

The role of the AGB and RGB phases on the integrated properties of single stellar populations

LÉO GIRARDI

Instituto de Física – UFRGS, Caixa Postal 15051, 91501-970 Porto Alegre RS, Brazil

ABSTRACT. We briefly comment on the effect that different prescriptions for the evolution along the TP-AGB phase have on the integrated properties of single stellar populations (SSPs). This with the aid of complete models of stellar tracks and isochrones, in which the TP-AGB phase is followed analytically. Firstly, we show that different prescriptions for the mass loss rates during the AGB phase give origin to very different results for the final remnant mass (either white dwarf or neutron star) as a function of initial mass and metallicity. Secondly, we describe in a realistic way the changes occurring in the integrated colors of SSPs at the onset of the AGB and RGB stars. The predicted behaviour differs in several details from that originally suggested by other authors. Also in this case, the effects of different prescriptions for the mass loss rates during the TP-AGB phase, and of the overluminescence with respect to the normal core mass-luminosity relation, are briefly considered.

1. Introduction

Stellar models predict that, over relatively small intervals of initial masses, stars start developing the AGB and RGB evolutionary phases. These events translate into major changes on the HRD properties of single stellar populations (hereafter SSPs; e.g. star clusters) over small time scales. Renzini & Buzzoni (1986), making use of the fuel consumption theorem, suggested that the development of both features should be accompanied by sudden jumps to redder integrated colors – events that were named AGB and RGB phase transitions, respectively. The existence and observational implications of these features, specially with regard to the distribution of integrated $B - V$ colors of LMC clusters, have been analysed by Chiosi et al. (1988), who first concluded that the development of the RGB was not accompanied by any noticeable jump in the colors. This result has been later reinforced by the works of Bressan et al. (1994) and Girardi et al. (1995). The AGB phase transition, on its turn, is probably accompanied by a real jump to redder colors, specially for low-metallicity SSPs. It has been recently suggested by Renzini (1991) that its appearance would be significantly delayed, due to the effect of overluminescence with respect to the standard core mass-luminosity relation occurring in the most massive intermediate-mass stars.

In this paper we reexamine the development of the AGB and RGB and their impact on the integrated colors of SSPs, exploring also the effect of different prescriptions for the mass loss rates. The models include all evolutionary phases from the main sequence to the end of the TP-AGB. Therefore, the fuel consumption during all the relevant phases is taken into account.

2. The tracks and isochrones

We base our discussion on a grid of $Z = 0.001$ stellar tracks with masses spaced by $0.1 M_{\odot}$ over the range of low-mass stars. This spacing is reduced to $0.05 M_{\odot}$ in the vicinity of the limit mass for the occurrence of the core He-flash, M_{Hef} . The mass resolution is enough to map the development of the tracks in the HRD, as well as to follow the growth of the core mass at the RGB-tip in the vicinity of M_{Hef} . The physical input is as in the series of papers fully referenced in Bertelli et al. (1994), with some updating in the equation of state and low-temperature opacities (Girardi et al. 1996). We recall that they include moderate convective overshoot, which reflects on the low value of $M_{\text{Hef}} = 1.7 M_{\odot}$, as compared to the value of $M_{\text{Hef}} \sim 2.2 M_{\odot}$ obtained from classical models, and on the low value of M_{up} , $5 M_{\odot}$. In order to allow a comparison with the solar-metallicity case, we also use the Bressan et al. (1994) tracks for $Z = 0.02$, although they have been constructed with a slightly lower mass resolution.

The TP-AGB evolution is followed analytically, starting from the first significant thermal pulse present in the evolutionary tracks. The core mass, total mass, effective temperature, and luminosity of the models are let to evolve according to the equations collected by Groenewegen & de Jong (1993) and Marigo et al. (1996). The end of the TP-AGB phase is determined either by the total loss of the envelope by stellar winds, or by the core mass growing up to the Chandrasekhar limit. We warn the reader that the TP-AGB model we use is very simplified compared to other synthetic calculations (Groenewegen & de Jong 1993; Marigo et al. 1996). However, it is fully adequate for an investigation of the gross features expected to appear in the evolution of SSPs, and of their dependence on some illy-known parameters of TP-AGB evolution.

For each value of the age, we construct an isochrone by interpolating in the grid of stellar tracks. From these isochrones we can easily calculate the integrated properties of the corresponding SSPs. Bertelli et al. (1994) present the procedures in detail. In order to simplify the analysis, in this paper we do not apply the algorithm used by the latter authors in order to take into account mass loss by stellar winds on the RGB. Only mass loss along the AGB is considered.

3. The different prescriptions for the synthetic TP-AGB evolution

Figure 1 presents the values of the final core mass attained by the models, $M_c^{\text{AGB-tip}}$, for 4 different mass loss rates: the canonical one by Reimers (1975) with $\eta = 1.0$, and the “superwind-like” rates of Bowen & Willson (1991), Vassiliadis & Wood (1993), and Blöcker (1995). Clear in the figure is that, contrary to the Reimers’ mass loss rates, the superwind-like formulas give origin to a strong metallicity dependence of the final core mass attained by intermediate mass stars. In this way, stars of lower metallicity can easily attain the minimum core mass for the explosion as supernovae, $1.4 M_{\odot}$, with evident implications for the theory of chemical evolution of galaxies. Exception is the result obtained from the Blöcker prescription, which gives origin to very high values of mass loss as soon as it is activated on the synthetic TP-AGB calculation. For this reason, in Fig. 1 the final core mass attained by the models with Blöcker’s mass loss is very close to the core mass at the start of the thermal pulses.

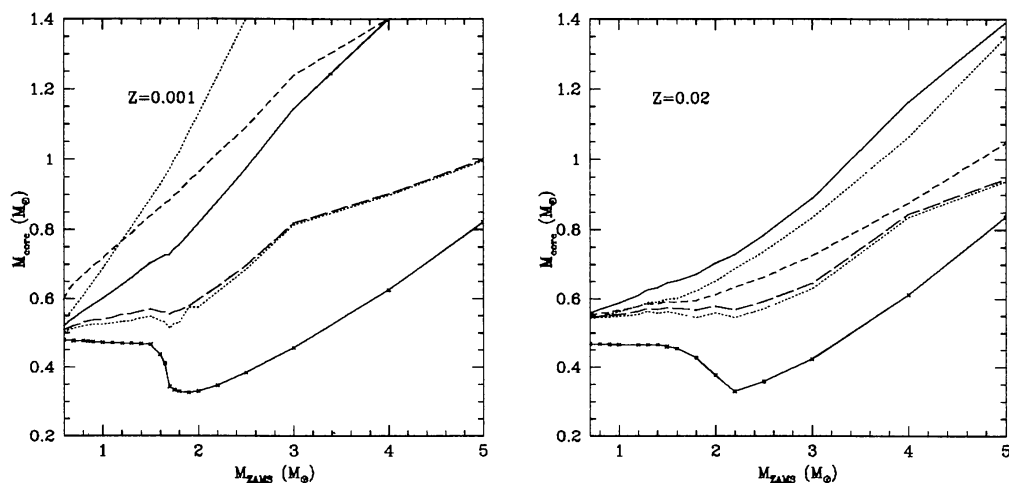


Fig. 1. The He-core mass as a function of initial mass, at both the RGB-tip (or quiet He-ignition for intermediate-mass stars), and at the TP-AGB-end, for initial metallicities $Z = 0.001$ (left panel) and $Z = 0.02$ (right panel). The lines are as follows: the lower continuous line represents the He-core mass at the beginning of He-ignition; the dotted line immediately above is the core mass at the start of the thermally pulsing regime on the AGB; then it follows the core mass at the end of AGB evolution (complete ejection of the envelope) for 4 different prescriptions of mass loss: Reimers (1975) with $\eta = 1.0$ (continuous line), Bowen & Willson (1991; dotted line), Vassiliadis & Wood (1993; short-dashed line) and Blöcker (1995; long-dashed line).

Important to the theory of evolutionary population synthesis is the fact that, irrespective of the adopted mass loss formula, the final core mass attained by AGB stars is a monotonic and smooth function of the initial stellar mass. This behaviour results naturally from the existence of a core mass-luminosity relation (hereafter CMLR) during most of the AGB evolution, and from the mass loss rates being simply expressed as a function of fundamental stellar parameters, as the effective temperature and luminosity. Considering the straight relation between the final core mass and the total fuel consumption of a star (see eq. 9 in Renzini & Buzzoni 1986, and consider that at the AGB-end the He- and H-exhausted cores have almost the same mass), it implies that the total fuel consumption is also a smooth and monotonic function of the initial mass, even in the mass range in which stars start developing the RGB ($M \simeq M_{\text{Hef}}$).

An important drawback of synthetic TP-AGB calculations is that they neglect the effect of overluminosity with respect to the standard CMLR, occurring in the intermediate-mass stars of higher masses (Blöcker & Schönberner 1991). For the sake of conciseness, we will refer to the maximum mass for the validity of the CMLR as M_{CMLR} , although it is not clear if this is the only parameter controlling the validity of this relation (the envelope mass, or both envelope and total mass, may well be the determinant factors). According to the suggestion of Renzini (1991), the break of the CMLR could have important effects on the evolution of the integrated properties of SSPs: as the AGB stars of mass higher than M_{CMLR} experiment a rapid rise in luminosity, the result would be a

fast increase in the mass loss rates, then dramatically reducing the duration of the AGB phase and its contribution to integrated light. Consequently, the AGB phase transition would be split into two separate events, being that associated with the transition mass M_{CMLR} the most prominent one.

However, this interpretation disagrees with the results of complete AGB evolution calculations including the effect of mass loss (Vassiliadis & Wood 1993). The $5 M_{\odot}$ model calculated by the latter authors experiments indeed a fast increase of the mass loss rates, but as soon as the star loses a certain amount of mass, it settles again on the standard CMLR valid for stars of lower masses, and in that regime it spends the rest of its AGB evolution. This behaviour is expected to be followed by all the stars initially massive enough to present the overluminosity effect, and the closer the stellar mass is to M_{CMLR} , the faster should be the transition to a normal CMLR. The result is then that no *sudden* shortening of the AGB lifetime occurs at the value of M_{CMLR} , instead we expect a gradual and monotonic shortening of the AGB lifetime with increasing mass. The same is valid for the *fuel consumption*, which is the relevant quantity for the theory of evolutionary population synthesis. Indeed, the Vassiliadis & Wood models do not present any evidence of a decrease of the final core mass (hence total fuel consumption) at the high mass end of intermediate-mass stars (see their Fig. 21).

4. The evolution of SSP colors

In Fig. 2 we show the evolution of SSP colors, calculated from sequences of isochrones with a very small age spacing, in the age range in which AGB stars are present. Let us look in detail at what happens when AGB and RGB stars appear in the SSPs:

The onset of the AGB, at $\sim 10^8$ yr, is marked by a sudden jump to redder colors (the AGB phase transition as defined by Renzini & Buzzoni 1986). The magnitude of this jump is highly dependant on the assumed mass loss rates. Also, as already noticed by a number of authors, we find that for near-solar metallicities the AGB stars have a negligible effect on visual colors (see bottom right panel in Fig. 2). The effect of the overluminosity with respect to the CMLR (Sect. 3) would be that of reducing the amplitude of the color jump at 10^8 yr. After that, colors would continuously change due to the increase of the AGB contribution, up to ages $\sim 3 \times 10^8$ yr in which the AGB stars would have a mass small enough to follow a normal CMLR during their entire evolution (This in the case that stars of mass as low as $3 M_{\odot}$ already experiment some overluminosity effect; this is a lower limit to the values found in the literature). And after that, the color evolution would follow the curves of Fig. 2.

At the age the RGB develops ($\sim 1.4 \times 10^9$ yr), we notice a sharp spike in the color evolution, towards redder colors. Before and after this red excursion, colours follow a nearly monotonic behaviour, without any evidence of a color jump as originally advocated by Renzini & Buzzoni (1986). The reason for this behaviour has been already described in the works of Chiosi et al. (1988) and Bressan et al. (1994): it reflects the fact that the development of the RGB is accompanied by the reduction of the AGB contribution to the integrated light. Notice that the same argument can be derived from the inspection of Fig. 1, as a result of the smooth and monotonic behaviour of the total fuel consumption (Sect. 3): what happens at the onset of the RGB is that fuel

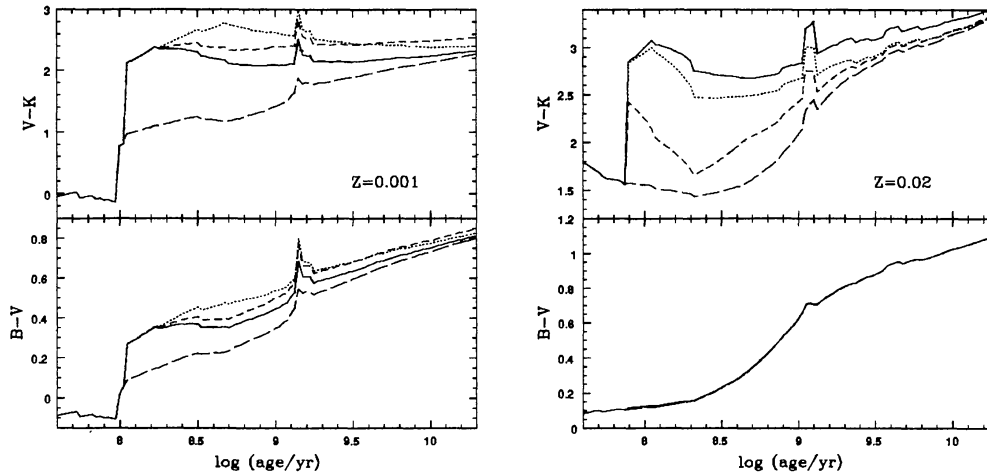


Fig. 2. The time evolution of $B - V$ and $V - K$ integrated colors, for the SSPs with metallicities $Z = 0.001$ (left panel) and $Z = 0.02$ (right panel), and according to four different prescriptions for the mass loss rates on the TP-AGB: Reimers (1975) with $\eta = 1.0$ (continuous line), Bowen & Willson (1991; dotted line), Vassiliadis & Wood (1993; short-dashed line) and Blöcker (1995; long-dashed line).

which otherwise would be consumed during the HB and E-AGB phases, is then consumed during the RGB phase. As all the stars involved in the transition have virtually the same spectral energy distribution, the integrated colors do not suffer a noticeable change during the transition. This behaviour is valid even for red and IR colors.

The transient red excursion, instead, occurs for a more subtle reason. As the RGB rapidly develops in a SSP, the effect of the growth of the core mass at He-ignition is not felt immediately by the AGB stars. A time lag corresponding to the central He-burning lifetime will follow, up to the time in which the fuel consumption on the AGB is correspondingly reduced. This time lag gives origin to the red excursion. Its maximum duration can be estimated to be similar to the He-burning lifetime ($\sim 1.5 \times 10^8$ yr in the vicinity of M_{HeF}). We notice that the effect can be found only in SSP sequences built with a very small age spacing. Moreover, use of naive methods of isochrone construction, or of heterogeneous sets of stellar tracks, can easily hide this feature. Its appearance cannot be revealed by the use of the isomass method of construction of SSPs (an alternative to the isochrone method used here), nor from the straight application of the fuel consumption theorem.

5. Concluding remarks

This work shows that some of the basic arguments used up to now to discuss the development of the “phase transitions” on the integrated light of SSPs, should be revised in the light of more realistic models. On the one hand, we show that our present understanding of TP-AGB evolution rules out the possibility of major color jumps occurring at the

development of the RGB. On the other hand, looking into the details, we notice that a transient red phase takes place due to the time lag between the RGB development and the response from the subsequent evolutionary stages, an effect previously unnoticed. With respect to the AGB phase transition, the effect of the overluminosity with respect to the CMLR must be properly included into SSP calculations in order to define more precisely its effect on the temporal widening of the AGB phase transition. Arguments are given that the effect of splitting of this transition into two separate ones (Renzini 1991), probably does not take place.

Many of the considerations presented here will be more thoroughly developed in a forthcoming paper (Girardi 1996, in preparation). We also intend to explore the possible causes for the sudden change on the $V - K$ colours inside the LMC star clusters of SWB type IV (see Renzini 1991). In this respect, the color evolution depicted in Fig. 2 suggests that this major color change can hardly be attributed to the development of the RGB.

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