Theoretical expectations for clump red giants as distance indicators

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Abstract. Variations of \( \sim 0.4 \) mag are expected in the \( I \)-band absolute magnitude of red clump giants, \( M^\text{RC}_I \), as a function of both stellar age and metallicity. This regardless of some potential theoretical uncertainties. Due to the quite large differences in mean ages and metallicities of clump stars among galaxies, systematic changes (also amounting up to \( \sim 0.4 \) mag) come out in their \( M^\text{RC}_I \). These numbers also indicate a distance to the LMC that is not necessarily “short”.

Introduction

Any measurement of distance modulus using red clump stars requires the determination of four quantities:

\[
(m - M)_0 = I^\text{RC}(\text{galaxy}) - M^\text{RC}_I(\text{Hipp}) - A_I + \Delta M^\text{RC}_I. \tag{1}
\]

The first two – the apparent clump magnitude in an external galaxy, \( I^\text{RC}(\text{galaxy}) \), and its absolute magnitude in the Solar Neighbourhood sampled by \textit{Hipparcos}, \( M^\text{RC}_I(\text{Hipp}) \) – can be accurately measured, with \( 1\sigma \) errors typically \(< 0.03 \) mag (e.g. Paczynski & Stanek 1998). Differently, determinations of the total absorption, \( A_I \), are often controversial at the level of about 0.2 mag, as demonstrated by the case of the LMC field population (Udalski 1998; Romaniello et al. 1999; Zaritsky 1999). Even more controversial is the assessment of the intrinsic differences in magnitude between \textit{Hipparcos} and the external populations of clump stars, \( \Delta M^\text{RC}_I \). In this regard, the dependence of \( M^\text{RC}_I \) on age and metallicity has been claimed to be either (i) small and empirically-calibrated (Udalski 1998ab, 2000), or (ii) more significant as suggested by stellar models (Cole 1998; Girardi et al. 1998) and observations of open clusters (Twarog et al. 1998; Sarajedini 1998). Moreover, Girardi & Salaris (2000) conclude that present empirical calibrations for \( \Delta M^\text{RC}_I \) (Udalski 1998ab, 2000) do not represent general relations, and hence are not suitable for being used in eq. (1). The discussion about \( A_I \) and \( \Delta M^\text{RC}_I \) is especially important in the case of the LMC, because the red clump method has been claimed to provide strong evidence for a “short” distance scale (Udalski 2000, and references therein).

In the limited space of this review, I just recall the main reasons why theoretical models predict non-negligible (up to 0.4 mag) \( \Delta M^\text{RC}_I \) values. For a detailed discussion – based on the same kind of analysis as here – of the related observational data, I refer to Girardi & Salaris (2000).
Why $M_{\text{RC}}^I$ changes with age and metallicity

Firstly, I recall that in the interval of effective temperatures that characterize red clump stars ($3.8 \lesssim T_{\text{eff}} \lesssim 3.6$; see Girardi et al. 1998), bolometric corrections in the $I$-band are almost constant (to within 0.1 mag) and depend very little on metallicity. This means that $M_{\text{RC}}^I$ reflects very well the behaviour of $\log L$, a quantity directly predicted by stellar evolution models.

And stellar models have since long predicted that core He-burning stars (CHeB) of low-mass (say $M < 2 \, M_\odot$), for a given metallicity, should cover a small interval of $\log L$ – as pointed out by e.g. Cannon (1970) and Castellani et al. (1992) – as a consequence of the similar core masses $M_{\text{core}}$ that they have at the He-flash. In fact, similar $M_{\text{core}}$ values imply nearly the same luminosities coming from their He-burning cores, i.e. $L_{\text{He}} \approx \text{const}$. However, it has not been much emphasized that, for the same $M_{\text{core}}$ and metallicity, the luminosity of the H-burning shell increases monotonically with the envelope mass, so that $L_{\text{H}} \propto M$ (roughly). Since $L = L_{\text{H}} + L_{\text{He}}$ with $L_{\text{H}} \approx 2 L_{\text{He}}$ at $M = 1 \, M_\odot$, it follows that low-mass clump stars must become some tenths of a magnitude brighter at larger masses/smaller ages. Another trend is that $L$ should decrease with $[\text{Fe/H}]$, due to the decrease of both $M_{\text{core}}$ and efficiency of the H-burning shell.

Some CHeB intermediate-mass stars do also occupy the clump region of the HR diagram (Girardi 1999). Their luminosities change a lot with age, reflecting mainly the proportionality between the core mass at He-ignition and the initial mass, that is followed by stars that do not develop $\text{e}^-$-degenerate He cores.

These behaviours are shared by most (if not all) sets of evolutionary tracks of CHeB stars present in the literature (e.g. Pols et al. 1998; Charbonnel et al. 1996; Girardi et al. 2000, among others), and are schematically presented in Fig. 1: $M_{\text{RC}}^I$ is expected to change by as much as $\sim 0.4 \text{ mag}$ with age at a fixed $[\text{Fe/H}]$, and by $\sim 0.4 \text{ mag}$ with $[\text{Fe/H}]$ at a fixed age. A few theoretical uncertainties (e.g. overshooting, mass-loss, the helium-to-metal enrichment ratio, as shown in Fig. 1) can change the details of this behaviour by $\sim 0.1 \text{ mag}$, but cannot change the general trends.

Figure 1. $M_{\text{RC}}^I$ as a function of age and $[\text{Fe/H}]$ (schematic).
Why \( M_I^{\text{RC}} \) changes among galaxies

Assessing the changes of \( M_I^{\text{RC}} \) with age and metallicity is only half of the problem in determining the \( \Delta M_I^{\text{RC}} \) values to be used in eq. (1). The other half corresponds to answering “What are the age and metallicity distributions of clump stars in galaxies?” This question finds quantitative answers from basic population synthesis theory, once we know the past star formation rate (SFR) and age-metallicity relation (AMR) of the galaxies considered (see Girardi & Salaris 2000). Fig. 2 shows two illustrative cases:

(i) In a late-type galaxy that has formed stars at a nearly constant rate since its formation until now (e.g. the disks of spirals, or irregulars), the age distribution of clump stars strongly concentrates at relatively young ages (1 − 3 Gyr). This effect comes out because: (i) the rate at which stars leave the main sequence decreases with age; and (ii) the He-burning lifetime has a maximum for stars of \( \sim 1 \) Gyr. Notice that a predominantly young clump implies a somewhat narrow \([\text{Fe/H}]\) distribution, since, in general, galaxies have experienced little chemical evolution in the last few gigayears.

(ii) In an early-type galaxy where star formation ceased after just a few Gyr (e.g. ellipticals and the bulges of spirals), clump stars younger than \( \sim 8 \) Gyr simply do not exist and the clump age distribution is narrow. These old populations, in general, present a broader distribution of \([\text{Fe/H}]\) values.

Of course, any intermediate (and even more extreme) behaviour can occur. The general situation is that quite different distributions of ages/metallicities of clump stars are expected among different galaxies. The local sample of stars that define the Hipparcos clump, is also expected to be quite different from those found in other Local Group systems.

Conclusions about \( \Delta M_I^{\text{RC}} \)

If we consider Figs. 1 and 2 together, the conclusions are almost immediate: non-negligible values of \( \Delta M_I^{\text{RC}} \) are expected among different galaxies. Girardi
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et al. (1998) and Girardi & Salaris (2000) find $\Delta M_{I}^{RC}$ values as large as $0.2 - 0.3$ mag for the Magellanic Clouds. When one uses these theoretical population corrections, and the Romaniello et al. (1999) or Zaritsky (2000) determinations for $A_I$, it turns out that the red clump method is still compatible with a “long” distance scale, with $(m - M)_{0}^{\text{LMC}} = 18.55 \pm 0.05$ mag for the LMC.

These conclusions seem to be in contradiction with Udalski (1998ab, 2000), who, on observational grounds, finds a small dependence of $M_{I}^{RC}$ on both age and metallicity. However, Girardi & Salaris (2000) clarify that (i) larger dependences, compatible with theoretical models, are found by Twarog et al. (1998) and Sarajedini (1999); (ii) Udalski’s empirical relations do not have general validity, since they reflect the particular distributions of ages and metallicities of clump stars included in the observational samples, and express the clump behaviour by means of a too simple relation between $M_{I}^{RC}$ and [Fe/H] (which, cf. Figs. 1 and 2, is not expected to be satisfactory, for both star clusters and galaxies). According to Girardi & Salaris, theoretical models still provide the most reliable $\Delta M_{I}^{RC}$ values, provided that the SFR and AMR of the galaxies under scrutiny are sufficiently well known.

In summary, theoretical predictions seem to survive to most tests provided by observational data (cf. Girardi & Salaris 2000), and yet lead to an interpretation of the data that is substantially different – and much more complete! – than the one sketched in present empirical $M_{I}^{RC}$ versus [Fe/H] calibrations. Can we really do without theoretical models?

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References

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