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Faint carbon stars from the evolution of close binaries

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Abstract. The assumption that faint carbon stars in the Magellanic Clouds are on the early asymptotic giant branch (E-AGB) evolutionary stage, is examined using population simulation techniques. It is assumed that these stars are formed as a result of the mass transfer in close binary systems while the primary is a carbon star on the thermally-pulsing AGB (TP-AGB) stage. The populations of carbon stars resulting from both single–star evolution and mass transfer in close binary systems have been calculated. For the heavy element abundance by mass Z = 0.002, the expected amount of E-AGB carbon stars is comparable with the amount of those in the TP-AGB stage. The theoretically obtained and observed luminosity functions of E-AGB carbon stars are similar. Examples illustrating the importance of correct identification of star's evolutionary stage for the interpretation of observations are given. The ignorance of the fact that AGB consists of two stages of the evolution leads to wrong cluster ages resulting from the luminosities of AGB stars.

Key words: stars: carbon – stars: evolution – stars: AGB – Magellanic Clouds – stars: binaries: close

1. Introduction

During the thermally-pulsing asymptotic giant branch (TP-AGB) stage, the elements freshly synthesized in the star's helium burning shell are carried to the surface by a process of convective dredging (third dredge-up mechanism), and these elements (carbon, s-process elements) should thus become observable. The nature of N-type carbon stars is associated with this stage of evolution. Both theory and observations (see, for example, Vassiliadis & Wood 1993, Groenewegen & de Jong 1993, 1994), show that the minimum luminosity of carbon stars in the TP-AGB stage is about $M_{\rm bol} = -3\overset{\rm m}{.}0$. The modern theory of close binary evolution allows to explain the origin of different types of stars with chemical composition peculiarities typical for the TP-AGB stage, but whose luminosity and effective temperatures indicate that these stars are not on this stage. Among such types we can mention barium stars, S stars without technetium, CH stars, CH subgiants, carbon dwarfs. In the review of McClure (1985) the attention was drawn to the fact that the origin of some of these types (barium, CH stars) is possibly associated with the binarity and the process of mass exchange from a companion. The latter is on the helium shell flashing stage, but the secondary star at the same time is probably a main sequence star, which has been evolving to become a CH subgiant and red giant barium star. The same idea regarding the CH stars was mentioned by Lloyd Evans (1986), at the same time suggesting that R stars probably do not have a high proportion of binaries and their origin has been associated with some other mechanism. More recently the quantitative results of the numerical calculations for scenarious of the binary evolution and the use of these results to understand the formation of different types of astrophysical objects, also those with abundances typical for TP-AGB stars, have been published (see, for example, Iben and Tutukov 1985, Frantsman 1992, Han et al. 1995).

According to JHK photometry (Westerlund et al. 1992) and a low-dispersion survey (Rebeirot et al. 1993) of carbon stars in the Small Magellanic Cloud (SMC), there are N-type stars fainter than $M_{\rm bol} = -3\overset{\rm m}{.}0$. Results for a more extensive material of JHK photometry of such stars have been presented by Westerlund et al. (1995). The least luminous stars among this group have $M_{\rm bol} \approx -1\overset{\rm m}{.}8$, and most of them are rather warm in comparison with the majority of carbon stars.

The aim of this paper is to determine the possible evolutionary status of N-type carbon stars which are too faint to be in the TP-AGB phase. The main idea is that these stars are in the so-called early-AGB (E-AGB) evolutionary phase. This is the first part of the AGB evolution, when the hydrogen burning shell extinguishes, and helium burns stationarily in a thin shell (towards the end of the E-AGB phase hydrogen is reignited in a thin shell and helium burning continues in the form of the periodic thermal pulses, as the TP-AGB stage begins). Our scenario of the formation of low-luminosity carbon stars assumes that these stars are the components of close binary systems. The mass was transferred from a carbon TP-AGB star by Roche lobe overflow to its companion, which, as a result, becomes a carbon-enriched star. If the overabundance of carbon with respect to oxygen in the primary component is sufficiently large, the secondary component, after mixing the infalling material with all matter of the secondary star (if the star is on the main sequence) or with the envelope (if the star is in the subgiant, giant or E-AGB phase), also becomes a carbon star. And during the subsequent evolution these stars run across all the later stages, also through the E-AGB stage. It should be noticed that the same idea was used for the possible estimation of the evolutionary phase of high-luminosity carbon stars in the Large Magellanic Cloud (LMC) whose effective temperatures are well above those of ordinary N-type stars (Frantsman and Pyleva 1995). These stars were previously suspected by Hartwick and Cowley (1988) and Cowley and Hartwick (1991) as CH stars. Feast and Whitelock (1992) suggested that these stars might be the products of either the merger of the binary stars components, or the extensive mass exchange in the binary system. The authors stated that the reason of the luminosity and effective temperature peculiarities of these stars was the high mass as a result of accretion from the second component. Suntzeff et al. (1993) did not take into consideration the binary star mechanism at all, and assumed that these stars belonged to a young population of AGB stars in the LMC, whose ages might be only about 10^8 years. In the paper mentioned above (Frantsman and Pyleva 1995) the populations of high-luminosity carbon stars, formed as a result of mass transfer in close binary systems, have been theoretically modelled.

The results of simulated population calculations of carbon stars in the E-AGB and TP-AGB phases, as well as a comparison with observations, are presented in this paper.

2. Computational details

Theoretical populations of stars were derived using the technique of population simulation. Stars are selected according to the probability that at present they are in the appropriate stage. Briefly, a large number of single and binary star models were generated for constant stellar birth rate history and Salpeter initial mass function. The procedure is explained in more detail by Frantsman (1992). Here only some aspects will be considered.

Most stellar characteristics in the AGB phase can be approximated by analytic formulae derived from precise stellar model calculations. The evolution of stars in the TP-AGB phase was followed using the formulas by Iben and Truran (1978) and Renzini and Voli (1981), and on the E-AGB phase – by Iben and Renzini (1984). It was assumed that at each thermal pulse, an amount of mass $\triangle M_{\rm dredge} = \lambda \triangle M_{\rm c}$ is added to the envelope, were $\triangle M_{\rm c}$ is the core mass growth during the preceeding interpulse period and λ is the dredge-up efficiency. In accordance with Iben's (1983) results, the value 0.1 for the coefficient λ was adopted for stars with low-mass cores.

Special attention must be paid to the problem of mass loss by stars on the AGB. In our calculations the mass loss was represented by Reimers (1975) law: $\dot{M} = -4 \times 10^{-13} \alpha LR/M$, where L, R, M denote the star's luminosity, radius and mass in solar units, and α is a dimensionless quantity usually taken to be of the order of unity. The observations, however, suggest that apart from the conventional stellar wind, some other mechanism (apart from planetary nebulae ejection) also operates during the AGB phase, substantially increasing the mass loss (Frantsman 1986, 1988, 1989). In our calculations, an abrupt tenfold jump

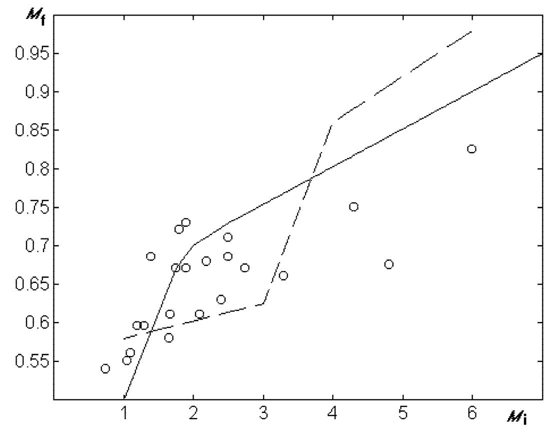

Fig. 1. The initial-final mass lelations. The solid line indicates our results of AGB evolution calculations based on the expressions from Iben and Truran (1978) and Renzini and Voli (1981), and assuming the coefficient α in Reimers (1975) mass loss intensity law as α = 1 for $M_{\rm bol} > -5^{\rm m}_{.}5$ and α = 10 for $M_{\rm bol} < -5^{\rm m}_{.}5$. The dashed line indicates the results of the calculations of Groenewegen and de Jong (1993). Dots represent the initial–final mass relations for stars in the Magellanic Cloud clusters (see text for details)

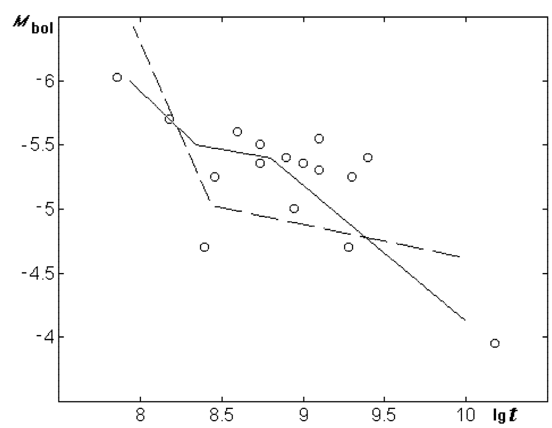

Fig. 2. The age–luminosity relations for the upper parts of the AGB. The difference between solid and dashed lines is described in Fig. 1. Dots represent the results for the Magellanic Cloud clusters: t – the age of the cluster, $M_{\rm bol}$ – luminosity of the most luminous star in the cluster

in the mass loss rate for the AGB stars reaching a certain luminosity is suggested (α = 1 for $M_{\rm bol} > -5^{\rm m}_{.}5$ and α=10 for $M_{\rm bol} < -5^{\rm m}_{.}5$), because a quantitative agreement of theoretical investigations with observations would require a rapid mass loss with increasing luminosity on the AGB. This assumption is somewhat supported by IRAS observations of the LMC (Reid et al. 1990). According to their interpretation, the observations suggest that the AGB stars pass through two stages with different mass loss intensity, and that the mass loss may be enhanced for AGB stars with $M_{\rm bol} < -5^{\rm m}_{.}5$.

The analytical expressions to trace the evolution of stars were taken from Iben and Truran (1978) and Renzini and Voli (1981), instead of more recent papers, as for example Groe-

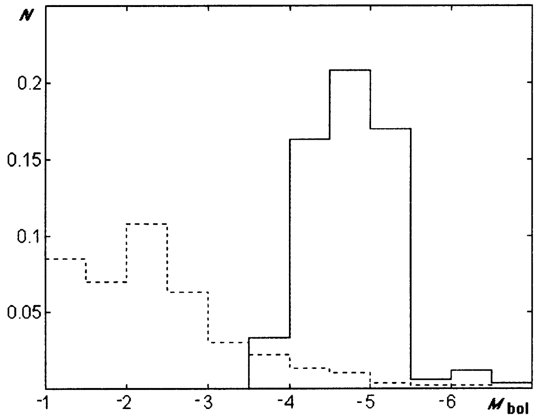

Fig. 3. The theoretical luminosity functions of carbon stars with heavy element abundance Z = 0.002. The coefficient α in Reimers (1975) mass loss intensity law is: α = 1 for $M_{\rm bol} > -5\overset{\rm m}{.}5$ and α = 10 for $M_{bol} < -5\overset{\rm m}{.}5$. Solid line indicates TP-AGB stars, dashed line – E-AGB stars (the result of the evolution of close binaries). The sum over all bins is normalized to unity

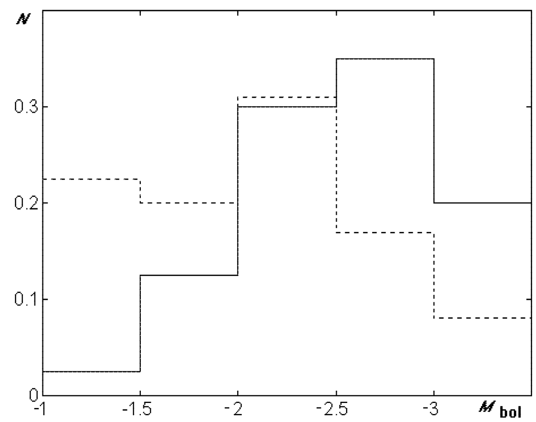

Fig. 4. The luminosity functions of faint ($M_{\rm bol} > -3\overset{\rm m}{.}5$) carbon stars. Solid line indicates the results of observations (Westerlund et al. 1995), dashed line – the results of our calculations (Z = 0.002, tenfold jump of mass-loss intensity for $M_{\rm bol} = -5\overset{\rm m}{.}5$). The sum over all bins is normalized to unity for each function

newegen and de Jong (1993), because, in my opinion, the former better coincide with observations. Fig. 1 represents the initial-final mass relations in accordance with the results of Table 5 of Groenewegen and de Jong (1993), and with ours, under the assumptions mentioned above. The values for the most luminous AGB stars in Magellanic Cloud (MC) clusters are also shown. The carbon–oxygen core mass was taken to be the final mass, as this will be very close to the mass of the remnant white dwarf. These masses were obtained from the AGB star luminosities according to the relations from Boothroyd and Sackmann (1988) and Groenewegen and de Jong (1993). The initial masses come from cluster ages obtained by classical methods; the paper by Frantsman (1988) reviews the references, whereas the age of cluster NGC 1718 is given by Elson and Fall (1988). The relation used between the age and initial mass was from Iben and Laughlin (1989). Our calculations better fit the observations than the calculations by Groenewegen and de Jong (1993), where the final masses for most stars are too large. The same conclusion can be made considering the age–luminosity relation for the most luminous TP-AGB stars in the MC clusters (Fig. 2).

It was assumed that 50% of the matter which is lost from the Roche-lobe-filling component is transferred to its companion and that 50% of all stars are close binaries. A large number of single and binary star models were generated, and for every system the evolution of the components was traced (as well as for every single star). It was assumed that both components of binary system were formed simultaneously and had a Salpeter initial mass distribution. In the course of evolution (depending on the semi-major axes), in some systems a primary component fills the Roche lobe being in the TP-AGB stage, but the secondary at the same time can be a main sequence star, subgiant, giant or E-AGB star. The distribution of binary stars over the primordial semimajor axes A was taken as $\mathrm{d}N \sim A^{-1}\mathrm{d}A$, and the distribution over the mass ratio $q = M_2/M_1$ (M_1 and M_2 are masses of the primary and secondary components) was taken as $\mathrm{d}N/\mathrm{d}q$ = const for 0.1< q <1 (Popova et al. 1982). The computational time step was taken as 10^4 yr.

3. Results and discussion

The results of simulating carbon star populations (the luminosity functions) are plotted in Fig. 3 for the initial heavy element abundance Z=0.002. The most significant result is a substantial extension of the carbon star luminosity towards lower luminosities in comparison with the TP-AGB carbon stars. The expected number of stars in these two stages is comparable. There are two reasons why the faint carbon stars in the MC have been discovered only recently: (a) they are apparently fainter in comparison to the TP-AGB stars, and (b) they have higher effective temperatures. The comparison between the theoretical luminosity function for E-AGB carbon stars, and the observational one for faint carbon stars in the SMC (Westerlund et al. 1995) is presented in Fig. 4. Both luminosity distributions are in qualitative agreement. The deficiency of the faintest stars in SMC, as compared to the theoretical prediction can be explained with the selection effect – the fainter the star, the more difficult it is to observe it.

Fig. 5 presents the HR-diagram for the SMC carbon stars, also showing the theoretically calculated borders of regions occupied by the E-AGB and TP-AGB models. For comparison, besides these results obtained under assumptions described above, the border of E-AGB region according to detailed tables of stellar models (Fagotto et al. 1994) are also displayed (for the heavy element abundance Z=0.004). The positions of carbon stars are taken from Westerlund et al. (1991, 1995). All stars under consideration can be divided in two groups: (a) more luminous and with lower effective temperatures, (b) and fainter but with higher temperatures. The former correspond closely to the TP-AGB model region, and the latter – to the E-AGB region. The

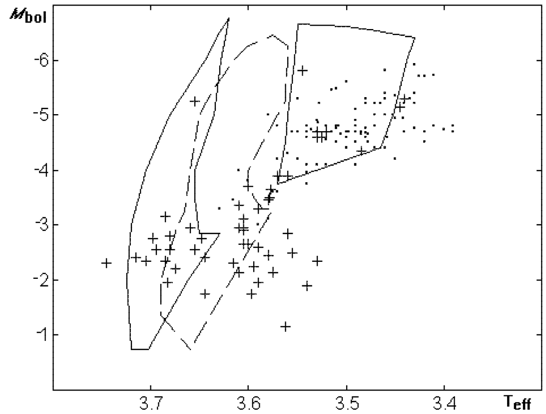

Fig. 5. The position of SMC carbon stars on the HR diagram. Dots represent the data from Westerlund et al. (1991), crosses – from Westerlund et al. (1995). The solid line contours denote, according to our calculations, the regions occupied by the E-AGB stars (left region) and by the TP-AGB stars (right region). The calculations were performed assuming $Z = 0.002$ and a tenfold jump of mass loss intensity for $M_{\rm bol} = -5\overset{\rm m}{.}5$. The dashed line contour denotes the E-AGB region according to calculations by Fagotto et al. (1994) for $Z = 0.004$

reasons of the relatively great scatter of the star positions on the HR diagram are the uncertainties due to the rather great observational errors for $M_{\rm bol} > -2\overset{\rm m}{.}5$ in $J - K$, from which effective temperatures are derived (Westerlund et al. 1995), and the dependence of AGB tracks on the star's initial chemical composition.

Hence it is likely that N-type carbon stars in the MC belong to two different evolutionary phases: the hotter and on the average more faint ones – to the E-AGB phase, but cooler and more luminous – to the TP-AGB phase. The greater part of carbon stars from Table 1 of Westerlund et al. (1995), which are named "faint C stars", are E-AGB ones, although some of them are TP-AGB stars (for example, this appears possibly to be the case for stars No 324, 452, 818, 1011, 1018, 1032, and, with higher possibility, such faint ones as No 91 and 428).

One would expect that there may be carbon stars in MC clusters on both evolutionary stages, on the TP-AGB as well as on the E-AGB stages. It is possible to divide these stars on the basis of luminosity and effective temperature. There are only a few candidates of such clusters from the data of Westerlund et al. (1991), because there are the selection effect (relatively low luminosity and high effective temperatures of E-AGB stars), and the effect, mentioned in the paper by Frantsman and Pyleva (1995) (the strong dependence of E-AGB stars luminosity on the initial composition, as is shown in Fig. 2 of the above-mentioned paper). The clusters NGC 1783, 1846, 1978 may be noted as possible examples. However there is still some possibility that low luminosity carbon stars G6 in NGC 1783, LE 12 and AZ-11 in 1978 and FMB 16 in NGC 1846 are not members of these clusters and they may be field stars.

From the preceding, it may be seen that it is necessary to be very careful in identifying evolutionary stage of stars and trying to use the results of such identifications for interpretation of observations. Now there is an example of possible consequences of ignoring the fact that the AGB stage consists of two stages of evolution. It seems that Mould and Aaronson (1982) used the E-AGB stars in the age determination of several clusters, assuming that these stars are in the TP-AGB stage. For example, the upper limit of the age of the cluster NGC 1872 was determined as 5 Gyr. Assuming that the most luminous star in this cluster is on the E-AGB stage, in my paper (Frantsman 1988) it was estimated that the age of this cluster does not exceed 0.1 Gyr. And it was somewhat confirmed recently by a classical method, when the age was determined as 0.136 Gyr (Santos et al. 1995).

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