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On the peculiar red clump morphology in the open clusters NGC 752 and NGC 7789

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Abstract. The red clump stars in the open cluster NGC 752 present a peculiar distribution in the colour-magnitude diagram (CMD): the clump is observed to present a faint extension, slightly to the blue of the main concentration of clump stars. We point out that a similar structure is present in the CMD of NGC 7789, and discuss their possible origins. This feature may be understood as the result of having, at the same time, stars of low-mass which undergo the helium-flash, and those just massive enough for avoiding it. The ages of both clusters are compatible with this interpretation.

Similar features can be produced in theoretical models which assume a non-negligible mass spread for clump stars, of about 0.2 $M_{\odot}$. However, one can probably exclude that the observed effect is due to the natural mass range of core helium burning stars found in single isochrones, although present models do not present the level of detail necessary to completely explore this possibility. Also the possibility of a large age spread among cluster stars can be refuted on observational grounds.

We then suggest a few alternatives. This spread may be resulting either from star-to-star variations in the mass-loss rates during the RGB phase. Alternatively, effects such as stellar rotation or convective core overshooting, could be causing a significant spread in the core mass at He-ignition for stars of similar mass. Finally, we point out that similar effects could also help to understand the distribution of clump stars in the CMDs of the clusters NGC 2660 and NGC 2204.

Key words: Galaxy: open clusters and associations: general – stars: late-type – stars: evolution – stars: interiors – stars: Hertzsprung–Russel (HR) and C-M diagrams

1. Introduction

The clump of red giants is a remarkable feature in the colour-magnitude diagrams (CMD) of intermediate-age and old open clusters (Cannon 1970). It is defined by stars in the stage of core helium burning (CHeB).

In the clusters for which the non-member field stars and binaries have been identified and excluded, the red clump may occupy a very small region of the CMD. A good example of this case is given by the 4-Gyr old cluster M 67: its 6 clump stars differ in colour by less than 0.01 mag in $B-V$, and 0.1 mag in V (see e.g. Montgomery et al. 1993). This small spread of the clump can be easily understood as the result of having low-mass core He-burning stars of very similar masses in this cluster.

However, some clusters clearly present a more complex clump structure. One of the best examples is given by NGC 752: Mermilliod et al. (1998) recently pointed out it presents a kind of dual clump. It is shown in detail in the Fig. 5 of Mermilliod et al. (1998): there we can notice the presence of the main clump centered at $B-V=1.01$, $V=9.0$ and composed of 8 member stars, and a distribution of 3 or 4 fainter stars, going down by about 0.5 mag in relation with this main clump. Importantly, all stars plotted are members of the cluster with probability $P>93\%$, and photometric errors are lower than 0.015 on V and 0.013 on the colours. Therefore, the structure seen in NGC 752 is real, and not an artefact of observational uncertainties.

On the other hand, recent works suggest that clumps with a faint extension may be a common feature in the field of nearby galaxies. In a few words, population synthesis models of galaxy fields predict that a secondary red clump may be formed at about $0.3-0.4$ mag below the main one, containing the CHeB stars which are just massive enough for starting to burn helium in non-degenerate conditions. Girardi et al. 1998 first suggested the presence of this feature in the CMD derived from *Hipparcos* data-base (Perryman et al. 1997; ESA 1997). The subject has been later extensively discussed by Girardi (1999). Bica et al. (1998) and Piatti et al. (1999) recently presented clear evidence showing that this feature is present in the LMC.

Could this feature provide an explanation also for the peculiar morphology of the clump in NGC 752? Is a similar clump morphology observed in other clusters as well? These are the main questions we address in this paper.

2. The clusters

First of all, we examined the available data for galactic open clusters, in order to identify if other clusters have clumps with the same general appearance as in NGC 752. We used the extended database of accurate photometry and radial velocity data

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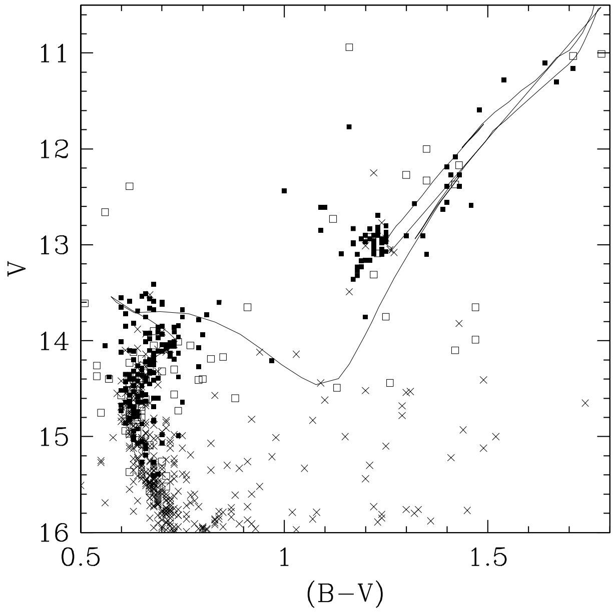

Fig. 1. CMD of NGC 7789. Filled squares denotes stars with membership probability $P > 75\%$, open squares stars with $P < 75\%$, and crosses stars without membership probabilities. The isochrone is from the models of Girardi et al. (2000) for solar metallicity and $\log t = 9.20$. Notice the fainter and somewhat bluer tail below the clump.

compiled by Mermilliod and collaborators. This data allows us to select the member stars and avoid the binaries in each cluster. In this way, clean CMDs can be produced. Indeed, Mermilliod & Mayor (1989, 1990) already noticed the presence of a number of stars below the clump in some clusters. The case of NGC 752, however, is remarkable for the high fraction of stars located below the "main clump" level, which causes its apparent bi-modality.

We searched for clusters with ages similar to that of NGC 752 ($9.1 < \log t < 9.3$). Several candidates were found. NGC 3680 and IC 4651 (Mermilliod et al. 1995) do not present the same characteristics as NGC 752 does. The red giant clump in NGC 3680 is rather concentrated, with few scatter in magnitude and colours, while the morphology of IC 4651 clump is more complex. NGC 2158 is a rich and very interesting cluster probably showing also a complex structure of the clump region. However, most data are photographic and there is presently no kinematical membership determination to identify the true members. A CCD study paying attention to the red giants would be worth. We shall therefore refrain to use this cluster. The fourth cluster is NGC 7789 for which BV CCD data have been published by Martinez Roger et al. (1994) and Jahn et al. (1995). Gim et al. (1998a) have published an extensive radial-velocity study which permits to reject the non-member stars and identify the binaries. Membership probabilities from proper motions for NGC 7789 have been published by McNamara & Solomon (1981) so that the membership of the red giants is rather well defined. Most other clusters containing numerous red giants and for which good photometric data are available are either younger

Table 1. Age estimates for NGC 752 and NGC 7789.

NGC	Age [Gyr]	Method	Reference
752	1.8	isochrone fitting	Meynet et al. (1993)
	1.5	synthetic CMD	Carraro & Chiosi (1994)
	2.0	isochrone fitting	Dinescu et al. (1995)
7789	1.3	synthetic CMD	Carraro & Chiosi (1994)
	1.6	isochrone fitting	Gim et al. (1998b)
	1.4	isochrone fitting	Vallenari et al. (1999)

(about 1 Myr) and have a large clump, with a few stars below or are older and have a more or less well developed giant branch.

As can be seen in Fig. 1, the red clump in NGC 7789 presents a tail of faint stars extending down to 0.4 mag below the main concentration of clump stars. Again, the fainter clump stars are observed to be slightly bluer than the main clump concentration.

A comparison between NGC 752 and NGC 7789 clearly evidences that both clusters have similar ages: suffice it to notice that the main sequence termination (TAMS) and red clump are observed at the same colour ($(B-V)_o = 0.5$ and $(B-V)_o = 1.0$, respectively), and that their magnitude difference is also very similar (of about $\delta V = 0.5$ mag) in both clusters. Also, we recall that both clusters have metallicities very close to each other: according to Friel & Janes (1983), [Fe/H] $= -0.16 \pm 0.05$ for NGC 752 and [Fe/H] $= -0.26 \pm 0.06$ for NGC 7789.

In Table 1, we list a limited number of age estimates for both clusters, in which the age-dating was based in models with overshooting.

It turns out that both NGC 752 and NGC 7789 should have an age of about 1.5 Gyr. These are indicative ages, which will be useful in the analysis of the following sections.

3. The models

In order to describe the evolution of clump stars as a function of cluster parameters, we make use of the stellar evolutionary tracks and isochrones from Girardi et al. (2000). This data-base of stellar models contains CHeB stars computed for a large number of initial masses, providing a detailed description of the position of these stars in both HR and colour-magnitude diagrams. Fig. 2 shows the location of the models for solar metallicity ($Z = 0.019$) in the M_V versus $B-V$ diagram. It can be noticed that CHeB models of varying mass distribute along a well defined sequence in this plot. This sequence is relatively narrow if we consider the initial fraction of 70% of the CHeB lifetime, where most of the CHeB stars are expected to be found. The remaining 30% fraction, instead, occupies a broad distribution in the diagram. Importantly, the sequence of CHeB models presents a well-defined lower boundary, which is also drawn in the plot. The same boundary line is shown for lower values of metallicity ($Z = 0.008$ and $Z = 0.004$), thus showing how the sequences of CHeB models get bluer as the metallicity decreases.

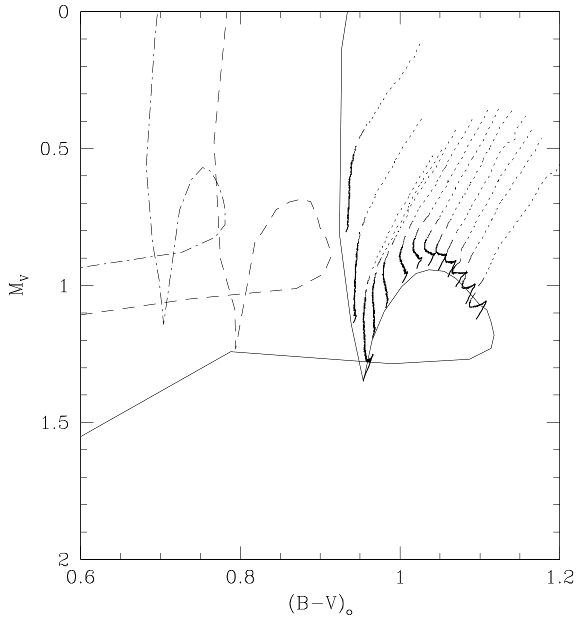

Fig. 2. The location of CHeB star models in the M_V versus $B - V$ diagram. In the right part of the diagram, we have a large sample of tracks of solar metallicity ($Z = 0.019$): the continuous lines denote the initial 70% fraction of the CHeB lifetime, for stars of different masses, whereas the remaining 30% fraction are marked with dashed lines. The mass range goes from 2.5 to 1.1 $M_\odot$ (from left to right). The continuous line denotes the lower boundary of the CHeB tracks as a function of initial mass. Similar curves denote the same lower boundary for tracks of metallicity $Z = 0.008$ (long-dashed line) and $Z = 0.004$ (dot-dashed line).

When clusters become older, we expect to find CHeB stars of lower and lower masses. Therefore, the position of clump stars in an ageing cluster roughly follows the sequence shown in Fig. 2, going from the upper left to the bottom right of the diagram. Along this sequence, however, the clump luminosity passes through a temporary minimum when the turn-off mass is of about 2 $M_\odot$. This effect is illustrated in Fig. 3, in which we simulate clusters with $Z = 0.019$ (i.e. solar metallicity) and ages between 1 and 2 Gyr. This age interval encompasses the probable ages of NGC 752 and NGC 7789.

In the sequence of simulations, the clump of CHeB stars decreases in luminosity as the cluster ages, up to about 1.26 Gyr. Then, up to an age of 1.56 Gyr, this luminosity increases by as much as 0.4 mag, remaining almost constant afterwards. This increase in luminosity in a relatively short timescale corresponds to the age (and stellar initial mass) at which the CHeB switches from quiescent ignition, to a mildly explosive ignition (the He-flash) inside an electron degenerate core. The increase in luminosity is mostly due to the large increase in the core mass required to ignite helium in a degenerate core. The basic theory of this transition is detailed in the classical work by Sweigart et al. (1990).

Girardi et al. (1998) and Girardi (1999) already explored the consequences of this transition in the CMDs of galactic fields. The most impressive effect they found is that the stars with age of ~ 1 Gyr may define a "secondary clump" feature extending below the main clump of red giants. Of course, the suggestion that the same feature may be present in star clusters like NGC 752 and NGC 7789 is immediate.

In fact, the age at which the transition occurs in the models is clearly in agreement with what is observed in the clusters: at 1.5 Gyr, main sequence and red clump are observed at $(B-V)_o = 0.5$ and $(B-V)_o = 1.0$, respectively, and their magnitude difference is of $\delta V = 0.5$ mag. These numbers are undistinguishable from those observed in the CMDs of NGC 752 and NGC 7789.

However, it is also clear that the models of single-age, single-metallicity stellar populations shown in Fig. 3 do not produce "dual clumps", neither clumps with fainter tails, as in the case of galaxy models. What clump models indicate is that the clump has an intrinsic elongated structure for ages lower than 1.2 Gyr, getting more concentrated at later ages, when the clump gets brighter. Therefore, they do not provide an obvious explanation for the clump morphologies observed in NGC 7789 and NGC 752.

4. Observed red giant clumps

The theoretical ZAHB and individual evolutionary tracks have been plotted over the observed red giants in NGC 7789 (Fig. 4a). Due to the shape of the red giant locus, the position of the ZAHB is rather obvious. The diagram can be interpreted as follows: a number of stars, with masses between 1.95 and 1.75 $M_\odot$ are close to or on the ZAHB, while other stars have already further evolved from the ZAHB. The bulk of the red giants has masses between 1.7 and 1.8 $M_\odot$. Open circles are known binaries. Some do show the effects of the secondaries because their colours are bluer, while several ones are right in the middle of the "clump". The theoretical shape of the ZAHB does give a very good representation of the observed morphology of the red giant clump.

The resulting image is that at the core Helium-burning phase we have a spread in masses and ages among the red giants. It is evident that stars do not arrive at the same time in the He-burning phase, but clearly the observed morphology is not compatible with the "classical" paradigm of evolution of single star, single mass isochrones. We observe, as is well known from the evolution on the main sequence, stars on the ZAHB and stars leaving this phase toward the asymptiotic giant branch. What is surprising is the size of the observed dispersion in mass on the ZAHB.

The individual evolutionary tracks permit to understand the vertical dispersion and assign it to the evolution away from the ZAHB. However, the solid part of the individual evolutionary tracks, covering 70% of the core Helium-burning lifetime is mostly limited to the very beginning of the tracks and seems to be a little too short with respect to the observed distribution of the stars.

The stars with $12.1 < V < 12.5$ and $B - V \sim 1.4$ form a bump at the exact position predicted by the models (see Fig. 1a). It corresponds to the phase when the H-burning shell mov-

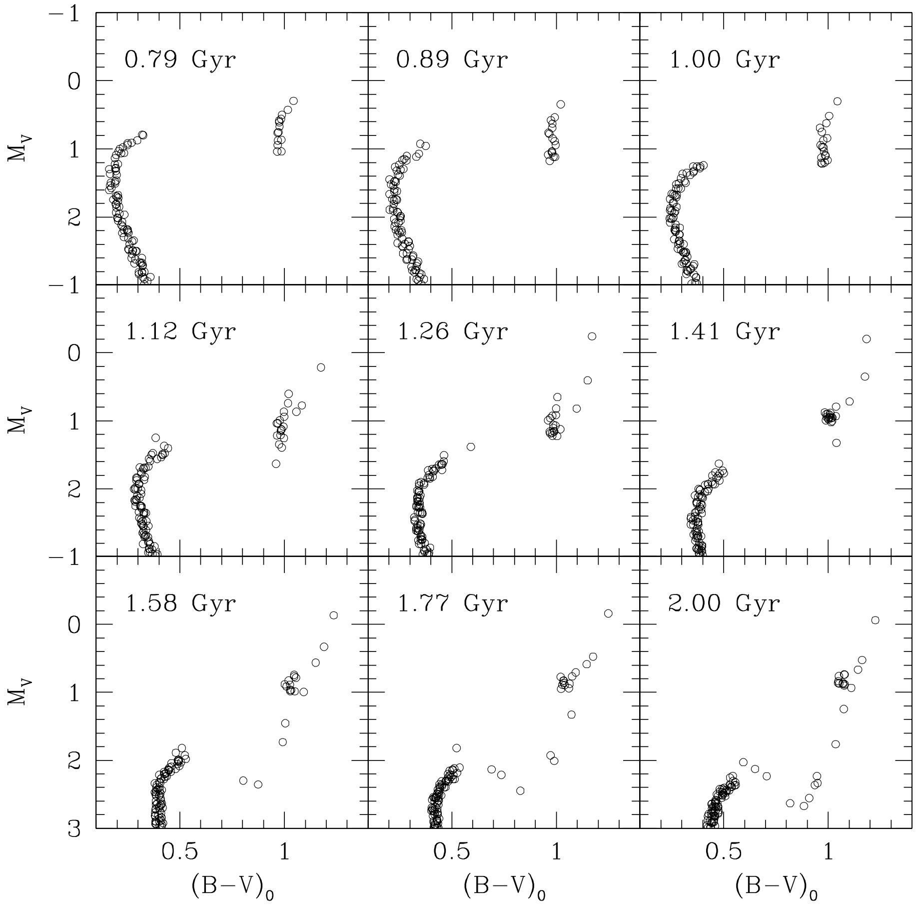

Fig. 3. Synthetic CMDs for a sequence of cluster models with solar metallicity. Cluster ages increase by a factor of 12 per cent from panel to panel. Notice the initial gradual fading of the clump, which gets again brighter between 1.26 and 1.58 Gyr.

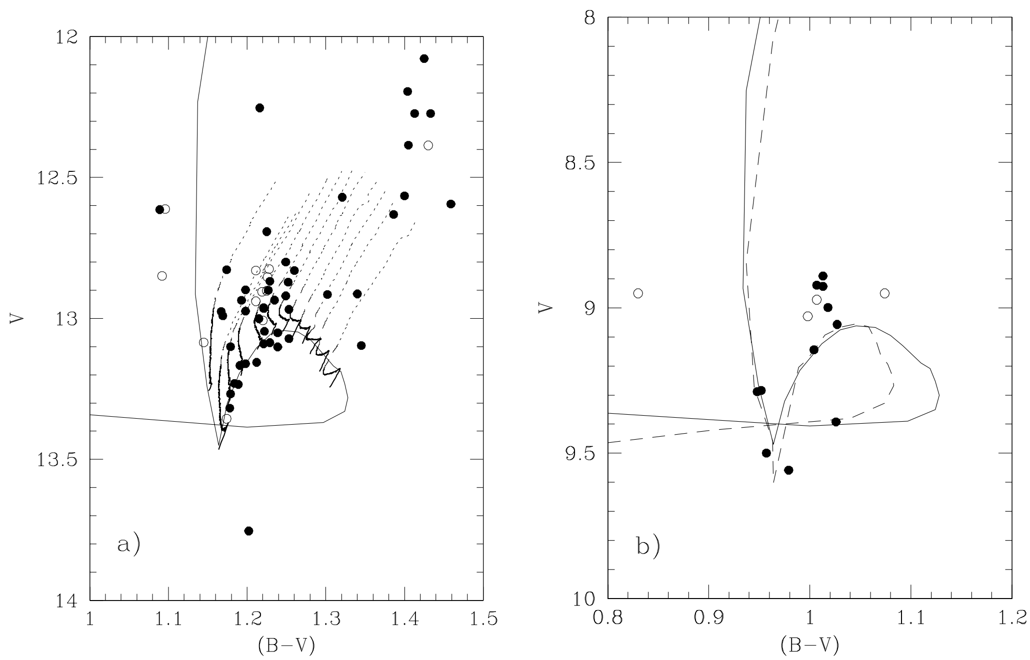

Fig. 4a and b A small region of the CMD, centered on the clump, is shown for the clusters NGC 7789 **a** and NGC 752 **b**. Only probable members are plotted. Single stars are shown as full dots, known binaries as open symbols.

ing outward encounters the H-discontinuity resulting from the first dredge-up. They are therefore not in an advanced core He-burning stage, but mark a pause in the ascent of the red giant branch.

The case of NGC 752 (Fig. 4b) can be understood in the same context. Even if there are less red giants, the explanation seems to be quite convincing. The "classical" clump is well marked, and the fainter stars, which define the so-called second

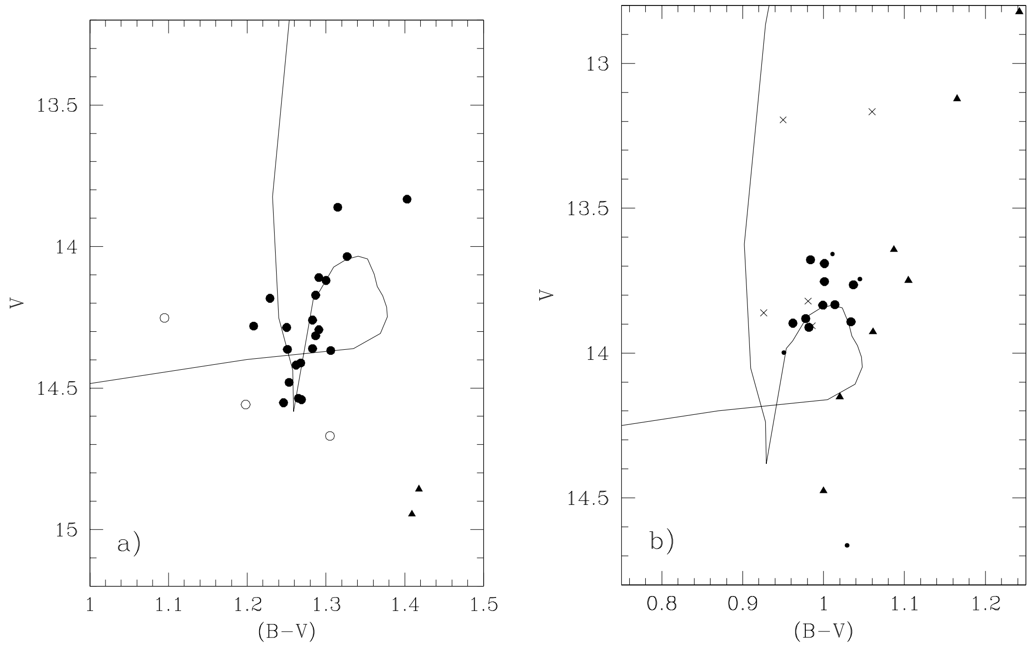

Fig. 5a and b CMDs for the clusters NGC 2660 (a) and NGC 2204 (b). Single stars are shown as full dots, known binaries as open simbols. Triangles denote stars on the ascending red giant branch and crosses, non-members according to unpublished CORAVEL radial-velocity observations.

clump, are pretty well aligned along the ZAHB. Two models have been plotted, that for solar metallicity ($Z = 0.019$) and half solar ($Z = 0.008$). If the track is fitted to the base of the clump, both curves equally well reproduce the positions of the points.

We have looked for other clusters to extend the interpretation of the clump morphology to further objects. One beautiful example has been found with NGC 2660, with the CCD photometry of Sandrelli et al. (1999). The striking shape of the red giant locus is fairly well reproduced by the ZAHB for $Z = 0.004$ (see Fig. 5a). The distribution of the points leads to masses comprised between 2.2 and $1.9\ M_{\odot}$. IC 1311 also presents a clump with a vertical sequence of stars, but in absence of membership criterion, it is difficult to separate the cluster and field stars.

On the oldest side of the age range, NGC 2204 shows a well defined and compact clump which contains stars on the ZAHB and stars slightly evolved (Fig. 5b).

This small sample of representative clusters shows that the clump morphology changes with ages and that the shape of the ZAHB predicted by the models, at various chemical compositions, do reproduce well the observed patterns. Still younger open clusters, with ages lower than 1 Gyr, have more massive red giants which do not evolve through the Helium flash and the morphology is again different. It seems that a single isochrone is also not able to reproduce the complexity of the clump structure.

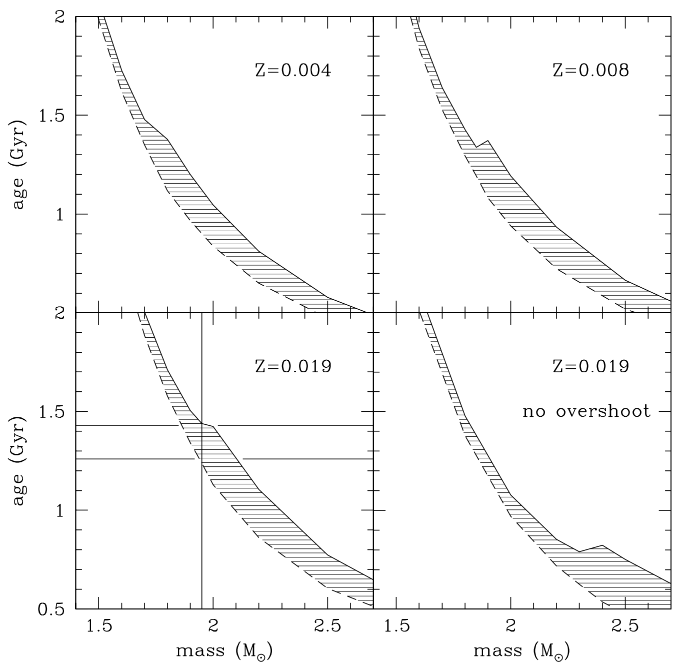

Fig. 6. The age–mass relation for core-He burning stars (shaded area), for 3 values of metallicity: $Z = 0.004$, 0.008, and 0.019. The three first panels are for models which adopt a moderate amount of convective overshooting. The last panel shows the same relation for "classical" (i.e. without overshooting) $Z = 0.019$ models. In the panel corresponding to $Z = 0.019$ with overshooting, we draw a vertical line which schematically separates the low-mass and intermediate-mass stars. Crossing this line from left to right, clump stars become less luminous by about 0.4 mag. The two horizontal lines limit the age interval in which we can find both types of clump stars contemporaneously in the same cluster.

5. Interpretation

After suggesting an interpretation to the red clump morphology in these clusters, it is convenient to further discuss details of the models. This in order to clarify whether we are really facing strange evolutionary behaviours.

First of all, it is interesting to consider the natural dispersion of mass in clump stars of different ages. Fig. 6 presents the locus of stars at both the beginning and end of the CHeB stage, on the age-initial mass diagram. These two lines delimit the region

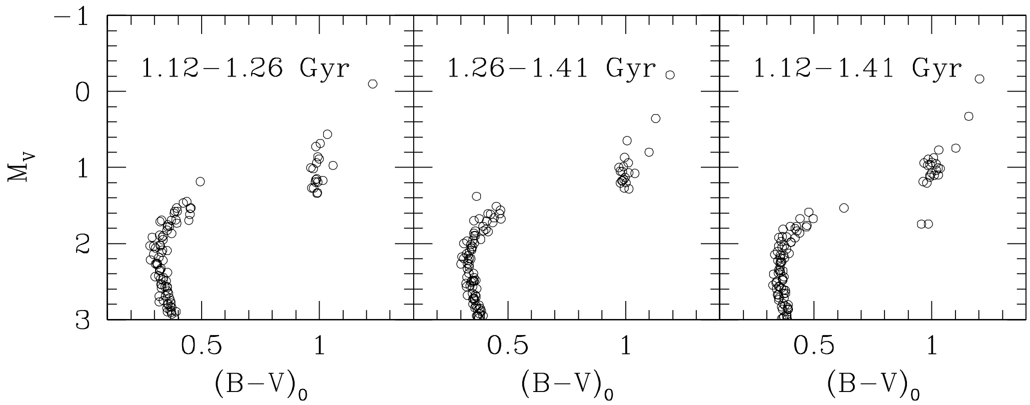

Fig. 7. CMD of models which assume constant star formation between two age limits: from the left to the right panel, respectively, ages are from 1.12 to 1.26 Gyr, 1.26 to 1.41 Gyr, and 1.12 to 1.41 Gyr.

allowed for clump stars. Singling out a single age for a cluster (i.e. a horizontal line), we immediately identify the mass range of its clump stars. It is interesting to notice that, at ages lower than about 1 Gyr, this mass range is about 0.2 $M_{\odot}$ wide. When we get to a certain age value (about 1.4 Gyr), it gets suddenly narrower, to about 0.1 $M_{\odot}$. This effect is the simple result from the sudden reduction of the CHeB lifetime, by a factor of about 2.5, which follows the onset of electron-degenerate cores: this lifetime is of about 10^8 yr for low mass stars, gets to a maximum of about 2.5×10^8 yr at the transition mass $M_{\rm Hef}$, and then decreases monotonically for stars of higher mass (see Girardi & Bertelli 1998; Girardi 1999). This particular behaviour simply reflects the different core masses necessary for igniting helium in stars of different masses.

Fig. 6 then helps to understand the origin of the elongated clumps noticed in the first panels of Fig. 3: they result from the higher dispersion of clump masses found in clusters before the transition.

Of course, there is also an age range in which we find both CHeB stars which ignited helium in non-degenerate conditions, and those which have done it quiescently. This is detailed in the lower-left diagram of Fig. 6. One can notice that, whereas the main sequence lifetime increases monotonically as we pass from $M_{\rm Hef}+\delta M$ to $M_{\rm Hef}-\delta M$, the CHeB (clump) lifetime roughly halves as we pass from $M_{\rm Hef}+\delta M$ to $M_{\rm Hef}-\delta M$. At a given age close to $t(M_{\rm Hef})$, we can then have the presence of both clump stars with $M_{\rm Hef}+\delta M$ at the end of their CHeB evolution, and stars with $M_{\rm Hef}-\delta M$ at the beginning of the same phase. The interest of this situation is that these two kind of stars (with $M_{\rm Hef}+\delta M$ and $M_{\rm Hef}-\delta M$) have CHeB initial luminosities differing by up to 0.4 mag, thus providing a good hint for the origin of dual clumps. The coexistence of both CHeB stars lasts for a maximum period of 0.2 Gyr. Interestingly, in some cases it may happen that stars in both regimes (degenerate and non-degenerate He ignition), for very short age intervals, are distributed over non-contiguous age intervals. In the Girardi et al. (2000) models, it happens for the $Z=0.008$ tracks, and for those with $Z=0.019$ computed without overshooting (see Fig. 6), for which we have a non-monotonic mass vs. age relation for stars at the late stages of CHeB, in the vicinity of $M_{\rm Hef}$. In the context of the present investigation, this is of course the most interesting situation, because it could alone generate a dual clump *in a single isochrone*, without any artificial assumption about the dispersion of age and mass of clump stars.

By means of simulations like those shown in Fig. 3, however, we have verified that dual clumps do not appear due to this effect of mass dispersion, because the clump stars of higher mass are found to be always more evolved than those of lower mass, and hence already departed from the ZAHB to much higher luminosities. Thus, at the age they are observed simultaneously with the brighter clump of the lower-mass stars, they no longer represent clump stars of lower luminosity.

On the other hand, we should notice that the possibility of having dual clumps in single isochrones may depend essentially on the velocity at which the clump gets brighter and short-lived with the stellar mass, or, equivalently, on the velocity at which the core mass at the He-flash increases along the transition mass $M_{\rm Hef}$. The present models (Girardi et al. 2000) may not present the level of detail necessary to explore this possibility further, due to their limited mass resolution, of about 0.05 $M_{\odot}$. This means that, at timescales faster than 0.06 Gyr, our models reflect the result of interpolating between the contiguous evolutionary tracks, more than the real evolutionary behaviour of the stars. An improvement by a factor of 2 in the model resolution would be desirable.

Other subtle effects can also be invoked to generate the dual clump features in the models.

One of them is the presence of a small dispersion of ages for the cluster stars. It would reflect in a larger range of masses for clump stars. Such effect is simulated in Fig. 7, in which we present synthetic CMDs computed by assuming constant star formation in the age intervals $1.12-1.26$, $1.26-1.41$, and $1.12-1.41$ Gyr. These age intervals were chosen so that we have the presence of stars in the transition region between degenerate and non-degenerate helium ignition. It can be noticed that the clump is only slightly broadened in Fig. 7, when compared to the simulations of Fig. 3. Moreover, notice that the assumption of an age dispersion implies also that the turn-off region of the CMD is slightly broadened, by at most 0.10 mag in colour, if compared to the single-age simulations of Fig. 3.

Similar effects, without however any broadening of the MS, can be obtained by assuming differential mass-loss by evolved stars.

It is worth remarking that an age spread of $\gtrsim 0.1$ Gyr, as assumed in Fig. 7, would represent an extreme case. 0.01 Gyr would represent a better upper limit to the age spread in a cluster, according to estimates based on the pre-main sequences of Orion and other very young open clusters (Prosser et al. 1994; Hillenbrand 1997).

6. Conclusions

In this paper, we suggest that the peculiar CMD morphology of the red clump in the open clusters NGC 752 and NGC 7789, may be indicating the presence of stars which ignited helium under both degenerate and non-degenerate conditions. This interpretation is suggested by the coincidence between the ages of the clusters (as derived from the main CMD features), with the ages at which evolutionary models undergo this main evolutionary transition. We remark that the event we are referring to, is equivalent ot the so-called "RGB phase transition" as mentioned in Renzini & Buzzoni (1986) and Sweigart et al. (1990).

This situation, however, cannot be reproduced by models which assume a single isochrone for the clusters, because the mass dispersion of clumps stars in any simple model can hardly be larger than 0.2 $M_\odot$. Moreover, the tendency found in the simple cluster models is that clump stars of higher mass are more evolved away from the ZAHB, and hence invariably more luminous than stars of lower masses. This happens despite that, in the vicinity of the transition mass $M_{\rm Hef}$, more massive clump stars start to burn helium at luminosities up to 0.4 mag fainter than the less massive ones.

Neither can this situation be simply reproduced assuming an age dispersion for the clump stars. The age dispersion required (more than 0.1 Gyr) is too large compared to present observational estimates. Moreover, such a high age dispersion would also cause a non-negligible –and so far not observed– spread in the main sequence region of the CMD.

We are left, then, with a couple of other possibilities. First, mass-loss on the RGB may cause a significant dispersion of clump masses, at a single age. Different amounts of mass-loss can be triggered, for instance, in stars with different rotational velocities. If this is the case, studying clusters like NGC 7789 we may be able to put constraints on the differential mass loss for stars of this approximate mass range, just in the way we actually do for stars in globular clusters (cf. Renzini & Fusi Pecci 1988). Second, the mass and age at which the transition occurs is somewhat dependent of the efficiency adopted for overshooting in stellar cores during the main-sequence phase. Any dispersion in this efficiency (caused, e.g. by different rotational velocities), should also reflect on a dispersion of H-exhausted cores masses at a given age. Such a dispersion would be more evident exactly in the mass range of the transition, because it is the mass interval in which the core mass–initial mass relation changes the most. For clusters older than 4 Gyr, for instance, the core mass at He ignition is practically constant and much less sensitive to the extension of convective cores.

If any of these interpretations is correct, we face some interesting possibilities. First, with more data for open clusters in the relevant age range, we may be able to constrain observationally the velocity at which the transition from non-degenerate to degenerate helium ignition occurs. Second, once this age interval is better documented, we may be able to attach independent observables (like the main sequence termination colour and magnitude) to this transition, to which theoretical models should comply. The present data for NGC 752 and NGC 7789 suggest that $(B-V)_0^{\rm TO} \sim 0.5$ at the transition mass $M_{\rm Hef}$, for near-solar metallicities. Alternative data for LMC clusters by Corsi et al. (1994), indicates $(B-V)_0^{\rm TO} \sim 0.25$ for the same transition mass at a metallicity of about half solar. These numbers seem to be reasonably well reproduced by the present models.

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References

Bica E., Geisler D., Dottori H., et al., 1998, AJ 116, 723
Cannon R.D., 1970, MNRAS 150, 111
Carraro G., Chiosi C., 1994, A&A 287, 761
Corsi C.E., Buonanno R., Fusi Pecci F., et al., 1994, MNRAS 271, 385
Dinescu D.I., Demarque P., Guenther D.B., Pinsonneault M.H., 1995, AJ 109, 2090
ESA, 1997, The Hipparcos and Tycho Catalogues. ESA SP-1200
Friel E.D., Janes K.A., 1983, A&A 267, 75
Gim M., Hesser J.E., McClure R.D., Stetson P.B., 1998a, PASP 110, 1172
Gim M., Vandenberg D.A., Stetson P.B., Hesser J.E., 1998b, PASP 110, 1318
Girardi L., Groenewegen M.A.T., Weiss A., Salaris M., 1998, MNRAS 301, 149
Girardi L., 1999, MNRAS 308, 818
Girardi L., Bertelli G., 1998, MNRAS 300, 533
Girardi L., Bressan A., Bertelli G., Chiosi C., 2000, A&AS in press
Hillenbrand L.A., 1997, AJ 113, 1733
Jahn K., Kaluzny J., Rucinski S.M., 1995, A&A 295, 101
Martinez Roger C., Paez E., Castellani V., Straniero O., 1994, A&A 290, 62
McNamara B.J., Solomon S., 1981, A&AS 43, 337
Mermilliod J.-C., Andersen J., Nordström B., Mayor M., 1995, A&A 299, 53
Mermilliod J.-C., Mayor M., 1989, A&A 219, 125
Mermilliod J.-C., Mayor M., 1990, A&A 237, 61
Mermilliod J.-C., Mathieu R.D., Latham D.W., Mayor M., 1998, A&A 339, 423
Meynet G., Mermilliod J.-C., Maeder A., 1993, A&AS 98, 447
Montgomery K.A., Marschall L.A., Janes K.A., 1993, AJ 106, 181
Perryman M.A.C., Lindegren L., Kovalevsky J., et al., 1997, A&A 323, L49
Piatti A., Geisler D., Bica E., et al., 1999, AJ 118, 2865
Prosser C.F., Stauffer J.R., Hartmann L., et al., 1994, ApJ 421, 517
Renzini A., Buzzoni A., 1986, In: Chiosi C., Renzini A. (eds.) Spectral Evolution of Galaxies. Reidel, Dordrecht: Reidel, p. 195
Renzini A., Fusi Pecci F., 1988, ARA&A 26, 199
Sandrelli S., Bragaglia A., Tosi M., Marconi G., 1999, 309, 739
Sweigart A.V., Greggio L., Renzini A., 1990, ApJ 364, 527
Vallenari A., Carraro G., Richichi A., 1999, A&A 353, 147