Tip of the Red Giant Branch distances to galaxies with composite stellar populations

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ABSTRACT
The accurate determination of galaxy relative distances is extremely important for the empirical calibration of the uncertain metallicity dependence of some standard candles like Cepheid stars, or for studying the galaxy space distribution and peculiar velocities. Here we have investigated the reliability of the widely used $I$-band Tip of the Red Giant Branch (TRGB) relative distances for a sample of Local Group galaxies with complex star formation histories (SFHs) and age–metallicity relationships (AMRs) namely the Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC) and LGS3. The use of the $K$ band is also discussed. By employing theoretical stellar population synthesis techniques, we find that using actual determinations of SFH and AMR of the LMC and SMC, their RGB is populated by stars much younger (by $\sim9$ Gyr) than the Galactic globular cluster counterparts, on which the $I$-band (and $K$-band) TRGB absolute magnitude is calibrated. This age difference induces a bias in both the photometric metallicity estimates based on the comparison of RGB colours with globular cluster ones, and the TRGB distances. The extent of the distance bias – which is not influenced by the actual value of the TRGB absolute magnitude zero-point – is strongly dependent on the specific TRGB technique applied, and on the assumed $I$-band bolometric correction ($BC_I$) scale adopted; the correction to apply to the SMC–LMC distance modulus ranges from 0 up to $+0.10$ mag. LGS3 is an example of a galaxy populated mainly by old stars, so that photometric metallicity and distance estimates using globular cluster calibrations are reliable. However, the relative distance moduli between the Magellanic Clouds and LGS3 are affected by the population effects discussed for the LMC and SMC. The correction to apply to the LGS3–LMC distance modulus ranges between $-0.05$ and $+0.14$ mag, whereas in the case of the LGS3–SMC distance modulus it goes from $-0.07$ to $+0.04$ mag. In the case of all three relative distances discussed before, the correction to apply to the $K$-band TRGB distances are larger than the $I$-band case.

Our results clearly show that the presence of a well-developed RGB in the colour–magnitude diagram of a stellar system with a complex SFH does not guarantee that it is populated by globular cluster-like red giants, and therefore the TRGB method for distance determination has to be applied with caution. A definitive assessment of the appropriate corrections for population effects on TRGB distances has, however, to wait for a substantial reduction in the uncertainties on the $BC_I$ scale for cold stars.

Key words: stars: distances – galaxies: distances and redshifts – Local Group – Magellanic Clouds – galaxies: stellar content.

1 INTRODUCTION
The red giant branch (RGB) is one of the most prominent and well populated features in the colour–magnitude diagram (CMD) of stellar populations with ages larger than $\sim1.5–2.0$ Gyr. The
upper boundary of the RGB locus is the so-called tip of the RGB (TRGB), populated by stars whose electron degenerate core is to start the helium flash. At the helium flash the electron degeneracy is lifted and quiescent helium burning will proceed in a non-degenerate core. The helium flash phase is extremely short, and after the degeneracy is lifted, stars are located at much lower luminosities during the quiescent central helium burning. The subsequent asymptotic giant branch phase – which basically overlaps with the upper RGB and then reaches higher luminosities – is much faster than the RGB one, and therefore the TRGB manifests itself as a discontinuity in the differential luminosity function of bright red stars in the CMDs of intermediate-age to old stellar populations.

As for the TRGB absolute magnitude, theoretical and semiempirical works – see, for example, Da Costa & Mantz (1990, hereinafter DCM90, Lee, Freedman & Madore (1993, hereinafter LFM93), Salari & Cassisi (1997, 1998) – all agree that observations of the TRGB in the I-band minimize its dependence on age and chemical composition, so that the $M_{TRGB}$ is considered to be a very good standard candle for stellar populations displaying an RGB in their CMDs. LFM93 presented a comprehensive calibration of the TRGB method to determine galaxy distances, using results from DCM90. The TRGB has been employed to derive distances to objects in the Local Group and beyond, out to the Leo I group and Virgo (e.g. LFM93; Sakai et al. 1997; Harris et al. 1998; Cioni et al. 2000; Jerjen & Rejkuba 2001; Méndez et al. 2002; Karachentsev et al. 2003; McConnachie et al. 2004). Such distance estimates are very important for calibrating and testing other distance indicators, for measuring the local velocity fields and also for determining star-formation histories of the galaxies under scrutiny.

Owing to the popularity of the TRGB as a standard candle, a series of works has been devoted to improving various aspects of the TRGB method. Different techniques for TRGB detection have been put forward, often to improve its detection in cases of sparsely populated CMDs, or in the presence of high photometric errors. The most used method is the one presented by LFM93, which employs an edge detection algorithm (zero sum Sobel kernel $[-2, 0, +2]$) to detect a discontinuity in the luminosity function of bright RGB stars. A refinement of this method was presented in Sakai, Madore & Freedman (1996), who applied a continuous edge detection function to the Gaussian smoothed luminosity function.

Alternative techniques have been discussed by Cioni et al. (2000), Méndez et al. (2002), Sarajedini et al. (2002), Frayn & Gilmore (2003) and McConnachie et al. (2004).

On the other hand, various theoretical, semiempirical or empirical calibrations of $M_{TRGB}$ have been published by Salari & Cassisi (1997, 1998), DCM90, Bellazzini, Ferraro & Pancino (2001); Bellazzini et al. (2004). Calibrations of the absolute magnitude of the TRGB in infrared bands ($I, J, K$) are also available (Ferraro et al. 2000; Bellazzini et al. 2004), which largely avoid uncertainties related to the effect of extinction but, as we will see later, have a stronger dependence on the metallicity, and hence are probably more sensitive to population effects.

Once a given TRGB calibration is employed – the zero-points of the existing calibrations span a range of $\sim 0.2$ mag – relative distance moduli obtained from the TRGB are considered to be extremely precise, sometimes with error bars of the order of only 0.05 mag or less (e.g. McConnachie et al. 2004). This precision has prompted the use of the TRGB as a reference standard candle on which to calibrate empirically the metallicity dependence of other widely used stellar distance indicators, like Red Clump stars (e.g. Pietrzyński et al. 2003) or Cepheid variables (e.g. Sakai et al. 2004).

A fundamental point to be stressed is that all calibrations of $M_{TRGB}$ (or the infrared counterparts) applied to determine TRGB galaxy distances assume that the observed stellar populations are ‘old’, with ages of the order of the Galactic globular cluster ones (12–14 Gyr). This stems from the implicit assumption that a well-developed RGB is populated by old, globular cluster-like stars. This is possibly a very good assumption when observing, for example, haloes of spiral galaxies, but it is not justified in the case of composite stellar populations. Barker, Sarajedini & Harris (2004) have recently studied the case of composite stellar populations with a fraction of stars with ages of the order of 1.5 Gyr, corresponding to the RGB phase transition (Sweigart, Greggio & Renzini 1990), i.e. when the He ignition happens in a progressively less-degenerate core. During this transition the TRGB moves at lower luminosities with respect to older populations and Barker et al. (2004) found that if more than 30 per cent of the total number of stars created in a given stellar population have an age of this order, the distance obtained applying the standard TRGB calibrations is overestimated by $\sim 10$–20 per cent. However, the authors conclude that the galaxy distances obtained from the TRGB method up to now have not been affected by this effect, since none of the observed stellar populations appears to have a star-formation history of this kind.

In this paper we complement the analysis by Barker et al. (2004) by studying the effect of the star-formation history on the TRGB distances, considering specific examples of galaxies in the Local Group, e.g. the Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC) and LGS3; our results are independent of both the TRGB zero-point calibration, and the adopted technique to detect the TRGB from the stellar luminosity function. We will show how even without the presence of a substantial population at the RGB phase transition, systematic errors of 0.1–0.2 mag in TRGB relative distances might be present when the stellar population under scrutiny is not uniformly as old as the Galactic globular clusters. The paper is organized as follows. Section 2 discusses briefly the TRGB method and its calibration in both the I and infrared passbands, while Section 3 presents a detailed reanalysis of the TRGB distances to LMC, SMC and LGS3 and discusses the biases in their relative distances if one follows the traditional use of the TRGB method. Conclusions follow in Section 4.

2 TRGB BRIGHTNESS AS A FUNCTION OF AGE AND METALLICITY

The bolometric luminosity of TRGB stars as derived from stellar-evolution models is largely determined by the size of the He core at the He flash, once the initial chemical composition is fixed. Since low-mass stars ignite He all with similar core masses (slightly increasing for decreasing stellar mass), $M_{bol}$ changes by a few hundreds of magnitudes in the typical age range of Galactic globular clusters (ages between $\sim 8$ and $\sim 13$ Gyr), as shown in Fig. 1. Using the scaled-solar models by Girardi et al. (2000). When approaching the RGB phase transition $M_{bol}$ increases sharply due to the lifting of electron degeneracy in the He core, which causes He ignition to occur at significantly smaller core masses.

On the other hand, once the age is fixed, $M_{bol}$ decreases for increasing metallicity, in spite of the decrease of the He core mass at the TRGB. As shown, e.g. in Kippenhahn & Weigert (1990) on
the basis of homology relations, this property stems from the fact that at a given core mass an increase of the molecular weight in the H-burning shell causes an increase of the RGB star luminosity. The net effect is a decrease of the TRGB brightness with decreasing [Fe/H]; in general, \( M_{\text{bol}}^{\text{TRGB}} \propto -0.20 \text{ [Fe/H]} \) at a fixed age far from the RGB phase transition (say, \( \gtrsim 3 \) Gyr) and for metallicities well below the solar value.

DA90 have provided a much used semiempirical calibration of \( M_{\text{bol}}^{\text{TRGB}} \) as a function of [Fe/H] in the Galactic globular cluster regime (old ages and [Fe/H] at most \( \sim -0.7 \)). They employed empirical determinations of the bolometric magnitude of RGB stars in a sample of clusters of known metallicity, assumed a globular cluster distance scale and fixed the slope of the \( M_{\text{bol}}^{\text{TRGB}} \) versus [Fe/H] relationship to the value given by Sweigart & Gross (1978) theoretical models, obtaining

\[
M_{\text{bol}}^{\text{TRGB}} = -0.19 \text{ [Fe/H]} - 3.81. \tag{1}
\]

A previous semiempirical determination by Frogel et al. (1983), as well as more recent theoretical and semiempirical evaluations of this relationship (e.g. Salaris & Cassisi 1997, 1998; Ferraro et al. 2000) including the results displayed in Fig. 1, have a slope very similar to the value of the DA90 calibration, although the zero-point can differ by 0.1–0.2 mag (see, for example, the discussion in Salaris, Cassisi & Weiss 2002).

Therefore, there is good general agreement on the way \( M_{\text{bol}}^{\text{TRGB}} \) behaves as a function of age or metallicity. But distance determinations using the RGB tip are mostly based on J- and K-band observations. In the following we will separately discuss the calibrations in these two bands.

### 2.1 TRGB brightness in the K-band

Fig. 2 displays the run of \( M_{\text{bol}}^{\text{TRGB}} \) as a function of age for various [Fe/H] values. Here we have used as a reference the theoretical models by Girardi et al. (2000), transformed to the K-band magnitude using the theoretical bolometric corrections (\( BC_K \)) by Girardi et al. (2000 – dashed line), the empirical \( BC_K \) by Montegriffo et al. (1998 – dotted line), and the combination of theoretical plus empirical \( BC_K \) (empirical data for effective temperatures \( T_{\text{eff}} < 3500 \) K) presented in Girardi et al. (2002 – solid line).

(1998 – dotted line), and the combination of theoretical plus empirical \( BC_K \) (empirical data for effective temperatures \( T_{\text{eff}} < 3500 \) K) presented in Girardi et al. (2002 – solid line).

It is easy to notice that in the K-band the effect of metallicity is enhanced with respect to the case of bolometric magnitudes. The general behavior is the same irrespective of the use of empirical or theoretical bolometric corrections, which produce mainly zero-point offsets.

In the case of Galactic globular clusters one finds semiempirically (e.g. Ferraro et al. 2000) that \( dM_{\text{bol}}^{\text{TRGB}} / \Delta [\text{Fe/H}] \propto -0.60 \), i.e. the metallicity dependence is a factor of \( \sim 3 \) higher than for the bolometric magnitudes, in agreement with the model predictions. This difference stems from the behavior of \( BC_K \), which is practically independent of [Fe/H], and strongly affected by \( T_{\text{eff}} \) (see, e.g. Frogel, Persson & Cohen 1981; Montegriffo et al. 1998) in the sense that \( BC_K \) decreases strongly for increasing \( T_{\text{eff}} \). This produces fainter magnitudes for the hotter TRGBs, which are also the more metal-poor and fainter ones in \( M_{\text{bol}} \), hence the increased dependence of \( M_{\text{bol}}^{\text{TRGB}} \) on [Fe/H] when compared to \( M_{\text{bol}}^{\text{TRGB}} \).

One can also notice that, owing to the behaviour of \( BC_K \), there is a non-negligible dependence of \( M_{\text{bol}}^{\text{TRGB}} \) on age, in the sense that a lower age at a given [Fe/H] mimics a lower metallicity at a given age.

In spite of the appeal due to the negligible dependence on reddening, \( M_{\text{bol}}^{\text{TRGB}} \) is in principle prone to serious uncertainties when the metallicity and age of the parent stellar population are uncertain.

### 2.2 TRGB brightness in the J-band

As shown by e.g. Bellazzini et al. (2004) for Galactic globular clusters, the TRGB magnitude dependence on [Fe/H] decreases when moving from the K-band to the J-band, i.e. \( dM_{\text{bol}}^{\text{TRGB}} / d[\text{Fe/H}] \propto -0.54 \) and \( dM_{\text{J}}^{\text{TRGB}} / d[\text{Fe/H}] \propto -0.26 \). In the J-band

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"Figure 1. \( M_{\text{bol}} \) of the TRGB as a function of age and [Fe/H], from the theoretical models by Girardi et al. (2000)."

"Figure 2. \( M_K \) of the TRGB as a function of age and [Fe/H]. The [Fe/H] values are listed in order of decreasing TRGB K-band brightness. The theoretical models are by Girardi et al. (2000), transformed to the K-band magnitude using the theoretical bolometric corrections (\( BC_K \)) by Girardi et al. (2000 – dashed line), the empirical \( BC_K \) by Montegriffo et al. (1998 – dotted line), and the combination of theoretical plus empirical \( BC_K \) (empirical data for effective temperatures \( T_{\text{eff}} < 3500 \) K) presented in Girardi et al. (2002 – solid line)."

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MI empirical relationship presented in LFM93, based on equation (1) supplemented by the DA90

\[ (V - I)_{0,3} - 3.5 \]

denoted as (2) to determine \( B_{C} \) from the intrinsic mean colour of TRGB stars. With these two quantities one obtains a second approximation to the real distance modulus from

\[ (m - M)_{0} = I_{0,TRGB} + B_{C} - M_{bol}^{TRGB}. \]

This procedure is then iterated until convergence is obtained. Since the almost vertical nature of the RGB, and the weak overall dependency of \( M_{bol}^{TRGB} - B_{C} \) (as discussed in the case of Galactic globulars on which this calibration relies) on [Fe/H], convergence is achieved usually within 2–3 iterations.

Alternative approaches to TRGB distance determinations either adopt theoretical \( B_{C} \) and \( M_{bol}^{TRGB} \) values from model atmosphere and stellar-evolution computations to determine directly a theoretical relationship \( M_{bol}^{TRGB} - [Fe/H] \) (as in Salaris & Cassisi 1998 for globular cluster-like ages), or derive empirical \( M_{bol}^{TRGB} - [Fe/H] \) relationships by detecting the TRGB in Galactic globular clusters with (empirically) known distances and metallicities (e.g. Bellazzini et al. 2001, 2004).

3 APPLICATION TO COMPOSITE STELLAR POPULATIONS

As discussed extensively in the previous section, all TRGB absolute magnitude calibrations applied for determining extragalactic distances are based on Galactic globular cluster stars (observations, models or both). Any difference between the calibrating stellar populations and the observed ones may have an impact on the inferred TRGB distances. As we will demonstrate shortly, the presence of a well populated RGB in a generic CMD does not automatically imply that the stellar population under scrutiny is equivalent to Galactic globular cluster populations. In the case of spiral galaxies, observing far in the halo will very probably minimize population differences, but when working with, e.g., irregular galaxies (like many of the components of the Local Group) there is not a clear-cut distinction between the homogeneously old stellar component and younger ones.

In the following we will discuss these population effects on the TRGB distances to the LMC and SMC by using population synthesis simulations of the galaxy stellar populations, in the same vein as in Girardi & Salaris (2001).

3.1 LMC

3.1.1 The simulated CMD

We have computed synthetic CMDs of the LMC stellar populations using the Star Formation History (SFH) and Age Metallicity Relation (AMR) displayed in Fig. 4, which are typical of the LMC bar stellar populations (see discussion in Girardi & Salaris 2001; Salaris, Percival & Girardi 2003). The synthetic CMDs have been computed using the same code employed by Girardi & Salaris (2001), and we made use of the stellar models by Girardi et al. (2000) and colour transformations by Girardi et al. (2002). We have included in the simulation a Gaussian 1σ photometric error of 0.02 mag (a typical error at the magnitudes of LMC and SMC TRGB – see, for example, the discussion in Barker et al. 2004), and a Gaussian 1σ spread of population reddening, one determines the intrinsic colours of the observed RGB stars. A preliminary distance modulus is then fixed and employed to determine a preliminary metallicity by measuring \((V - I)_{0,3} - 3.5\) and using equation (3). With this preliminary [Fe/H] estimate, one applies equation (1) to determine \( M_{bol}^{TRGB} \), and equation (2) to determine \( B_{C} \) from the intrinsic mean colour of TRGB stars. With these two quantities one obtains a second approximation to the real distance modulus from
3.1.2 The apparent discrepancy in mean [Fe/H]

Overplotted in Fig. 5 are the RGBs of two globular cluster isochrones (of age 12.5 Gyr) with the labelled [Fe/H] of −0.9 and −1.5. They delimit the bulk of RGB stars found in the simulation. By comparing the (V−I) colours of the globular cluster isochrones and the LMC population, we can derive, in a way similar to the use of equation (3), the mean [Fe/H] value for the RGB stars in the LMC.

A first fundamental point has to be noticed at this stage. Our synthetic LMC population has been computed using the scaled solar models by Girardi et al. (2000). The LMC chemical evolution models by Pagel & Tautvaisiene (1998) and the spectroscopic observations by Hill et al. (2000) and Smith et al. (2002) show that at low metallicity the α-elements (i.e. O, Ne, Mg, Si, S, Ca, Ti) are mildly enhanced with respect to Fe, i.e. [α/Fe] ∼ 0.1–0.2. However, the relevant [Fe/H] range of the RGB stars will turn out to be − as thoroughly discussed in the following – such that [α/Fe] ∼ 0 according to the results mentioned before, and our use of scaled solar models for the simulation of LMC red giants is fully justified.

The Galactic globular cluster RGB isochrones employed to determine the photometric metallicity of our LMC synthetic population, following the LFM93 method, must however take into account the fact that [α/Fe] ∼ 0.3 in globular cluster stars (see, for example, Salaris, Chieffi & Straniero 1993; Carney 1996 and references therein). For metallicities typical of the Galactic halo, α-enhanced theoretical stellar models are well reproduced by scaled solar ones with the same total metallicity [M/H] (Salaris et al. 1993), and therefore the globular cluster isochrones displayed in Fig. 5 are the scaled solar ones by Girardi et al. (2000) with the appropriate choice of the total metallicity that mimics [α/Fe] = 0.3, i.e. [M/H] = [Fe/H] + 0.2 (for a scaled solar mixture [M/H] = [Fe/H]).

The mean [Fe/H] obtained comparing the mean colour of our synthetic LMC population at $M_I = -3.5$ (the reference magnitude used in the LFM93 method) with the colours of individual globular cluster isochrones, of various [Fe/H] and at the same $M_I$, is $[Fe/H] = -1.08$. This is in very good agreement with values obtained by LFM93 and Sakai et al. (2000) from V−I LMC observations. We also redetermined the mean [Fe/H] of LMC giants employing photometry of the LMC OGLE field 6 (Udalski et al. 2000) and the method by LFM93. After correcting for the effect of extinction using the reddening maps by Udalski et al. (1999) we obtained a mean [Fe/H] of $-1.15$.

This [Fe/H] value obtained from the synthetic CMD and in agreement with estimates from observed CMDs is however greatly discrepant from the results of spectroscopic observations of bright RGB stars in the LMC bar published by Cole et al. (2000), who found a mean [Fe/H] of $-0.60$. It is important to notice that if we apply the LFM93 technique and calibrations, this [Fe/H] difference, taken at face value, would produce a systematic change in the distance modulus by $\sim 0.10$ mag, because $BC$ in equation (4) is fixed by the observed (V−I) colour, and $M^\text{min}_{\text{syn}}$ changes by 0.10 mag for a 0.5 dex change of [Fe/H].

The bottom panel of Fig. 5 shows the [Fe/H] distribution for the stars in our simulation that populates the upper RGB. Here we find a mean [Fe/H] of $-0.61$, in excellent agreement with the spectroscopic result of $-0.60$. This means that the synthetic LMC population also displays the ∼0.5-dex discrepancy between the RGB [Fe/H] inferred from the RGB colour and the true value (the spectroscopic one in the case of real LMC stars).

The reason for this discrepancy is twofold. The first cause is related to the age distribution of LMC stars compared to the age of globular clusters. Fig. 6 displays the binned luminosity function

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**Figure 4.** SFH and AMR adopted for our LMC simulation. The SFH (bottom panel) is the one derived by Holtzman et al. (1999, fig. 4) from HST photometry of a field in the LMC bar. The AMR (top panel) comes from the bursting chemical evolution model of Pagel & Tautvaisiene (1998), and agrees well with AMRs derived from observations of LMC star clusters (see, for example, Hill et al. 2000).

**Figure 5.** Simulation of the LMC bar population using the SFH and AMR of Fig. 4. The top panel shows the simulated $M_I$ versus $V-I$ CMD detailing the upper part of the RGB (dots), and compares it with two globular cluster isochrones for [Fe/H] equal to $-1.5$ and $-0.9$, respectively (continuous thick lines). The bottom panel shows the metallicity distribution of the simulated upper RGB stars.

0.1 dex around the [Fe/H] values displayed in Fig. 4, but the following results are completely independent of the photometric errors and [Fe/H] dispersion.

The top panel of Fig. 5 shows the $M_I - (V-I)$ CMD of the synthetic LMC RGB population. It is evident in this figure that the position of the TRGB is at about $M_I \sim -4$. 

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Figure 6. Luminosity functions for all red stars (V−I > 1) in the LMC simulation (heavy line), and separated in four age bins (light lines). Notice that the TRGB discontinuity, detectable at about M_{bol} = −3.6, is mainly caused by stars in the 2−4 and 4−6 age bins.

(bins 0.04-mag wide) of all bright red stars (V−I > 1.0) in the LMC^2 and the partial luminosity functions for different age ranges. The discontinuity corresponding to the TRGB is clearly visible, and for what follows the technique used to identify the location of the discontinuity is completely irrelevant.

The mean age of bright RGB stars is ∼4 Gyr, much lower than the age (12–13 Gyr, see for example Salaris & Weiss 2002) of the Galactic globular clusters on which the RGB colour–[Fe/H] relationship is calibrated. Although the RGB colour is weakly sensitive to the age of the parent stellar population, an age difference of ∼9 Gyr has an appreciable influence, in the sense that the younger LMC population is bluer than the globular cluster one at fixed chemical composition. If we shift the mean colour of the LMC RGB to the red, to account for the effect of a 9-Gyr age difference with respect to a typical globular clusters RGB, we would determine a photometric [Fe/H] value that is ∼0.3 dex lower than the intrinsic one.

After correcting for the age effect there are still ∼0.2 dex of mismatch in [Fe/H] to be accounted for. This remaining difference is related to the different metal mixture of the calibrating globulums. Since a given [Fe/H] value coupled to [α/Fe] > 0 corresponds to a higher [M/H] than for a scaled solar mixture, RGB stars in the LMC appear to be bluer than the counterpart in globulars with the same [Fe/H]. This causes an underestimate of the LMC stars [Fe/H] of about 0.2 dex if [α/Fe] ∼ 0.3 for Galactic globular clusters, and in this way the full difference between photometric and real [Fe/H] is explained.

Let us for a moment suppose that the underestimate of [Fe/H] for the LMC RGB is due only to this latter effect, and denote by [Fe/H]' the value obtained from equation (3) increased by 0.2 dex. We know that M_{bol}^{TRGB} is determined by the total stellar metallicity [M/H] (e.g. Salaris et al. 1993), and that the calibration given by equation (1) is based on α-enhanced globular cluster stars, for which [M/H] = [Fe/H] + 0.2. This means that the use of the photometric [Fe/H] given by equation (3) instead of [Fe/H]' does provide the correct M_{bol}^{TRGB} for the LMC stars, because at a given [Fe/H]' their [M/H] is lower by 0.2 dex than the globular cluster counterpart, and this mismatch is compensated for by the use of the ‘wrong’ photometric [Fe/H]. The bottom line is that, from the point of view of the expected absolute magnitude of the TRGB for LMC stars, the 0.2-dex [Fe/H] mismatch due to the α-enhancement in Galactic globular clusters does not play a role in the LFM93 method.

3.1.3 Implications for the TRGB distance to the LMC using the LFM93 method

The following few facts can be derived from the above discussion.

(i) The TRGB discontinuity (in M_{bol}, but the same is true for the I- and K-band) in the LMC is determined by stars with ages of the order of ∼4 Gyr. Older and younger RGB stars, although certainly present, are either too few (in the case of old stars), or do not contribute significantly to the detected TRGB discontinuity (in the case of stars younger than 2 Gyr), or both.

(ii) Since most of the RGB stars in the LMC are intermediate-age, it is wrong to determine their [Fe/H] by simply comparing their V−I colours with those of globular cluster giants.

(iii) When using the LFM93 method in the LMC, a number of additional steps has to be followed: whereas B/G is fixed by the observations, M_{bol}^{TRGB} has to be corrected for a 0.3-dex metallicity increase effect (which increases the M_{bol}^{TRGB} at fixed age) and for the age decrease with respect to the globular cluster ages (this effect is however very small), as predicted by the theoretical models. Applying these corrections, the LMC distance modulus increases by 0.05 mag with respect to results with the original LFM93 method and calibrations.

A particular remark should be made regarding item (ii). As seen in Fig. 4, in the LMC the SFH has been variable and presents a gap from 7 to 9 Gyr, which nearly coincides with the usual separation between populations of intermediate (∼1 to 7 Gyr) and old (∼9 Gyr) ages. At intermediate ages, the mean SFH is just 3.1 times higher than the mean one at old ages. It may seem surprising that this moderate excess of the SFH at intermediate ages has caused the RGB to be dominated by ∼4-Gyr old stars, with just a minor contribution from old ages (see Fig. 6). Actually, there is no surprise in this result: The number of evolved stars of a given kind and age is proportional to both the SFH at that age, and to their intrinsic lifetime and birth rate. The birth rate is a function that strongly decreases with the stellar age, and this would cause the predominance of intermediate-age stars even for the case of constant SFH. This issue has been thoroughly discussed in the case of red clump stars by Girardi & Salaris (2001); the situation for RGB stars close to the TRGB is a very similar one.

Therefore, the dominance of the intermediate-age RGB is not a result specific to the LMC: it is the case for any galactic component in which star formation at intermediate ages has been significant compared to old ages. This includes the discs of spirals, most of the irregulars, and a significant fraction of the dwarf spheroidal galaxies.

3.1.4 Implications for the TRGB distance to the LMC using other methods

Other methods usually consider a constant M_{I}^{TRGB} for ‘metal-poor’ stellar populations taken from calibrations based on Galactic...
globulars. For example, Frayn & Gilmore (2003), Karachentsev et al. (2003) and McConnachie et al. (2004), use a constant $M_{TRGB}$ value based on globular cluster calibrations, and apply it to the observed RGB population of the parent galaxy. Of course, in these cases we have again the assumption that the RGB population, or at least the RGB stars that cause the detected TRGB discontinuity, are old and metal poor. As we have just shown, this is not the case for the LMC bar population.

To check the bias in the LMC distance obtained with this method one can use theoretical isochrones differentially, once we have identified – by means of simulations like the one of Fig. 5 – the typical ages and metallicities of TRGB stars.

First, we can directly compare $M_{TRGB}$ obtained from the isochrones for a typical halo globular cluster metallicity $[\text{Fe/H}]$ of $-1.6$ and an age of 12.5 Gyr, with the $M_{TRGB}$ obtained using the true $[\text{Fe/H}]$ and true age of the TRGB stars in the LMC. The difference between the two $M_{TRGB}$ values, hereafter defined as

$$\Delta M_{TRGB} = M_{TRGB}(12.5 \text{ Gyr}, -1.6) - M_{TRGB}(\text{true})$$

provides the correction we have to apply to our distance determination. We have performed this exercise, based on the synthetic data of Fig. 5.

Somewhat surprisingly, we find that the results depend in a non-negligible way on the adopted set of transformations between the theoretical $(M_{bol}, T_{eff})$ and the observational $(M_I, V-I)$ plane. The results can be summarized as follows:

(i) using Girardi et al. (2000) transformations the LMC distance has to be increased by 0.07 mag;
(ii) using Girardi et al. (2002) transformations the LMC distance has to be decreased by 0.14 mag;
(iii) using Yale transformations (Green 1988) the LMC distance is unchanged;
(iv) using Westera et al. (2002) transformations the LMC distance is unchanged.

Fig. 7 illustrates the behaviour of the quantity $\Delta M_{TRGB}$ as a function of age and metallicity, for the above-mentioned sets of transformations. We recall that they are derived from libraries of stellar isochrones. We limit ourselves to a few comments. In the case of old-metal poor populations, differences in $\Delta M_{TRGB}$ are limited to $\approx 0.1$ mag, but anyway cannot be considered negligible. High metallicities and old ages, as soon as the $T_{eff}$ value of TRGB stars becomes lower than $\sim 4000$ K, the discrepancies among the curves become dramatic. In fact, the transformations in the range $T_{eff} \lesssim 3500$ K are (1) subject to larger variations owing to the appearance of molecular bands in stellar spectra, and (2) dealt with differently by different authors. A value $T_{eff} = 3500$ K is the minimum temperature for the ATLAS9 theoretical model atmospheres (see, for example, Kurucz 1993), which constitute the backbone of the transformations by Westera et al. (2002) and Girardi et al. (2000, 2002).

Below this $T_{eff}$ (and to a certain extent also in the range $\sim 3500$–$4000$ K), the different transformations rely on sets of empirical spectra and colour-$T_{eff}$ relations, which are more prone to be implemented in different ways. Therefore, it is no surprise that $\Delta M_{TRGB}$ heavily depends on the adopted transformations in the case of high metallicities.

It is also important to notice that the theoretical uncertainties in $\Delta M_{TRGB}$ cannot be avoided by using the empirical relationship to compute $BC_I$ employed by the LFM93 technique (see equation 2), since it has a non-negligible $1\sigma$ scatter of 0.057 mag that DA90 attribute to observational errors. Moreover this empirical $BC_I$ calibration by DA90 does not reach the true mean $[\text{Fe/H}]$ of the LMC RGB stars, its upper limit of validity being $[\text{Fe/H}] = -0.7$ (the metallicity of 47 Tuc).

Could one avoid the uncertainties in the transformations by deriving a TRGB distance using infrared instead of $I$-band observations? As indicated by Fig. 2, different sets of transformations provide almost the same behaviour of $M_{TRGB}$ as a function of age and metallicity, thus suggesting that $\Delta M_{K} = 1.38$ (corresponding to $[\text{Fe/H}] = -1.38$) is a more reliable TRGB distance. The problem in this case is related to the high dependence of $M_{TRGB}$ on age and metallicity: the computation of the correction $\Delta M_{TRGB}$ requires knowledge of the age and metallicity distribution of RGB stars, any error in these quantities is likely to produce substantial errors in $\Delta M_{TRGB}$. Since the calibration of $M_{TRGB}$ is based on globular clusters – located at one extreme of the age–metallicity plane allowed to RGB populations – biases are expected to be high. The maximum bias is obtained when using the $K$-band magnitude of the TRGB coupled to a semiempirical or theoretical $M_{TRGB}$ calibration based on globular clusters, and a calibration (e.g. Ferraro et al. 2000) $(V-K)-[\text{Fe/H}]$ or $(J-K)-[\text{Fe/H}]$ obtained from globulars. By using differentially the theoretical isochrones in infrared passbands, the $[\text{Fe/H}]$ and age biases discussed before would produce a bias of $\lesssim 0.2$ mag (true distance larger than the value obtained from the globular cluster calibration) in the TRGB distance, when considering a globular cluster age of 12.5 Gyr. In addition, for the $K$-band – as mentioned before – the precise age of the Galactic globulars plays also a role.
3.2 SMC

After discussing in detail the case of the LMC, we now examine the SMC. Many of the considerations made for the LMC apply also to the SMC, and will not be repeated for the sake of conciseness.

For our simulations, we select the ‘global’ SFH and AMR derived by Harris & Zaritsky (2004) from $UBV_I$ photometry of the entire main body of the SMC, and shown in Fig. 8. Their SFH is certainly the best available estimate for the SMC, whereas the AMR relation is in good agreement with those derived from observations of SMC star clusters. Scaled solar models are again appropriate for the relevant metallicities of the RGB stars, according to the discussion in Pagel & Tautvaisiene (1998 – their fig. 9 and discussion in Section 3).

The simulation is presented in Fig. 9. The photometric mean $[\text{Fe}/H]$, as derived from comparing the RGB with those of old isochrones and considering their $\alpha$-enhancement, is $[\text{Fe}/H] = -1.4$. From OGLE-II photometry of SMC OGLE field 3, dereddened, we get a similar value, $[\text{Fe}/H] = -1.5$.

The true mean RGB metallicity, as derived from the simulation itself, is $[\text{Fe}/H] = -0.82$. Again, we have a discrepancy of 0.6 dex between the two values of $[\text{Fe}/H]$, which can be explained as follows: 0.2 dex are due to the $\alpha$-enhancement, 0.4 dex are due to the mean younger age of SMC RGB stars with respect to old globular clusters. In fact, the mean age of bright RGB stars in the SMC is of just $\sim 3.7$ Gyr.

The TRGB discontinuity is mainly determined by stars with ages $\sim 4$ Gyr, and not by the oldest component with globular cluster-like ages, as is evident by looking at the partial LFs depicted in Fig. 10.

Using the LFM93 method, the effect of the $[\text{Fe}/H]$ discrepancy is an increase of 0.07 mag for the SMC distance.

Using the ‘constant $M_{\text{TRGB}}^I$’ methods, the results again depend on the selected set of transformations. Using the Girardi et al. (2002) ones, the SMC distance has to be decreased by 0.04 mag. With the other transformations tested in Fig. 7, the SMC distance is basically unchanged. In the $K$-band, the $\Delta M_{K}^{\text{TRGB}}$ amounts to $\sim 0.2$ mag, for all the different sets of transformations.

Comparing the LMC and SMC cases, we can conclude the following: in both cases, the use of LFM93 will lead to a small underestimate of their distance moduli, amounting to 0.05 for the LMC, and 0.07 mag for the SMC. These small errors are still lower than the overall accuracy of the TRGB methods (defined by the uncertainty in the zero-points, of 0.1–0.2 mag), but are not completely negligible. Moreover, the errors seem to be systematic in the sense of decreasing distances to the galaxies that have had significant star formation at intermediate ages. Fortunately enough, there is no impact on the relative SMC–LMC distance (but one has always to keep in mind that the $BCI$ relationship by DA90 is used outside its range of validity for the LMC TRGB).

When using the ‘constant $M_{\text{TRGB}}^I$’ methods, instead, the results depend on the set of transformations one uses to derive the...
quantity $\Delta M_{\text{TRGB}}$. Using the Girardi et al. (2002) transformations, for instance, one derives that the straight use of a constant $M_{\text{TRGB}}$ value lead to errors in distance moduli amounting to $-0.14$ mag for the LMC, and $-0.04$ mag for the SMC. This would imply an error of $0.10$ mag (true distance being longer) in the derived relative SMC–LMC distance. This is a significant error, which may bias the calibration of other standard candles as a function of the metallicity. On the other hand, if one uses Westera et al. (2002) transformations to derive $\Delta M_{\text{TRGB}}$, both SMC and LMC distance moduli remain unchanged, as well as their relative distance and the calibration of other standard candles on the Magellanic Clouds.

### 3.3 LGS3

As an example of galaxy where the globular cluster TRGB calibration is appropriate, we have considered the case of LGS3. Miller et al. (2001) provide a global SFH and AMR for this galaxy, displayed in Fig. 11. A main burst of star formation happened at the beginning of the galaxy life, after which the SFH level has been very low and almost constant. The spread around the mean AMR is also accounted for, following the estimates of Miller et al. (2001).

Fig. 12 displays the age distribution of RGB stars obtained from our simulation. The main component is made of the oldest objects formed during the strong initial burst of star formation. RGB stars born after the initial burst amount only to about half of the oldest objects. Since the age and metallicity ([Fe/H] $\approx -1.3$ for the majority of LGS3 RGB objects) of the bulk of the LGS3 RGB stars is comparable to the globular cluster counterparts, the standard calibrations of the TRGB absolute magnitude can be applied with confidence to this galaxy.

In more detail, when employing the LFM93 method a 0.2 dex underestimate of [Fe/H] is possible, if LGS3 stars formed all with a scaled solar metal distribution (as assumed in our simulation). However, as seen before, this does not affect the TRGB distances with LFM93 technique. Also when employing the ’constant $M_{\text{TRGB}}$’ methods, the true distance is recovered.

The relative distance modulus LGS3–LMC is affected at the level of 0.05 mag by the population effects discussed before when using the LFM93 method. The ’constant $M_{\text{TRGB}}$’ methods provide different results, depending on the set of bolometric transformations adopted, the maximum effect amounting to a significant 0.14 mag on the relative distance modulus.

### 4 CONCLUSIONS

The previous analysis of the TRGB distances to the galaxies LMC, SMC and LGS3 allowed us to point out a series of uncertainties affecting the current TRGB distance determinations and RGB photometric metallicity estimates for composite stellar populations.

All TRGB distance methods rest on the hypothesis that the RGB populations observed in external galaxies are as old as the stars in Galactic globular clusters, on which the TRGB calibrations are based. This is however not always true, as we have demonstrated for the specific cases of the LMC and SMC, whose RGB populations have ages of the order of 3–4 Gyr, instead of the 12–13 Gyr typical of the Galactic globulars. This age difference (and eventual differences in the [$\alpha$/Fe] ratio between the Galactic globular clusters and external galaxies) affects the TRGB distances and [Fe/H] estimate of the parent RGB stars, as has been already pointed out by Davidge (2003), Rizzi et al. (2003) and Salaris et al. (2003). In the case of LMC and SMC we found that [Fe/H] estimates based on the comparison of the RGB colour with the globular cluster counterparts are too low by $\sim 0.5$ dex owing to the effect of both age ($\sim 0.3$ dex) and different heavy element distribution ($\sim 0.2$ dex). These effects explain the discrepancy between the photometric metallicity of the LMC RGB determined from a comparison with the colours of globular cluster RGB stars, and the spectroscopic measurements.

The younger age of a galaxy RGB population with respect to globular cluster ages may induce a bias also in the $I$-band TRGB distance, whose extent is strongly dependent on the adopted $BC_{I}$ scale. TRGB relative distances between Magellanic Clouds-type galaxies and galaxies like LGS3 populated by mainly globular cluster-like stars can be appreciably affected by these population effects, up to $\sim 0.15$ mag, depending on the $BC_{I}$ scale adopted. In more detail, the correction to apply to the LGS3–LMC distance modulus ranges between $-0.05$ and $+0.14$ mag, whereas in the case of the LGS3–SMC distance modulus it ranges between $-0.07$ and $+0.04$ mag. As for the distance modulus SMC–LMC, the correction due to population effect ranges from 0 up to $+0.10$ mag.
The use of $K$-band TRGB calibrations – the $K$-band bolometric correction scale appears to be more secure as far as the trend with $T_{\text{eff}}$ is concerned – does not help much, owing to the strong dependence of $M_{\text{TRGB}}^K$ on both [Fe/H] and age; biases of the order of 0.2 dex can be present in $K$-band TRGB distances when using calibrations of the TRGB method based on Galactic globular cluster stars.

In order to isolate the most metal-poor and oldest RGB component to which one may safely apply the TRGB globular cluster calibration, one might try to apply a colour cut to the RGB data, i.e. selecting stars bluer than a given $(V-I)$ value, as suggested by our referee. We have however verified in the specific cases of the SMC and LMC that this procedure does not achieve in general the desired results. In more detail, we have divided the RGB with $-3.70 \leq M_I \leq -4.05$ into three colour intervals, i.e. $1.3 \leq (V-I) < 1.5$ (blue), $1.5 \leq (V-I) < 1.7$ (middle) and $1.7 \leq (V-I) < 1.9$ (red) and studied the associated distributions of age and [Fe/H] values. For SMC stars we find that the oldest population is spread between the red and middle interval, whereas for the LMC the oldest population is located in the blue interval. This difference reflects the AMR of the two galaxies. In the case of the SMC the AMR used in these simulations is approximately flat for ages down to $\sim 3$ Gyr; a sizable number of bluer objects belonging to different evolutionary phases of much younger ($< 2$ Gyr) and the oldest objects are necessarily located towards the red side of the RGB. For the LMC the oldest stars are also the most metal poor and therefore they tend to cluster at the blue side of the RGB.

It is evident from this example that the same colour cut applied to different galaxies may imply very different distributions of ages and [Fe/H] owing to different star formation and chemical enrichment histories; we have therefore to conclude that there is no general rule for selecting a particular kind of RGB stellar population based on colour cuts along the RGB CMD.

As for the possibility to detect the TRGB of the oldest populations in the LMC and SMC using the colour analysis described before, the following has to be noticed. The oldest SMC population is generally superimposed on the younger and more metal-rich one, which determines the level of the TRGB discontinuity. As for the LMC, the bluest RGB stars in a narrow colour range, $1.3 \leq (V-I) < 1.5$, can in principle provide a reasonably clean sample of an old globular cluster-like population, but their CMD location overlaps with a sizable number of bluer objects belonging to different evolutionary phases of much younger ($\lesssim 0.5$-Gyr) populations, which can be clearly seen in the upper left part of Fig. 5. The large fraction of these non-RGB objects populating the same colour bin may hamper a clear detection of the LMC old metal-poor TRGB.

To conclude, our results show that the presence of a well developed RGB in the colour–magnitude diagram of a stellar system with a complex SFH does not guarantee that the RGB is populated by globular cluster-like red giants, nor that its TRGB is determined by them; this means that the TRGB method for distance determinations has to be applied with caution to all galaxies that present signatures of intermediate-age stars. A definitive assessment of the appropriate corrections for population effects on TRGB distances has however to wait for a substantial reduction of the uncertainties on the $BC_I$ scale for cold stars.

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