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Mass loss from red giant stars in M 67: Is there any evidence for a metallicity dependence?

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Abstract. Recent claims in the literature, that the rate of mass loss from red giant branch (RGB) stars in old, open clusters like M 67 and NGC 6791, increases with the metallicity above the value holding for Globular Clusters and predicted by the classical Reimers (1975) relation, are thoroughly scrutinized by means of the global fit of the color-magnitude diagram (CMD) of these clusters (M 67 in particular) to modern sets of theoretical isochrones. The above claim stems from recognizing that there is wide agreement in literature on the metallicity (nearly solar), age (about 5 Gyr), and distance modulus ((m − M)=9.55) of M 67, and from estimating the mass of its giant stars in the red clump to be about 0.7 $M_\odot$. At the above age, the masses at the turn-off and near the tip of the RGB are about 1.2 $M_\odot$ and 1.3 $M_\odot$, respectively. This means that in clusters with nearly solar metallicity, much more mass ought to be lost by the red giant stars than classically predicted. In this paper we show that in order to be able to derive the mass of the red stars in the clump from their position in the CMD, the color difference $\Delta(B-V)$ between the turn-off and the base of the RGB should be known with a precision smaller than $\delta[\Delta(B-V)] = 0.01$ mag and, at the same time, the distance modulus should be determined with a precision higher than 0.025 mag. The analysis of the problem clarifies in fact that in the global isochrone fitting technique, both the distance modulus and mass of the clump stars depend on the above color difference according to the relations $\partial M_V^{TO}/\partial\Delta(B-V) \simeq -9.2$ and $\partial M^{HB}/\partial\Delta(B-V) \simeq -22\ M_\odot$/mag. Therefore, an uncertainty in $\Delta(B-V)$ as small as $\delta[\Delta(B-V)] = 0.01$ mag implies an uncertainty in the distance modulus of $\delta(m-M) = 0.1$ mag and, even more important, an uncertainty in the mass of the clump stars of 0.22 $M_\odot$. Fits of the CMD of M 67 (and NGC 6791) are presented, in which the classical value of the mass for the stars in question is recovered. The claim that the rate of mass loss from RGB stars increases with the metallicity is not supported by the present day data for M 67. Finally, the claim that in NGC 6791 the metallicity higher than in M 67 is the cause of the occurrence of a few faint, blue stars, and in turn that mass loss plays the key role in generating stars that are potential candidates as sources of UV flux in elliptical galaxies and bulges, are also not supported by current data.

Key words: stars: mass-loss – stars: horizontal branch – Galaxy: open clusters: M 67 – Galaxy: abundances – ultraviolet: galaxies

1. Introduction

Mass loss from RGB stars in old, open clusters has been the subject of recent studies aimed at understanding whether or not the rate of mass loss strongly depends on the metallicity.

In the classical view of this problem, mass loss from RGB stars of Globular Clusters is governed by the empirical relation proposed long ago by Reimers (1975)

$$\dot{M} = -4 \times 10^{-13} \eta \frac{L}{gR}\ M_\odot/\mathrm{yr} \qquad (1)$$

where L, g and R are the luminosity, gravity and radius expressed in solar units, respectively, and η is a free parameter whose value is constrained by observation. It is worth recalling that according to the Reimers (1975) relation, mass loss along the RGB actually takes place near the RGB tip. For Globular Clusters, comparison with the horizontal branch (HB) morphology confines η within a narrow range, i.e. $\eta = 0.4 \pm 0.2$ (see Iben & Renzini 1983 for details). Higher values would suppress the core He-burning phase altogether, and HB stars in turn, whereas lower values would always yield red HBs, both alternatives being in contrast with observed CMDs of globular clusters.

Over the mass range of low mass stars (those undergoing core He-flash, i.e. up to 1.8 - 2.2 $M_\odot$) the straight application of the Reimers formula predicts that the total amount of mass lost by RGB stars gets smaller and smaller at increasing mass. This results from the fast decrease of the RGB lifetime with the star mass that is not compensated by an equal increase in the mass-loss rate of Eq. (1) despite its dependence on the luminosity.

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Furthermore, according to Eq. (1) there is no dependence on the chemical composition. Both trends are consistent with the observational information on the mass loss from cool stars (cf. Dupree 1986).

However, for a number of reasons (cf. the recent review by Chiosi et al. 1992) the rate of mass loss during the RGB phase is expected to increase both with the star mass and the metallicity. The second hint, in particular, is inferred from the current idea that dust or molecule opacity might allow radiatively driven winds in cool stars similar to those of hot stars (MacGregor & Stencel 1992).

In this context, Greggio & Renzini (1990) propose the following relation

$$\dot{M} = -4 \times 10^{-13} \eta \left(1 + \frac{Z}{Z_{\rm crit}} \right) \frac{L}{gR} \; M_{\odot}/{\rm yr} \qquad (2)$$

where the factor $(1 + Z/Z_{\rm crit})$ mimics a dependence on metallicity, with $\dot{M}$ increasing with Z by an amount which by definition is a factor of 2 at $Z = Z_{\rm crit}$, where $Z_{\rm crit} \geq Z_{\odot}$. Therefore, for $Z \ll Z_{\rm crit}$ the standard value of $\dot{M}$ is recovered, whereas a certain increase is obtained for $Z \gg Z_{\rm crit}$.

In addition to mass loss from RGB stars, the morphology of the HB is controlled also by the helium-metallicity ratio $\Delta Y/\Delta Z$. This topic has been discussed in great detail by Greggio & Renzini (1990) to whom the reader should refer. The ratio $\Delta Y/\Delta Z$ is currently highly uncertain, likely being comprised between 1 and 3 (Pagel 1989, Steigman et al. 1989).

Therefore, both mass loss and $\Delta Y/\Delta Z$ concur to produce, at a suitable value of the age, stars of low mass whose core He burning stages are hotter than the RR Lyrae stars, i.e. with $T_{\rm eff}$ hotter than about 10,000 K and therefore potential candidates to the source of UV flux observed in elliptical galaxies and bulges (Burstein et al. 1988).

The origin of the UV flux has been the subject of recent studies among which we recall Greggio & Renzini (1990), Bressan et al. (1994), and Dorman et al. (1993). From these studies it emerges that UV emission candidates are likely old, low-mass stars in distinct evolutionary stages. These are the post-red giant branch stars (P-RGB) failing core He-burning because of heavy RGB mass loss likely driven by high metallicity: the hot horizontal branch stars (H-HB) burning helium in the core, both of very low and very high metallicity, and their progeny, namely AGB-manqué and post-early AGB stars (P-EAGB), and finally the classical post AGB stars (P-AGB), burning either He or H at the surface. All these stars have akin structure: a compact core surrounded by an outer, much less dense envelope. If for whichever reason the mass of the outer envelope falls below a certain critical value, the star rapidly shifts to high $T_{\rm eff}$, either at constant or decreasing luminosity. Mass loss is an obvious mechanism for decreasing the envelope mass, like in the hypothetical P-RGB and the H-HB stars of composition typical of Globular Clusters (low Z and Y = 0.235). However, the rate at which the central core grows under the action of nuclear burning in the H- and/or He-shells is another way to achieve the same goal like in the case of H-HB stars of high Z and Y (e.g. the stellar models by Fagotto et al. 1994).

However, both the accurate scrutiny of the various possibilities (Greggio & Renzini 1990) and the detailed models of galaxy evolution (Bressan et al. 1994) have restricted the number of plausible candidates to the following list:

(*a*) The classical P-AGB stars (see Bruzual 1992, Bruzual & Charlot 1993, Charlot & Bruzual 1991).

(*b*) The blue HB stars of extremely low metallicity (see Lee 1994).

(*c*) The H-HB of high metallicity and their progeny, the AGB-manqué stars (see Bressan et al 1994).

HUT observation of Ferguson et al. (1991) and Ferguson & Davidsen (1993) of the UV excess in the bulge of M31 shows a drop-off short-ward of about 1000 Å whose interpretation requires that the temperature of the emitting source must be about 25,000 K. Only a small percentage of the $912 \leq \lambda \leq 1200$ Å flux can be coming from stars hotter than 30,000 K and cooler than 20,000 K.

Bressan et al (1994), taking also into account these observations, show in details that cases (*a*) and (*b*) are not able to account for observed properties of UV excess and spectral distribution in elliptical galaxies. They include in their spectro-photometric models of elliptical galaxies the evolution of chemical abundances according to the enrichment law $\Delta Y/\Delta Z$=2.5 (the solar ratio) and find that metallicities high enough to activate the H-HB and AGB manqué stars even in presence of normal RGB mass loss (η = 0.35) are present. Therefore they favour the idea that the dominant source of UV flux are the stars of type (*c*) expected to be present, albeit in small percentages, in the stellar content of bulges and elliptical galaxies.

In contrast, Dorman et al. (1993) favour other alternative to produce H-HB and AGB manqué stars, i.e. enhanced RGB mass loss as a function of the metallicity. Their conclusion is likely to be influenced by the results of Tripicco et al. (1993) and Liebert et al. (1994) on the RGB mass loss in two open clusters of high metallicity (at least compared to solar).

Tripicco et al. (1993) studied the CMD of M 67 and in particular the location of the clump of red giants, for which they are able to assign a mass of 0.7 $M_{\odot}$. Compared to the turn-off mass of about 1.2 $M_{\odot}$ typical of a cluster with 5 Gyr age, this implies mass-loss rates along the RGB much higher than given by the classical Reimers (1975) relationship. Since M 67 has nearly solar metallicity, Tripicco et al. (1993) conclude that the rate of mass loss must increase as the metallicity increases over the value typical of Globular Clusters. Of course the stars of M 67 cannot be sources of UV radiation, but the road is open to the claim that at even higher metallicities more mass is lost and thus H-HB can be formed.

Indeed this is the conclusion reached by Liebert et al. (1994) analyzing the CMD of the metal-rich cluster NGC 6791, where both the normal red clump and a group of a few faint, extremely blue stars are visible. Liebert et al. (1994) assign the mass of 0.7 $M_{\odot}$ to the stars in the red clump in analogy to the Tripicco et al. (1993) result, and argue that the faint, blue objects are of even smaller mass (0.5 $M_{\odot}$), so that a bimodal distribution of mass for the evolved stars is present. In principle, the faint blue stars belong to the category of H-HB models and therefore are good UV emitters. Admittedly they cannot satisfactorily explain the unusual HB morphology in NGC 6791, i.e. the bimodal mass distribution. However, as the metallicity of NGC 6791 is higher than in M 67 they conclude that the stars in question provide evidence for a strong dependence of the mass-loss rate on metallicity, and thoroughly speculate about their potential role as UV emitters in elliptical galaxies.

Therefore, we are facing the issue whether the stars responsible of the the UV flux in elliptical galaxies and bulges are the result of chemical enrichment alone as favoured by Bressan et al. (1994) or mass loss from RGB stars enhanced by chemical enrichment as favoured by Dorman et al. (1993).

Owing to the far reaching implication of the Tripicco et al. (1993) result, we feel it wise to thoroughly scrutiny the observational evidence for an enhancement of the RGB mass loss rate with the metallicity.

2. Are the red stars in the clump good indicators of mass loss?

For the sake of better understanding we summarize here the key steps of the Tripicco et al. (1993) analysis.

- All studies concur that the metallicity of M 67 is virtually indistinguishable from solar, [Fe/H] = -0.09 ± 0.07 according to Friel & Janes (1993), [Fe/H] = -0.04 ± 0.12 according Hobbs & Thorburn (1991).
- All studies concur that the age of M 67 is 5 Gyr with uncertainties of only a fraction of a Gyr (Demarque et al. 1992). It is refreshing to note that with this age the turn-off mass is about 1.1 $M_\odot$ while that of the giant stars near the tip of the RGB is about 1.3 $M_\odot$. There might be a little dependence on the exact composition and physical input of the models which is not relevant here.
- Reddening in M 67 is very small $E_{B-V} = 0.032$ according to Nissen et al. (1987).
- The apparent distance modulus is $(m - M) = 9.55$.

With these assumptions and the aid of a suitable relation converting the $(V - K)$ colors into $T_{\rm eff}$, Bell & Gustafsson (1989) in their analysis, Tripicco et al. (1993) locate the red giant stars of the clump in the theoretical plane ($\log L/L_\odot$, $\log T_{\rm eff}$) and compare them with isochrones and the locus of the zero age horizontal branch (ZAHB) of low mass stars. A mass of the clump stars of about 0.7 $M_\odot$, and the claim for substantial mass loss passing from the RGB tip down to the ZAHB follow immediately. According to Tripicco et al. (1993) this conclusion is also substantiated by the color difference between the clump stars and the RGB. Specifically, the clump stars are separated from the RGB by 0.1 mag in $(B - V)$, which corresponds to $\Delta T_{\rm eff} \simeq 250$ K. Looking at the distance of ZAHB models from the RGB (cf. their Fig. 3 and/or Table 1) they conclude that *a temperature gap of 250 K can be only explained if the clump giants have lost nearly half of their mass before helium burning commences.* They also note that *this result is insensitive to the adopted age, as the RGB shifts quite slowly with age.*

However, the right question to be addressed is whether this conclusion is insensitive to $(m - M)$ and all other ingredients of the analysis, i.e. theoretical models, isochrones, and $(V - K)$ - $T_{\rm eff}$ and BC-$T_{\rm eff}$ relations, in particular.

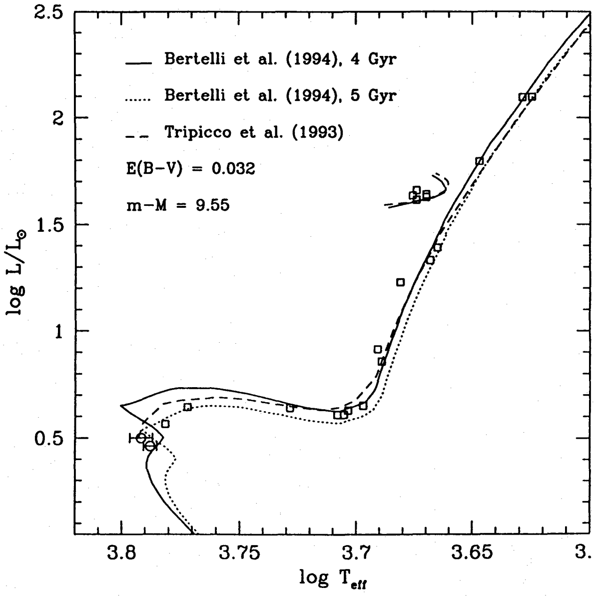

Fig. 1. Selected stars of M 67 in the fundamental plane ($\log L/L_\odot$, $\log T_{\rm eff}$). The open squares are the giants, while the the open circles near the TO regions are the two stars by Hobbs & Thorburn (1991) for which the $T_{\rm eff}$ has been determined. The transformation from apparent magnitudes and colors is made using the apparent distance modulus $(m - M)=9.55$ the color excess $E_{B-V}=0.032$, and the color-temperature calibration of Bell & Gustafsson (1989). See the text for more details. Superposed are three isochrones: the 5 Gyr (dashed line) calculated by Tripicco et al. (1993), and the 4 Gyr (solid line) and 5 Gyr (dotted line) derived from the Bertelli et al. (1994a) library and the locus of the ZAHB models. See the text for details about the chemical composition and input physics of the underlying stellar models

It is an easy matter to understand that the great villain of the problem is the distance modulus, which must be known with very high precision, together with the color-BC-$T_{\rm eff}$ relation. Indeed a good fit of the whole CMD of M 67 will be shown in which $(m - M)=9.65$. Unfortunately a difference of about 0.1 mag in $(m - M)$, and an additional uncertainty of about 0.05 mag caused by the color-BC-$T_{\rm eff}$ relation (see below), are sufficient to falsify the Tripicco et al. (1993) conclusion. In fact $\Delta(m - M) = 0.1$ plus 0.05 mag corresponds to $\Delta \log L/L_\odot = 0.06$. The clump stars get brighter by this amount and, sliding almost parallel to the RGB so that their distance of 0.1 mag in $(B - V)$ is maintained (see below), fall along the ZAHB near the models with about 1.2 $M_\odot$. This means negligible mass loss from the RGB tip down to the ZAHB in agreement with the classical prediction.

In order to prove the above statement, we perform the following exercise.

First, we compare our isochrones with those used by Tripicco et al. (1993). This is shown in Fig. 1, which displays the 5 Gyr isochrone by Tripicco et al. (1993) for $Z=0.0169$ and $Y=0.270$ and the 4 and 5 Gyr isochrones with $Z=0.018$ and $Y=0.275$ derived from the Bertelli et al. (1994a) library. The rea-

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son for the slightly different chemical parameters will become clear in Sect. 4. The two 5 Gyr isochrones basically coincide considering that the Tripicco et al. (1993) models are calculated with the Los Alamos (Huebner et al. 1977) and Alexander (1975, 1981) low-temperature opacities, whereas the Bertelli et al. (1994a) isochrones are calculated with the Livermore opacities (Iglesias et al. 1992) supplemented in the low-temperature regions by the analytical relationships by Bessell et al. (1989, 1991) based on the Alexander (1975) and Alexander et al. (1983) tabulations. Furthermore, the mixing length in outermost convection is 1.6 H_p in Tripicco et al. (1993), based on the fit of the RGB of M 67, whereas it is 1.63 H_p in Bertelli et al. (1994a), based on the fit of the solar properties. Finally, at this stage of the analysis it is worth clarifying once for all that in the age and hence mass range we are looking at, no problem arises with convective overshoot from the central core.

Second, we plot in this diagram the giant stars following the same series of transformations used by Tripicco et al. (1993) to convert magnitude and colors into luminosities and $T_{\rm eff}$. The V and K magnitudes are taken from Mathieu et al. (1986) and Cohen et al. (1978), respectively. The resulting $V-K$ color, dereddened by $E_{V-K} = 2.72E_{B-V}$ (Savage & Mathis 1979), is converted to $T_{\rm eff}$ according to the color-temperature relation by Bell & Gustafsson (1989). Finally $(m-M)$=9.55 is adopted. The data are shown in Fig. 1. This exactly corresponds to Fig.3 of Tripicco et al. (1993). We have also added to the sample of red giants two stars near the TO region, for which the $T_{\rm eff}$ has been independently determined by Hobbs & Thorburn (1991). The two brightest, hottest stars have $T_{\rm eff} = 6165 \pm 60$ K.

It is soon evident that the giant stars are now better fitted by the 4 Gyr isochrone. This is the obvious consequence of the small albeit significant differences in the underlying stellar models. This will be the reason for the different fit of the CMD of M 67 to be discussed in Sect. 4, yielding $(m-M)$=9.65, E_{B-V}=0.025 and age of 4 Gyr. The position of the two stars near the main sequence does not help to choose a particular value of the age as they are reasonably well matched by both isochrones. The agreement in $T_{\rm eff}$ is however remarkable.

Finally, we have to single out the effect of using different color-temperature relations (e.g. Kurucz 1992, Gratton 1994) and/or BC-$T_{\rm eff}$ relations (Flower 1977, VandenBerg 1992, and Kurucz 1992). To this aim we display in the various panels of Fig.2 the position of the red giant stars obtained from using different color-$T_{\rm eff}$-relations (as indicated) and $(m-M)$=9.65 with our 4 Gyr isochrone. The careful inspection of the $\log L/L_\odot$ assigned to the giant stars shows that, while Flower (1977) and Kurucz (992) relations yield identical results, VandenBerg (1992) calibration yields luminosities fainter by $\Delta \log L/L_\odot = 0.02$ or equivalently $\Delta M_V = 0.05$ mag, because of the slightly different BC scale and $M_{{\rm bol},\odot}$ at $\log T_{\rm eff} \simeq 3.7$.

What we learn from this comparison is that the position of the clump red giants in the CMD and the derivation of their mass rely on the assumed color-BC-$T_{\rm eff}$ relation and distance modulus. With $(m-M)$=9.55 and the Vandeberg (1992) relation, the Tripicco et al. (1993) result is recovered, i.e. the clump stars have mass of 0.7 $M_\odot$, whereas, with $(m-M)$=9.65 and the other calibrations, the clump stars have mass in the range 1.2-1.3 $M_\odot$. Both solutions are equally legitimate. Anyway, the distance modulus plays the key role.

It is worth recalling that Tripicco et al. (1993) did not determine the distance modulus but took it from literature, where it has been derived from isochrone fitting of the turn-off in the observational CMD.

Instead of arguing which distance modulus and calibration ought to be preferred, we address the general question whether the mass of the clump stars and the efficiency of mass loss from the RGB stars in turn, can be safely determined from a method which ultimately stands on the isochrone fitting procedure. The analysis is made looking at the response of the results to even small variations of the various key parameters.

3. Uncertainties of the isochrone fitting technique

The bottom line of our reasoning is that despite the accuracy of present day theoretical models and isochrones and the high quality of the photometric data (magnitudes, colors, etc.) exact coincidence between theory and observation is not yet possible.

Let us consider the age as the unknown parameter and the magnitude, colors of the TO, SGB, RGB, and clump stars as the constraints of the problem.

The isochrone fit method, from which both the age and the distance modulus are derived (and often a guess of the metallicity as well), seeks coincidence between the locus drawn by stars in the CMD and a particular isochrone. Depending on the quality of the fit either all or part of the above constraints are matched. In the most accurate fits, the so-called *Global Fit* is searched, i.e. the simultaneous matching of the luminosities and colors of the TO, SGB, and RGB. Aim of our analysis is to point out the uncertainty intrinsic to the fitting technique itself.

Let us now suppose that the set of models, isochrones in use are not perfectly suited to the CMD under examination, either because the assumed chemical composition slightly differs from the real one or the mixing length parameter has not been fully calibrated or any other reason. If the difference is small, the set of isochrones is not rejected and the fit yields a value for the age somewhat different from the real one.

For the sake of illustration, let us suppose that the uncertainty comes from the theoretical RGB. Indeed the RGB is more sensitive to even small variations in the metallicity and mixing length. This is the typical source of disagreement found in the fitting procedure. As a consequence of it, matching the observed RGB stars by a slightly cooler theoretical RGB implies a slightly older age and vice-versa. A different age, implies also a slightly different separation between the TO and the HB and hence, as a result of the global fit, a different location of the expected HB stages in the CMD. For slightly older ages, also slightly brighter HB stars are expected.

While a small error in the age is tolerable, because an uncertainty in the age of an old clusters amounting to a fraction of a Gyr is not relevant in general, an uncertainty in the HB star magnitude as small as 0.2 mag or 0.08 in $\log L/L_\odot$ is not, in

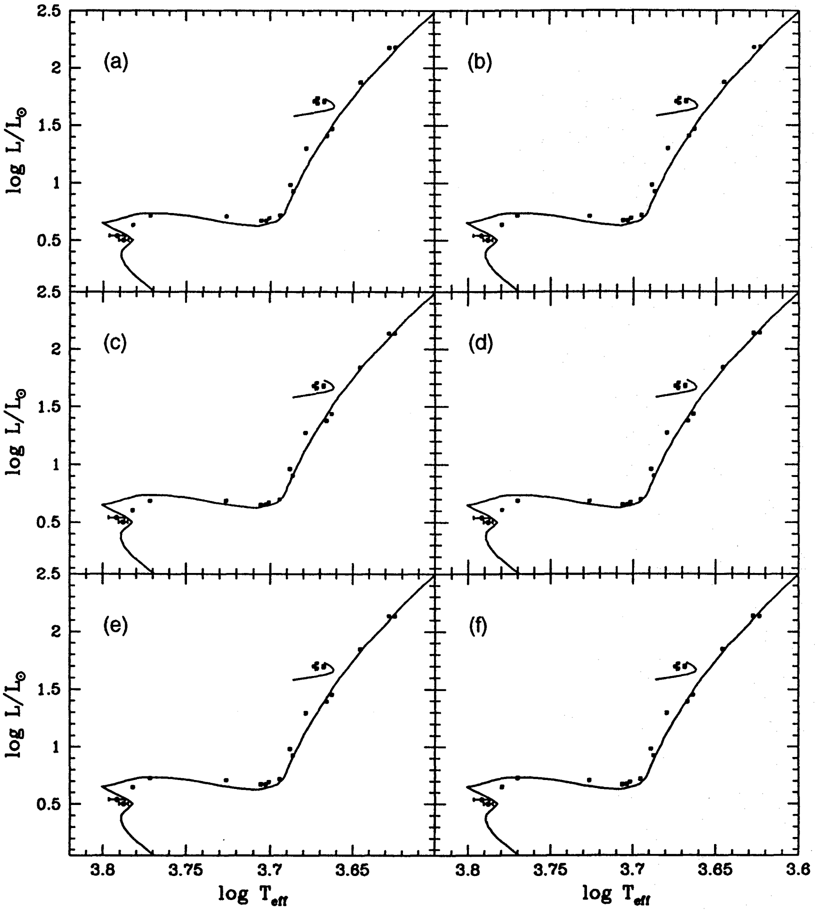

Fig. 2a–f. Comparison of selected stars of M 67 with the 4 Gyr isochrone and ZAHB derived from the Bertelli et al. (1994a) library. The apparent distance modulus is (m − M)=9.65; the color excess is E_{B-V}=0.025. See the text for more details. The full dots are for the giants, whereas the barred dots are for the two main sequence stars with determined T_{eff}. Each panel corresponds to different BC-T_{eff} relationships. Panel **a** T_{eff} from Gratton (1994), BC from Kurucz (1992). Panel **b** T_{eff} from Bell & Gustafsson (1989), BC from Kurucz (1992). Panel **c** T_{eff} from Gratton (1994), BC from VandenBerg (1992). Panel **d** T_{eff} from Bell & Gustafsson (1989), BC from VandenBerg (1992). Panel **e** T_{eff} from Gratton (1994), BC from Flower (1977). Finally, Panel **f** T_{eff} from Bell & Gustafsson (1989), BC from Flower (1977)

particular if these stars are used to infer the efficiency of mass loss along the RGB phase.

One of the key steps of the isochrone fitting is to look at the color separation Δ(B − V) between the TO and the bottom of the RGB, because Δ(B − V) is often considered as one of the best age indicators.

From the library of theoretical isochrones by Bertelli et al. (1994a) and limited to the age range typical of M 67 (say at about 4 Gyr), the various quantities in use are reported in Table 1, we derive the following relationships as a function of the age for Δ(B − V) and the TO absolute visual magnitude (M_V^{TO})

$$\frac{\partial \Delta(B-V)}{\partial t} \simeq -0.02 \text{ mag/Gyr} \tag{3}$$

and

$$\frac{\partial M_V^{TO}}{\partial t} \simeq 0.185 \text{ mag/Gyr} \tag{4}$$

from which we get

$$\frac{\partial M_V^{TO}}{\partial \Delta(B-V)} \simeq -9.2 \tag{5}$$

Thus an offset in Δ(B − V) (caused by a small uncertainty in the RGB as small as $\delta[\Delta(B-V)]$=0.01 mag) means an intrinsic offset in the TO magnitude amounting to $\delta M_V^{TO} \simeq 0.09$ mag. This constitutes a sort of minimal uncertainty in the derivation of the distance modulus. Consequently, there is an offset in the age of about 0.5 Gyr toward older ages.

How would this uncertainty reflect on the determination of the mass of the HB stars ? The ZAHB of low mass stars is actually far from being horizontal but draws in the HRD a sort of vertical bow whose apex is toward the low temperature side, high mass HB stars being brighter than that of the low mass ones (see the panels of Fig. 2).

The difference in M_V between ZAHB stars with mass 1.3 M$_\odot$ and 0.7 M$_\odot$ is about 0.25 mag (Bertelli et al. 1994a), thus in this mass interval the following relation holds

$$\frac{\partial M^{HB}}{\partial M_V^{HB}} \simeq -2.4 \ M_\odot/\text{mag} \tag{6}$$

where M_V^{HB} and M^{HB} are the absolute visual magnitude and mass of the ZAHB stars, respectively (see Table 1).

Therefore, if one tries to determine the mass of a HB star by the sole luminosity difference with respect to the sub-giant branch (SGB) as actually done in the global isochrone fitting technique, the small uncertainty in the RGB implies

$$\frac{\partial M^{HB}}{\partial \Delta(B-V)} \simeq -22 \ M_\odot/\text{mag} \tag{7}$$

The net result is that an offset in the predicted color difference between the TO and the RGB as large as $\delta[\Delta(B-V)]$=0.01 gives rise to an offset of 0.22 $M_\odot$ in the HB star mass.

The above offsets in the distance modulus and masses of the red giant stars are a sort of minimum values, because at this stage of the discussion we have not yet taken into account the effect of different color-BC-$T_{\rm eff}$ relations.

Conversely, if the theoretical RGB is somewhat hotter than appropriate ($\delta[\Delta(B-V)]$=-0.01), we may also have the manifestly wrong result that the HB mass is greater than that at the RGB tip. This because with $\delta[\Delta(B-V)]$=-0.01, a younger age and fainter HB stars in turn, would be deduced from the global fitting technique.

In this latter alternative, the wrong conclusion is easily avoided by resorting to other isochrones (for instance different metallicities), whereas in the former case the potential error may not be immediately evident so that one is led to accept the result of isochrone fitting.

Going back to the Tripicco et al. (1993) study, the authors claim that no direct use of the luminosity is made to determine the mass of the HB stars. Instead, this is derived from the observed color difference between the HB location and the RGB. With the assumed distance modulus and age, the above color difference corresponds to a HB mass of about 0.7 $M_\odot$. Since the TO mass is about 1.3 $M_\odot$ their conclusion of an amount of mass lost during the RGB as high as 0.6-0.7 $M_\odot$ follows immediately.

However, we have already noted that looking at their own theoretical HRD another solution exists, i.e. another point of ZAHB is located at the observed distance from the RGB. This is the model of about 1.3 $M_\odot$, which however is about 0.25 mag brighter than the model of 0.7 $M_\odot$. Therefore, if the clump stars are actually 0.25 mag brighter than assumed, this solution is legitimate as well. AS a matter of fact, an offset in $(m-M)$ amounting to only 0.1 mag together with an uncertainty of 0.05 mag caused by the color-BC-$T_{\rm eff}$calibration are fully sufficient. Since the magnitude of the HB stars adopted by Tripicco et al. (1993) is the consequence of the assumed age, distance modulus, color excess, and color-BC-$T_{\rm eff}$ calibration, i.e. of the isochrone fitting technique performed in the original sources, our analysis of the intrinsic uncertainty affecting these important parameters is applicable.

As a conclusion, we are left with the following alternatives

- All the parameters both implicit in the fitting method or adopted in the specific analysis of the HB stars (mixing length, metal abundance, color conversion, only to enumerate those most directly affecting the location of the RGB relative to the TO), are *absolutely correct* . The results by Tripicco et al. (1993) are valid, i.e. the HB stars have mass of about 0.7 $M_\odot$ and about 0.6 $M_\odot$ have been lost during the RGB phase. The mass-loss rate must be much higher than expected from the the Reimers (1975) relation.
- Plausible uncertainties affect the above key parameters of the isochrone fitting technique and concur to make somewhat uncertain the location of the RGB with respect to the TO. In our exemplification of the problem, this translates into asking how large should it be the uncertainty on the color difference $\Delta(B-V)$ in order to have solutions of the problem in agreement with the classical efficiency of mass loss from RGB stars. It is an easy matter to understand that an uncertainty in the adopted RGB amounting only to $\delta[\Delta(B-V)] \simeq 0.02$ is fully sufficient to recover the classical solution. Indeed correcting the isochrone for this small offset will provide the higher values for the HB masses. i.e. $\simeq$1.3 $M_\odot$. In such a case the amount of mass lost during the RGB phase is negligible in agreement with the classical view of this subject.

As a consequence of the above discussion, we must ask ourselves whether *the isochrone fitting technique is free from even small uncertainties, so that both* $(m-M)$ *and* $\Delta(B-V)$ *are known within say 0.1 and 0.02 mag respectively. We dare to say that this is not the case.*

Although establishing which of the two alternatives ought to preferred is beyond the scope of this study, we will present below a fit of the CMD of M 67 which is as good as the one obtained by Tripicco et al. (1993) but provides the opposite result, i.e. normal mass loss.

4. Another fit of the CMD of M 67

A recent study of the CMD of M 67 is by Carraro et al. (1994) to whom we refer for a summary of the current information about metallicities, reddening, and distance modulus. The analysis make use of the CMD by Gilliland et al. (1991) and the main results can be summarized as follows: (*a*) With classical stellar models (i.e. without convective overshoot) and the chemical composition Y=0.28 and Z=0.02, they obtain the color excess E_{B-V}=0.02, the apparent distance modulus $(m-M)$=9.60, and the age of 4.3 Gyr: (*b*) with stellar models allowing for a small amount of convective overshoot and the same chemical composition they get the color excess E_{B-V}=0.02, the apparent distance modulus $(m-M)$=9.50, and the age of 4.8 Gyr. Details of the stellar models in use can be found in Bertelli et al (1994).

Because of its better completeness with respect to older CMDs, we prefer to adopt here the CMD derived by Montgomery et al. (1993) using CCD photometric data in the BVI pass-bands. This CMD is shown in Fig.3.

As already recalled, the most recent studies set the metallicity in the range [Fe/H] = -0.09 ± 0.07 (Friel & Janes 1993) to [Fe/H] = -0.04 ± 0.12 (Hobbs & Thorburn 1991). The estimate by Friel & Janes (1993) is from high-resolution spectroscopy of a handful of cluster giants, whereas that by Hobbs & Thorburn (1991) is from high dispersion spectra of five stars located along the main sequence.

Reddening and distance modulus span an ample range of values. Limiting ourselves to recent estimates, the former goes from E_{B-V}=0.01 (Burstein et al. 1986), E_{B-V}=0.032 (Nissen et al. 1987) to E_{B-V}=0.06 (Janes 1984), whereas the latter varies from $(m-M)$=9.57 (Racine 1971), $(m-M)$=9.61 Nissen et al. (1987) to $(m-M)$=9.63 (Anthony-Twarog 1987). Both red-

Table 1. Key points along isochrones with metallicity Z=0.018

Age Gyr	M_V^{TO} mag	$(B-V)_0^{TO}$ mag	M_{TO} $M_\odot$	$(B-V)_0^{RGB}$ mag	M_{Tip}^{RGB} $M_\odot$	$\Delta(B-V)$ mag	M_V^{HB} mag	M_{HB} $M_\odot$
3.5	3.778	0.505	1.181	0.912	1.395	0.407	0.901	1.290
4.0	3.869	0.522	1.144	0.919	1.335	0.393	0.930	1.233
4.5	3.963	0.538	1.125	0.925	1.293	0.387	0.955	1.175

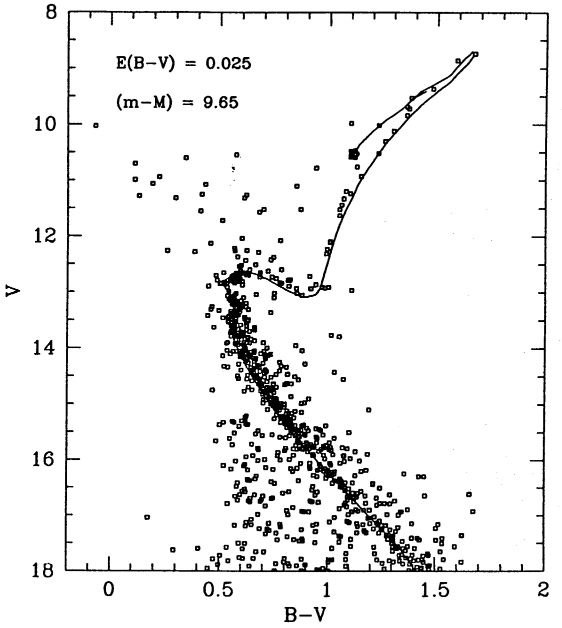

Fig. 3. CMD of M 67 from Montgomery et al. (1993). Superimposed is the isochrone of 4 Gyr with composition Y=0.275 and Z=0.018. Mounting of the theoretical isochrone in the observational CMD is for E_{B-V}=0.025 and (m − M)=9.65. See the text for more details

dening and distance modulus will be derived from the fit of the CMD together with the age.

The theoretical isochrones are calculated using the library of stellar models of the Padua group by means of an upgraded version of the algorithm described by Bertelli et al. (1994a) which allows us to generate isochrones and simulated CMDs at varying chemical composition. Details of the new algorithm can be found in Ng et al. (1994) and Bertelli et al. (1994b) in their study of the stellar content of the Galactic Bulge. The greatest advantage offered by the new algorithm is that now the chemical abundances can be iteratively changed in a continuous fashion until a good match is reached. In previous studies (cf. Carraro et al. 1994 and Bertelli et al. 1994a) the abundances of the isochrones could not differ from those of the underlying stellar models.

The conversion from $\log L/L_\odot$ and $\log T_{eff}$ to magnitude and colors is as in the isochrones tabulations by Bertelli et al. (1994a), i.e. derived from the Kurucz (1992) library of stellar spectra. However, since the T_{eff}- (B − V) relation in Kurucz (1992) is not fully adequate (cf. Worthey 1994), we have replaced it with the calibration by R. Gratton (1994, private communication).

Finally, the rate of mass loss along the RGB is according to the Reimers (1975) relation with η = 0.35 i.e. similar to that for globular clusters. This is a very conservative assumption for an intermediate age cluster like M 67.

We find that a good reproduction of the M 67 CMD is possible for the following set of parameters: Y=0.275, Z=0.018, (m − M)=9.65, E_{B-V}=0.025, and finally age of 4 Gyr. These values are all compatible with other current estimates. The isochrone in question is mounted on the CMD of Fig. 3. The present estimate of (m − M), E_{B-V} and age differ from those found by Carraro et al. (1994) because of the different CMD, the slightly different chemical composition and the different T_{eff}-(B − V) relation. Once more this proves the extreme sensitivity of the results to even small changes in the observational data and analysis technique.

We feel it wise to remark that our isochrone provides a good fit of all major features of the CMD, namely the TO luminosity and color, the SGB and RGB, and finally and more important the luminosity and color of the HB in the red clump. In particular our isochrone matches the detailed shape of the main sequence band near the TO region.

The value of the TO mass is 1.14 $M_\odot$, that near the tip of the RGB is 1.33 $M_\odot$, and finally that of the clump stars is 1.23 $M_\odot$.

No need of an increase of the mass-loss rate from the RGB tip to the red clump is found.

5. Concluding remarks

The main results of the present study are briefly summarized as follows:

- The isochrone global fitting method cannot give distance moduli with a precision better than 0.1-0.2 mag unless the separation $\Delta(B-V)$ between the TO and the bottom of the RGB can be determined with a precision smaller than $\delta[\Delta(B-V)] < 0.01$ mag, cf. Eq. (5). To this aim, highly accurate photometric data and theoretical calibrations would be required that are perhaps still beyond the present day feasibility.
- The intrinsic uncertainty affecting the distance modulus immediately reflects onto the determination of the mass of the clump stars. Indeed, as shown by Eq. (7), an offset in $\Delta(B-V)$ as small as $\delta[\Delta(B-V)]$ = 0.01 mag implies an offset of 0.22 $M_\odot$in the mass of these stars. This makes

hopeless the use of the clump stars as a way for inferring the amount of mass lost during the RGB phase. As a matter of facts, to get an estimate of the mass of these stars with an accuracy of 5% (a minimum limit for the kind of problem in question) one would require a distance modulus known with a precision higher than about 0.025 mag.

Before concluding this study, we would like to comment on the problem raised by the stellar content of NGC 6791. As already recalled the CMD of the metal-rich, globular-like cluster NGC 6791 (Kaluzny & Udalski 1992) shows both the normal clump of red stars and the faint blue group, otherwise named H-HB stars. A recent analysis of this CMD has been made by by Carraro & Chiosi (1995), using the same method and library of theoretical isochrones described here for M 67. A very good global fit of the CMD has been reached with the following results: metallicity Z=0.028, helium content Y=0.300, color excess E_{B-V}=0.15, distance modulus (m − M)=13.50, age equal to 9 Gyr, TO mass of 1.1 $M_\odot$, mass at the RGB tip of 1.15 $M_\odot$, and finally mass for the stars in the red clump equal to 0.9 $M_\odot$. This latter has been derived adopting $\eta = 0.35$ in the RGB mass-loss rate. Also in this case, no need for a increase in the mass loss efficiency above the Reimers (1975) prediction has been noticed.

Of course the existence of the H-HB stars cannot be accounted for. The analysis of Liebert et al. (1994) has shown that these stars have masses much smaller than those in the clump, 0.5 $M_\odot$ in their estimate. With the Carraro & Chiosi (1995) evaluation of the clump star mass, the difference is even larger than in Liebert et al. (1994). Clearly, the mass of about 0.5 $M_\odot$ and the little dispersion about it strongly suggest that we are in presence of nearly bare core structures with the original envelope almost entirely stripped away.

Although the mechanism leading to their formation is unknown, Liebert et al. (1994) are able to put some general constraints on it. They notice that (a) *it is difficult to see how such large fraction of faint blue stars with almost identical envelope mass could have been produced by single star mass loss rates with any reasonable dispersion*; (b) *It seems equally difficult to understand how a binary mass transfer mechanism could be so fine-tuned*; (c) *It appears that the processes that makes H-HB in Globular Clusters need only to stretch out the blue HB stars by removing a tiny extra bit of envelope mass from a small fraction of the normally occurring blue HB majority, whereas in NGC 6791 an extra 0.2* $M_\odot$*(or 0.4* $M_\odot$*in our case) of envelope mass must be stripped away in what amounts to an all-or-nothing event.*

We would like to comment that the binary hypothesis deserves further investigation before being excluded. Indeed, the fine-tuning of H-HB star masses could be simply the result of mass loss of binary nature from stars made of a compact core and a dilute envelope. The body of literature on the physical response of stellar structure to mass exchange in binary systems (cf. Structure and Evolution of Single and Binary Stars, by C. de Loore & Doom, 1992) has shown that the primary stars, losing mass in the so-called B and C cases, for which the above structure applies, cannot halt the removal of the envelope until the bare core is exposed. Suppose that a fraction of the stars in the cluster are binaries with such a large separation that the primary can reach the tip of the RGB without undergoing mass transfer. Mass loss by stellar wind occurs over, perhaps removing part of the total angular momentum and thus shrinking the separation. Mass transfer can then start with the result that the primary is turned into a bare core. Since stars at the RGB tip have almost identical cores, the net result would be that almost identical H-HB objects are formed. Although all this is merely speculative, certainly it deserves further investigation.

In alternative, single star evolution is at the base of the H-HB occurrence. The last remark by Liebert et al. (1994) perhaps suggests that we are in presence of a threshold value for the envelope mass, below which sudden ejection may occur. It seems as if there is some yet unknown instability, perhaps manifesting itself only in presence of high metallicities, blowing off the envelope.

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