1996A&A...316L...1M

Astron. Astrophys. 316, L1–L4 (1996)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Carbon stars in LMC clusters revisited

P. Marigo[1], **L. Girardi**[2], **and C. Chiosi** [1]

[1] Department of Astronomy, University of Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy
[2] Instituto de Física, UFRGS, Caixa Postal 15051, 91501-970 Porto Alegre RS, Brazil

Received 19 September 1996 / Accepted 8 October 1996

Abstract. Examining the available data for AGB stars in the Large Magellanic Cloud (LMC) clusters, we address the question about the mass interval of low- and intermediate-mass stars which eventually evolve into carbon stars (C stars) during the TP-AGB phase. We combine the data compiled by Frogel, Mould & Blanco (1990) – near infrared photometry and spectral classification for luminous AGB stars in clusters – with the ages for individual clusters derived from independent methods. The resulting distribution of C stars in the $M_{\rm bol}$ – log(age) plane evidences that the upper and the lower limits of the mass range for the formation of C stars cannot be derived from cluster data. The explanation of this resides in the presence of two different periods of quiescence in the cluster formation history of the LMC, shaping the age (and progenitor mass) distribution of C stars. The most recent of these quiescence episodes could also explain the lack of very luminous AGB stars (with $-6 > M_{\rm bol} > -7$) in the clusters, contrary to what observed in the field. Finally we compare the distribution of C stars in the $M_{\rm bol}$ – log(age) diagram with synthetic models of AGB evolution which were previously constrained to reproduce the observed luminosity function of C stars in the field. These models provide a good description of the relative frequency of M- versus C-type stars.

Key words: Magellanic Clouds – galaxies: star clusters – stars: evolution – stars: AGB and post-AGB – stars: carbon

1. Introduction

C stars are not only very luminous, but their peculiar spectral features make their identification in objective prism or grism surveys quite easy. So far, they have been searched for in several galaxies of the Local Group, and for a handful of them complete surveys are available. The same applies to some selected areas in the Galaxy and the Magellanic Clouds. The presence of C stars is recognized as a tracer of the existence of low- and intermediate-mass stars, with initial masses ranging from ~ 1.2 to $\sim 4-5$ $M_{\odot}$, and with ages from a few 10^8 yr up to a few Gyr. However, the exact values of these mass and age limits are controversial because they depend on a number of factors – e.g. the presence of convective overshoot from stellar cores, and the efficiency of the third dredge-up and of hot bottom burning in the envelope of the most massive AGB stars.

To better understand the distribution of C stars in galaxies of the Local Group, more precise answers to the following questions are needed: which are the exact values of masses and metallicities that lead to the formation of C stars, and at which luminosities does the M-C transition occur? Answering these questions would put stringent constraints on the chemical yields from intermediate mass stars (Gustafsson & Ryde 1996), and improve upon the interpretation of the abundance patterns observed in planetary nebulae as well.

Star clusters in the Magellanic Clouds are the suitable sites to explore the subject. Several clusters with a well defined sequence of C stars are known. Frogel, Mould & Blanco (1990; hereafter FMB) compiled the most complete catalog of AGB stars belonging to Magellanic Cloud clusters. Among the various conclusions reached by the authors, two are especially remarkable: 1) In clusters C stars are almost always more luminous than M stars; 2) C stars are present only in clusters of SWB types from IV to VI. We remind the reader that the SWB classification (Searle, Wilkinson & Bagnuolo 1980) represents a sequence of increasing age and decreasing metallicity.

While FMB have convincingly limited the range of cluster ages, and hence stellar masses, in which C stars have formed in the Clouds, they did not answer directly the question of the initial masses of C stars, because they made use of a mean age for each SWB group, instead of dealing with individual ages for the host clusters. This letter reports on what happens coupling the FMB data

---

Send offprint requests to: P. Marigo

on AGB stars with ages for their parent clusters obtained from independent methods.

Table 1. Ages for LMC star clusters

Cluster (NGC)	$\log \frac{t}{\mathrm{yr}}$	$\log \frac{t_S}{\mathrm{yr}}$	Cluster (NGC)	$\log \frac{t}{\mathrm{yr}}$	$\log \frac{t_S}{\mathrm{yr}}$
1651	–	9.00	2058	–	8.05
1652	–	9.22	2107	8.37	8.56
1751	–	9.15	2108	8.77	8.85
1783	–	8.93	2121	–	9.58
1806	–	9.00	2136	–	8.05
1841	"old"	10.17	2154	–	9.00
1846	–	9.07	2173	9.06	9.22
1850	7.90	7.91	2209	8.96	8.78
1854	–	7.83	2213	–	9.00
1866	8.14	8.27	2214	7.92	7.91
1978	–	9.22	2231	–	9.00
1987	8.76	8.78			

2. Ages of LMC clusters

Reliable ages of star clusters can be obtained only by means of photometry down to the turn-off magnitude. In the case of LMC clusters, about half a hundred of them have been recently age-dated thanks to accurate CCD photometry. Girardi et al. (1995) selected 24 between the best CCD color-magnitude diagrams available at the time, and re-derived the ages of those clusters by means of the Bertelli et al. (1994) theoretical isochrones.

For those clusters for which no good quality color-magnitude diagrams are available, reasonable age estimates can be derived from their integrated *UBV* colors. The traditional method is due to Elson & Fall (1985) who introduced the S parameter which is found to correlate linearly with the logarithm of the age. Elson & Fall's (1985) method has been refined by Girardi et al. (1995) who took into account the effect of dispersion in the *UBV* colors on the age estimate.

Table 1 lists the ages t_S obtained by Girardi et al. (1995) limited to those clusters of the FMB sample containing AGB stars with assessed membership. Many of these clusters have ages determined directly from the CMD that were used by Girardi et al. (1995) to derive the age calibration. In these cases, both age estimates are presented, and the reader can notice that age differences amount to 0.2 dex in log(age) at most.

One of the most important results of Girardi et al. (1995) relevant to the present study is the age distribution function for the whole sample of LMC clusters of the Bica et al. (1996) catalogue. Convincing evidence was given for the occurrence of recurrent periods of enhanced cluster formation followed by quiescence during the history of the LMC. In brief, after an initial burst of activity followed by a major period of quiescence (Vallenari et al. 1996) up to about $3-5$ Gyr ago, two more recent peaks of activity seem to have occurred at about $1-2$ Gyr and 10^8 yr ago, respectively. These last two episodes of cluster formation bear very much on the discussion below.

3. The M_{bol} – log(age) diagram

From the FMB data (their Table 1) we select those stars which were considered probable members of LMC clusters. The apparent bolometric magnitudes are translated into the absolute ones by using the distance modulus to the LMC of $(m-M) = 18.5$ mag (Panagia et al. 1991). It is worth recalling that the FMB survey is fairly complete for AGB stars brighter that $M_{\mathrm{bol}} = -3.8$.

With the aid of the ages of the parent clusters listed in Table 1, we get the M_{bol} – log(age) diagram of Fig. 1. Stars of type M, C, and uncertain spectral classification are shown with different symbols. On the top axis of Fig. 1, we show the age-S-parameter relationship and an approximate correspondence between the SWB type and the age[1]. On the bottom axis we show the initial mass - lifetime relationship of the stellar models in usage here (Fagotto et al. 1994). Finally, the results of theoretical TP-AGB models (solid and dashed lines), to be described in the following section, are superimposed to the observational data.

A remarkable feature of Fig. 1 is the narrowness of the area populated by C stars, which is bounded to the left by a region virtually void of clusters with ages $8.3 < \log(t/\mathrm{yr}) < 8.8$, and to the right by a gap in the age range $9.6 < \log(t/\mathrm{yr}) < 10.1$. The left boundary coincides with one of the recent quiescence periods pointed out by Girardi et al. (1995), whereas the right boundary corresponds to the major gap in the distribution of cluster ages indicated by several authors (e.g. van den Bergh 1991, Da Costa 1991, Girardi et al. 1995). Futhermore, the absence of C stars at the right side of Fig. 1 simply reflects the well known fact that old star clusters, both in the Galaxy and in the LMC, are known not to contain C stars[2]. If the gaps in the past history of cluster formation in the LMC are responsible for the right and the left boundaries of the distribution of C stars in Fig. 1, we will face the embarrassing situation that *both the upper and lower transition masses for the formation of C stars cannot be inferred from the present observational data.*

---

[1] Strictly speaking, the SWB type does not increase linearly with the S parameter, according to the work of Girardi et al. (1995).

[2] Exceptions are known for the oldest SMC star clusters NGC 121 and 339, and for the galactic globular cluster ω Cen (see FMB); they contain a few low-luminosity C stars whose origin is not yet understood.

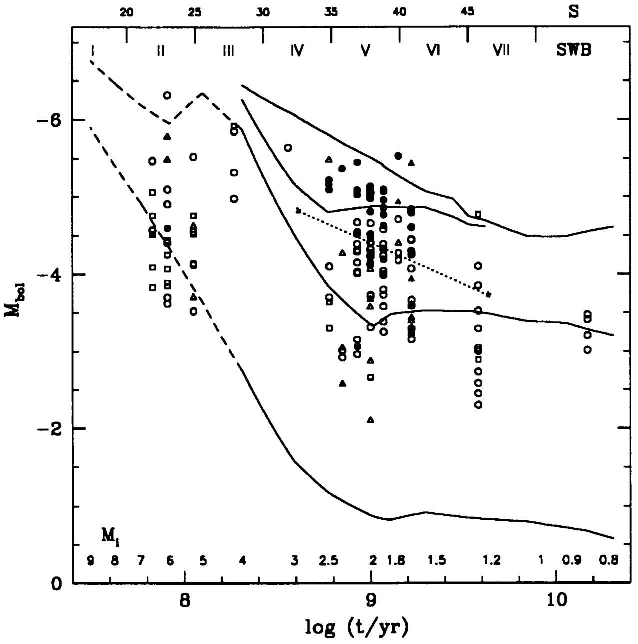

Fig. 1. Absolute bolometric magnitudes of LMC AGB stars as a function of the age of the parent cluster. The data are from Frogel et al. (1990). The distance modulus to the LMC of 18.5 mag is adopted (Panagia et al. 1991). The ages are taken from Girardi et al. (1995; see Table 1). Open circles refer to M stars; filled circles correspond to C stars, open and filled triangles indicate stars which are presumably M and C stars; open squares refer to stars whose spectral type is not assigned. The lines represent the theoretical models by Marigo et al. (1996).

4. The M – C star transition

In order to check whether the observed distribution of M and C stars in the diagram of Fig. 1 can be interpreted by current theoretical models we make use of the recent results by Marigo et al. (1996) for TP-AGB stars, to whom the reader should refer for all details. Suffice it to recall what follows. The starting models for the TP-AGB phase were extracted from the complete evolutionary calculations by Fagotto et al. (1994), which include the effect of overshoot from convective cores. This has the effect of lowering the upper mass limit for stars developing degenerate CO cores, from the values 8 – 9 $M_\odot$ typical of classical models to 5 – 6 $M_\odot$. Mass loss along the AGB was accounted for according to the semi-empirical formalism of Vassiliadis & Wood (1993). The two parameters describing the third dredge-up – the efficiency λ, and the minimum core mass for dredge-up to occur $M_c^{\rm min}$ – were calibrated to reproduce the observed luminosity function of field C stars in the LMC (see also Groenewegen & de Jong 1993). A complete envelope model was used to evaluate the changes in the surface chemical composition due to envelope burning. This was found to occur only in stars with initial mass $M \geq (3-4)\ M_\odot$.

The models of Marigo et al. (1996) for the case with chemical composition ($Y = 0.25, Z = 0.008$) are compared in Fig. 1 with the observational data. The set of the four solid lines plotted in the diagram refer, from the fainter to the brighter magnitudes, to the starting of the E-AGB, the onset of the thermal-pulse cycle, the transition from oxygen-rich stars (M-type) to the carbon-rich stars (C-type), and the end of the AGB evolution, respectively. The solid curves correspond to the range of initial masses ($0.7 \leq M/M_\odot \leq 4$).

In the mass range from 5 to 9 $M_\odot$ the dashed lines show the stage at which the stars reach the Hayashi track for the second time during their evolution (bottom line), and the level at which carbon ignition occurs (top line). It is worth noticing that, in the framework of stellar models with convective overshoot, the stars observed in this part of the diagram are in the stage of double-shell burning of H and He around non-degenerate cores, and do not correspond to AGB stars.

In the central strip of the diagram, vertically delimited in age by the youngest and the oldest clusters where C stars are present, moving from the fainter to the brighter magnitudes, we notice that the AGB sample is firstly composed only by M-type stars, then by a certain admixture of M- and C-type stars, and finally is dominated by C-type stars. This trend is well reproduced by the models. While evolving along the AGB, a star is expected to belong to the M-class, possibly to undergo the transition to the C-class after the onset of thermal pulses, and finally to ascend in luminosity as a C star afterwards. The probability of transition and the range of luminosity spanned as a C star depend on whether the third dredge-up occurs, and on the number of dredge-up episodes experienced before the envelope is removed by stellar winds.

The solid line showing the transition from M- to C-type stars, refers to the quiescent luminosity predicted by the standard core mass-luminosity relation. Considering that the real light-curve of a low-mass TP-AGB star undergoes a series of fall-offs induced by the powering-down of the helium-shell flash following each pulse (Boothroyd & Sackmann 1988a; Vassiliadis & Wood 1993), we expect a low mass star to spend as much as about 20 – 30% of its interpulse period at a luminosity a factor two fainter than the value given by the standard core mass-luminosity relation. As a consequence of this, there is a certain probability of detecting C stars below the transition line, down to about 1 mag. This limit is illustrated by the dotted line connecting the stage above which the 1.2 and 3 $M_\odot$ stars, soon after becoming C stars, have 90% detection probability (see also Boothroyd & Sackmann 1988a). This agrees with the luminosity interval in which both M and C-type stars are observed. Note also that the maximum theoretical luminosity of the C stars as a function of the cluster age is confirmed by observations, as no stars but two exceptions are detected above the line corresponding to the end of the AGB evolution.

5. Discussion and concluding remarks

Our analysis points out first that the information on C stars in LMC clusters is not complete over the whole mass range of progenitors because of the particular history of cluster formation in this galaxy, second that existing data can be interpreted by theoretical models for the formation of C stars via the third dredge-up mechanism. However, we remind the reader that we have been able to reproduce the luminosity function of field C stars by tuning two important parameters of the TP-AGB models (cf. § 4 and Marigo et al. 1996), a kind of difficulty encountered by almost all complete evolutionary calculations in literature (Boothroyd & Sackmann 1988b).

The lack of information on the upper mass limit for the C star progenitors is particularly frustrating. Stars more massive than $3 - 4\,M_\odot$ are expected to experience envelope burning with distinct predictions as far as the surface chemical abundances are concerned (e.g. Marigo et al. 1996). Futhermore, these stars might significantly deviate from the standard core mass-luminosity relation (Blöcker & Schönberner 1991; Boothroyd & Sackmann 1992). Their observational counterparts are probably bright ($-6 > M_{\rm bol} > -7$) long period variables detected in fields of the Magellanic Clouds (cf. Wood et al. 1983), which show strong spectral lines of lithium (Smith & Lambert 1990). Observations of these stars in clusters would put stringent constraints on the range of initial masses in which envelope burning can occur.

Westerlund et al. (1991) already noticed that bright AGB stars with $-6 > M_{\rm bol} > -7$ are detected in fields, but not in clusters of the LMC. For this reason, they stress that cluster AGB stars do not offer a complete coverage of the types of AGB stars existing in the Clouds, contrarily to what expressed in FMB's work. With respect to this point, we observe that the results shown in Fig. 1 strongly suggest that *a period of reduced cluster formation between* $\sim 2 \times 10^8$ *and* 6×10^8 *yr could simply explain the absence of cluster AGB stars as luminous as those observed in the field.*

We notice, however, that a few LMC clusters, such as NGC 2107, 1831, 2249, and 1868 (Girardi et al. 1995), fall in this age interval. In any case, first the clusters in question are less populous than the brightest clusters of younger and older ages, second overluminous AGB stars are expected to be very short-lived (the rapid increase in luminosity probably triggers very high mass-loss rates). Therefore, detecting bright AGB stars in these clusters is highly improbable, if not impossible. Despite the above intrinsic difficulty, *careful scrutiny of the brightest red giant stars in and around these clusters* is a primary target to seek for possible signatures of envelope burning.

With respect to C stars in the SMC, the situation is even more complicated. Several factors indeed make it difficult to explain the distribution of C stars in the clusters of this galaxy. First of all, the ages of SMC clusters are much more poorly determined than in the LMC. In addition to this, the method of age ranking with the aid of integrated *UBV* colours has not yet been properly tested in the case of SMC. Second, SMC (both in clusters and fields) possesses a kind of low-luminosity C stars that likely originate from a mechanism different from that leading to the formation of the very luminous C stars (Westerlund et al. 1995). The possibility that the history of cluster formation in the SMC may significantly differ from that in the LMC (van den Bergh 1991), together with the observational evidence that field C- and super-Li rich AGB stars are by far more numerous in SMC than in LMC, spur to dedicated studies of the SMC.

Acknowledgements. We are grateful to A. Bressan for his useful remarks and kind interest.

References

Bertelli G., Bressan A., Chiosi C., Fagotto F., Nasi E., 1994, A&AS 106, 275

Bica E., Claria J.J., Dottori H., Santos Jr. J.F.C., Piatti A., 1996, ApJS 102, 57

Blöcker T., Schönberner D., 1991, A&A 244, L43

Boothroyd A.I., Sackmann I.-J., 1988a, ApJ 328, 632

Boothroyd A.I., Sackmann I.-J., 1988b, ApJ 328, 671

Boothroyd A.I., Sackmann I.-J., 1992, ApJ 393, L21

Da Costa G.S., 1991, IAU Symp. 148, The Magellanic Clouds, eds. R. Haynes and D. Milne, Dordrecht: Reidel, p. 183

Frogel J.A., Mould J., Blanco V.M., 1990, ApJ 352, 96 (FMB)

Fagotto F., Bressan A., Bertelli G., Chiosi C., 1994, A&AS 104, 365

Girardi L., Chiosi C., Bertelli G., Bressan A., 1995, A&A 298, 87

Groenewegen M.A.T., de Jong T., 1993, A&A 267, 410

Gustafsson B., Ryde N., 1996, preprint.

Marigo P., Bressan A., Chiosi C., 1996, A&A 313, 545

Panagia N., Gilmozzi R., Macchetto F., Adorf H.-M., Kirshner R.P., 1991, ApJ 380, L23

Searle L., Wilkinson A., Bagnuolo W.G., 1980, ApJ 239, 903

Smith V.V, Lambert D.L., 1990, ApJ 361, L69

Vallenari A., Chiosi C., Bertelli G., Aparicio A., Ortolani S., 1996, A&A 309, 367

van den Bergh S., 1991, ApJ 369, 1

Vassiliadis E., Wood P.R., 1993, ApJ 413, 641

Westerlund B.E., Azzopardi M., Breysacher J., Rebeirot E., 1991, A&AS 91, 425

Westerlund B.E., Azzopardi M., Breysacher J., Rebeirot E., 1995, A&A 303, 107

Wood P.R., Bessell M.S., Fox M.W., 1983, ApJ 272, 99

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.