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The red tail of carbon stars in Local Group galaxies

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Abstract. C-stars separate well from O-rich giants in near-infrared colours, drawing a striking red tail in recent colour-magnitude diagrams for Local Group galaxies. Most present-day stellar models are unable to account for this feature. However, it is naturally reproduced when AGB models are computed with consistent variable molecular opacities.

Key words. C stars – Local Group galaxies

1. Introduction

The bulk of carbon (C) stars observed in nearby galaxies are nowadays interpreted as resulting from the third dredge-up events during the thermally pulsing AGB evolution of low- and intermediate-mass stars. C-stars are know to separate well from O-rich giants (of late-K to M types) in near-infrared colours. They even draw a striking red tail in recent colour-magnitude diagrams for Local Group galaxies, which is particularly evident in the 2MASS (Fig. 1) and DENIS data for both Magellanic Clouds.

However, such an impressive feature of CMDs has so far been absent from theoretical models. Actually, there are two problems: First, very few isochrone sets in the literature do include the complete AGB evolution (such as e.g. Bertelli et al. 1994; Girardi et al. 2000). Second, even fewer isochrone sets do contain the C-star phase: Marigo & Girardi (2001) are presently the only available ones to include calibrated AGB tracks with third dredge-up and hot bottom burning. Anyway, the C-stars in these isochrones do not draw a red tail: they have the right luminosities (as calibrated using the carbon star luminosity functions in the Magellanic Clouds, in Marigo et al. (1999)), but wrong near-IR colours (see Fig. 2).

Then, what is the problem with theoretical models? One may imagine two simple solutions:

(A) We may be using wong $T_{\rm eff}$–colour relation for C-stars: In this case, for the typical C-star temperatures predicted by the models, $J-K_{\rm s}$ should be underestimated by several tenths of magnitude. Yet, empirical data for C-stars indicate this is not possible, unless extremely high (and unrealistic) values of surface C/O are assumed for C-stars (see Marigo et al. 2003).

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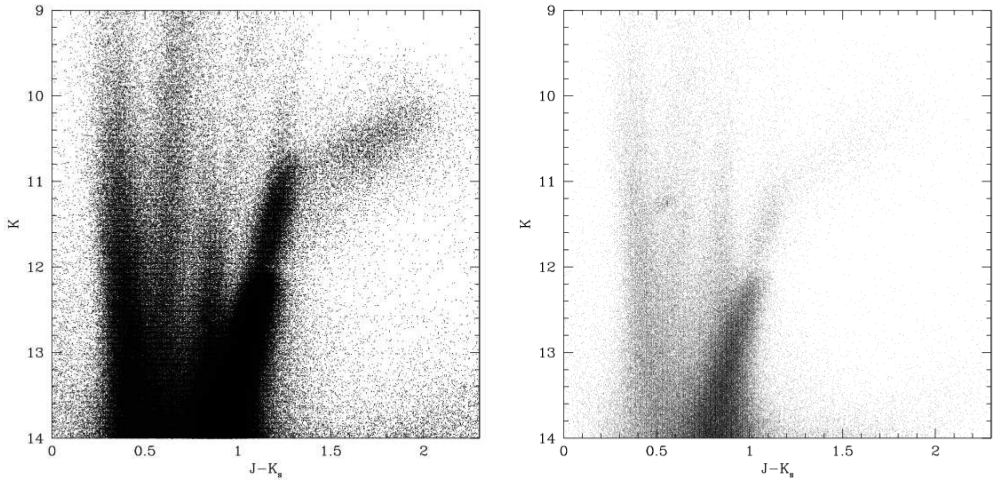

Fig. 1. K versus $J-K$ diagram for the LMC and SMC, as derived from 2MASS data Cutri et al. (2002). The red tail of C stars is well evident in both cases at $J-K > 1.4$ and $K < 12$.

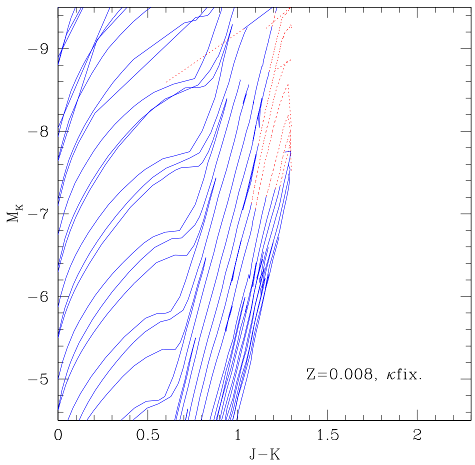

Fig. 2. Marigo & Girardi (2001) isochrones with O-rich (blue) and C-rich (red) stars. They are derived from models computed with fixed solar-scaled molecular opacities from Alexander & Ferguson (1994), which is the usual choice for most present-day stellar evolutionary models.

(B) We may predict wrong $T_{\rm eff}$ for C-stars: In this case, $T_{\rm eff}$ should be overestimated by several hundreds of Kelvin. Although such large errors may seem unbelievable – in fact, all theoretical C-star models in literature have similar $T_{\rm eff}$ – new C-star models with variable molecular opacities Marigo (2002) indicate exactly this possibility.

2. Variable molecular opacities in AGB models

In fact, Marigo (2002) models drop the usual assumption of solar-scaled low-temperature opacities. At every time-step along an evolutionary track, the actual chemical composition of the stellar envelope is used to derive molecular concentrations and opacities via equilibrium equations. In this way, the large changes in opacities that occur when the surface carbon abundance exceeds that of oxygen, are naturally taken into account. The main effect is that, as the C/O ratio increase above 1 – which corresponds to the transition from M to C spectral type – a sudden increase of molecular opacities takes place, with consequent significant cooling of the model carbon star.

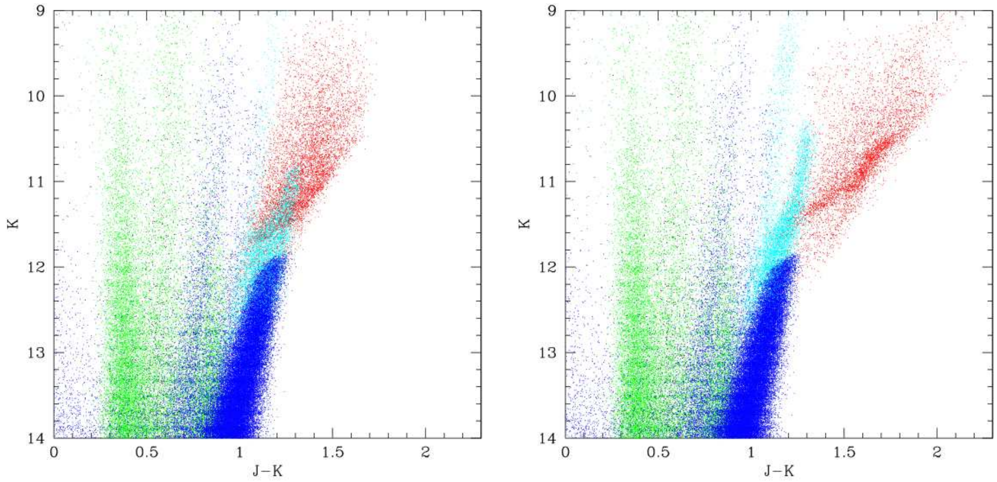

Fig. 3. Two simulations of the near-infrared CMDs of the LMC. Left: using Marigo & Girardi (2001) isochrones, from models computed with fixed solar-scaled molecular opacities, and adopting appropriate colour–$T_{\rm eff}$ transformations. In this case, C-stars (red dots) simply depart from the sequences of O-rich giants (of spectral types late-K to M; blue and cyan dots) towards higher luminosities. The simulation also includes the foreground Galaxy stars (green: thin and thick disks, black: spheroid). Right: the same simulation using new isochrones computed with Marigo (2002) variable molecular opacities. It is well evident how the C-stars (red dots) now draw a red tail well separated from O-rich giants (blue and cyan dots). This is to be compared with the 2MASS data presented in Fig. 1.

We have generated thoretical isochrones using Marigo (2002) opacities, and for several assumptions regarding the efficiency of the third dredge-up. The results, regarding the red tail of carbon stars, are very encouraging (see Marigo et al. 2003). In fact, models that include variable molecular opacities present a red tail of C stars, well-separated from the M-type ones. This is illustrated in Fig. 3.

Additionally, the use of variable molecular opacities brings along several important implications for AGB evolutionary models:

- an earlier onset of super-wind phase and hence shorter lifetimes;
- lower mean C/O values for C-stars;
- marked variations in the efficiency of hot bottom burning for the most massive AGB stars;
- significant changes in the chemical yields of CNO elements;
- additional dependences of $T_{\rm eff}$, lifetimes, C/O ratios, yields, and other stellar parameters, on the initial metallicity.

These and other effects are explored in a series of recent (Marigo 2002; Marigo et al. 2003) and forthcoming papers. Despite these important implications, it is amazing that the variable molecular opacities have been ignored for so long in evolutionary models of AGB stars.

3. A few conclusions

- The red tail of C-stars, a conspicuous feature of near-IR colour–magnitude diagrams of Local Group galaxies, is naturally explained by AGB models wich

consider the changes in molecular opacities resulting from the third dredge-up process.
- Present-day AGB models are actually missing this important and basic physical effect, which affects not only the near-IR colours of AGB stars, but also their lifetimes, dredge-up efficiency, chemical yields, etc.

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