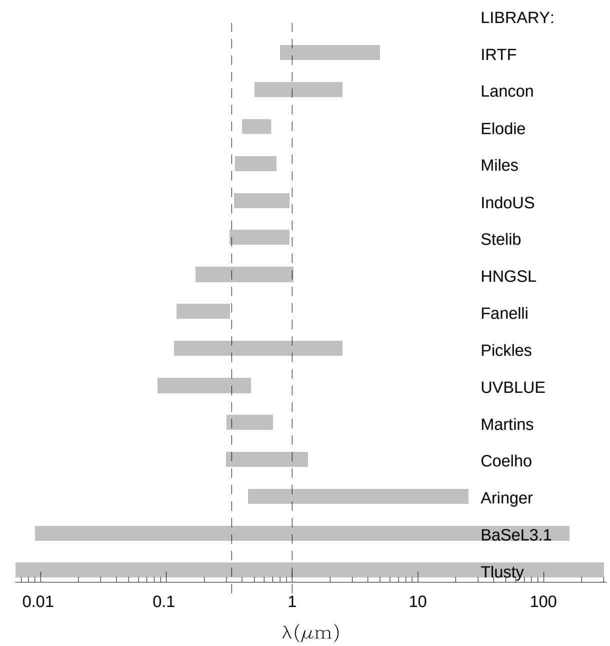

Fig. 10. Wavelength range covered by most spectral libraries commonly used in population synthesis models. The Tlusty models are the models computed by Lanz & Hubeny (2003, 2007).

• 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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