Fine structure of the red clump in Local Group galaxies

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Abstract. Some fine structures can nowadays be identified in the high-quality colour-magnitude diagrams (CMD) of Local Group galaxies. The clump of red giants, for instance, may present a significant colour spread, and extensions to both brighter and fainter luminosities. Such features are predicted by population synthesis models which consider stars in the complete relevant ranges of ages and metallicities, and are potentially useful for constraining the star formation histories of the parent galaxies over scales of gigayears. We briefly comment the cases of fields in the Magellanic Clouds, M31, and the local CMD from \textit{Hipparcos}.

Introduction

The red clump is a striking feature in the CMDs of intermediate-age and old open clusters, and in those of the nearest galaxies. It is composed mostly by low-mass stars in the stage of core helium burning (CHeB). In these stars, the onset of electron degeneracy after the central H-exhaustion postpones the He-ignition until the core mass grows to about $M_c \simeq 0.45 \, M_\odot$. It causes all low-mass CHeB stars to have similar luminosities and hence position in the CMD.

In open clusters, the red clump typically presents a very small dispersion in both colour and magnitude. For instance, in M 67 the red clump is defined by 6 stars with $\sigma(B - V) \lesssim 0.05$, $\sigma(V) \lesssim 0.1$ mag (see e.g. Montogomery et al. 1993). This results from the small spread of masses and metallicities among these stars. On the contrary, red clump stars in galaxy fields present a significant spread in both mass and metallicity; as a consequence, these clumps are expected to present a fine structure in the CMD (Girardi 1999).

This fine structure is not evident in the case of most ground-based observations of nearby galaxies, for which the clump spread in the CMD reflects, to a large extent, the presence of large photometric errors. The \textit{Hipparcos} satellite, however, has provided an impressive CMD of the nearby stars (Perryman et al. 1997), in which the red clump clearly presents an intrinsic structure (Girardi et al. 1998). HST has also provided very nice CMDs for the Magellanic Clouds (MC) and other nearby dwarf galaxies, in which sub-structures of the clump seem to be present. In the case of the MCs, however, too few clump stars can be sampled in a typical WFPC2 frame, so that the clump features are not so clear. This situation is expected to improve with the FORS camera.
Fig. 1. For $Z = 0.019$, we present the mean luminosity (upper panel) and effective temperature (middle) of CHB stars as a function of mass. The lower panel shows their mass distribution for a galaxy model with constant star formation rate up to 10 Gyr ago.

at VLT since it can provide CMDs with quality comparable to the HST ones (at least for the Magellanic Clouds), but sampling much larger fields.

**Theoretical expectations**

In order to simulate the clump structure in different galaxy models, we make use of the extensive set of evolutionary tracks and isochrones of Girardi et al. (1999). This database covers a large interval of stellar initial masses (from 0.15 to 7 $M_{\odot}$) and metallicities (from $Z = 0.001$ to 0.03), with a very good mass resolution. Synthetic CMDs are then generated by means of a population synthesis tool, for any arbitrary history of star formation and chemical enrichment.

Fig. 1 illustrates the location of solar metallicity ($Z = 0.019$) CHB stars in the HR diagram, as a function of mass, and their mass distribution in a model galaxy which formed stars at a constant rate from 0.1 to 10 Gyr ago, with a Salpeter IMF and with Reimers’ mass-loss rates along the RGB (see Girardi 1999 for details). The following aspects are evident in this figure:

- stars with $M \lesssim 2 M_{\odot}$ (i.e. low-mass stars) constitute most of the clump, distribute over a non-negligible range in $T_{\text{eff}}$, and with an almost constant luminosity. They form the main red clump feature we are used to.
- stars with $M \simeq 2 M_{\odot}$ not only occupy a particular region of the HR diagram (they are about 0.4 mag fainter, and slightly bluer than most clump stars), but represent a second peak in the mass distribution. Therefore, these stars define a fainter secondary red clump.
• stars with $M \gtrsim 2 \, M_\odot$ (i.e. intermediate-mass stars) appear at higher luminosities and in non-negligible quantities. They may originate a plume of bright clump stars (or the so-called *vertical red clump*).

These structures are evident in the synthetic CMD of Fig. 2. We remark that essentially the same features appear at different metallicities, provided that $Z \gtrsim 0.004$. For lower metallicities, the colour spread of the clump gets very low, unless for the tail of lowest-mass clump stars, which may distribute over a blue horizontal branch if ages are high enough. On the other hand, models which assume an intrinsic age-metallicity relation for clump stars, tend to present the main clump distributed over a large colour interval, but still at an almost constant luminosity (Girardi 1999).

**Observations and practical implications**

From the above-mentioned work, it results that the clump structure in the CMD contains potentially useful information about the history of star formation and chemical enrichment of the parent galaxy. The most evident example is given by the secondary clump stars in a field: their number should be simply proportional to the SFR at an age of $\sim 1$ Gyr ago (corresponding to an initial mass of $2 \, M_\odot$ in the present models). The colour distribution of the main clump, instead, should reflect both the age and metallicity distribution of clump stars, over timescales of gigayears. Importantly, this information appears at a luminosity level which is at least 3 mag brighter than the oldest turn-offs of most galaxies.

Also, it is important to emphasise that the model predictions are supported by a number of interesting observations. For instance, a secondary clump has been noticed in the *Hipparcos* CMD of local stars (Girardi et al.
1998) and in some LMC fields observed by Bica et al. (1998). Also, Corsi et al. (1994) observed a minimum in the clump luminosities for LMC clusters of ages \( \sim 1 \) Gyr, which corresponds to the secondary clump we mention here.

Other important observation which can be accounted for by present models is the nearly constancy of the clump \( I \)-band luminosity, \( M_I \), with the \( V - I \) colour, noticed by Paczyński & Stanek (1998), Stanek & Garnavich (1998), Udalski et al. (1998) and Stanek et al. (1998). This was interpreted as indication that the clump luminosity does not depend on the stellar population. If this were the case, the red clump would be an excellent standard candle, with a zero point precisely determined by means of \textit{Hipparcos} data. Theoretical models instead indicate a non-negligible dependence of \( M_I \) on age and metallicity, amounting to a maximum of 0.6 mag (see also Cole 1998). At first sight, it seems in contradiction with the observations. However, constant \( M_I \) as a function of \( V - I \) can easily be obtained in population synthesis models, if we assume either a nearly constant \( Z \) with varying age, or a \( Z \) decreasing with age according to a normal age–metallicity relation (see Girardi et al. 1998 and Girardi 1999, for details). The first case seems to describe reasonably what observed in the \textit{Hipparcos} CMD, whereas the second case would correspond better to what observed in M 31.

It follows that the red clump may be a useful distance indicator only if we know the distribution of ages and metallicities inside the galaxy we are observing. Otherwise, systematic errors as large as \( \sim 0.4 \) mag may be present in the distance modulus derived by means of this method.

Acknowledgements Part of this work has been carried out at the Max-Planck-Institut für Astrophysik during a stay funded by the Alexander von Humboldt-Stiftung. The collaboration with A. Weiss, M.A.T. Groenewegen and M. Salaris was decisive during this period. I thank ESO for a travel grant to attend the VLT opening symposium.

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