The distance to the Sgr dwarf spheroidal galaxy from the Red Giant Branch Tip

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ABSTRACT

We derived the distance to the central region of the Sagittarius dwarf spheroidal galaxy from the Red Giant Branch Tip. The obtained distance modulus is \((m - M)_0 = 17.10 \pm 0.15\), corresponding to a heliocentric distance \(D = 26.30 \pm 1.8\) Kpc. This estimate is in good agreement with the distance obtained from RR Lyrae stars of the globular cluster M 54, located in the core of the Sgr galaxy, once the most accurate estimate of the cluster metallicity and the most recent calibration of the \(M_V(\text{RRLy})\) vs. \([Fe/H]\) relation are adopted.

Key words: stars: Population II - galaxies: distances and redshifts - Local Group

1 INTRODUCTION

The Sagittarius dwarf spheroidal galaxy (Sgr dSph) is a nearby satellite of the Milky Way [Ibata et al. 1994, 1997] that is currently disrupting under the strain of the Galactic tidal field. The relic of the process of disruption is observed as a huge coherent structure of stars escaped by the main body of the galaxy that remains approximately aligned along the original orbital path (the Sgr Stream, see Ibata et al. 2001, 2002; Newberg et al. 2002; Bellazzini et al. 2003; Majewski et al. 2003, and references therein). This occurrence provides an unprecedented occasion to study in detail the mechanism of merging of galactic sub-units as well as to constrain the mass and the shape of the dark matter halo of the Milky Way [Ibata et al. 2001]. and it has triggered a burst of theoretical efforts to accurately model the dynamical evolution of the Sgr system [see, for example Velasquez & White 1993; Ibata & Lewis 1998; Johnston et al. 1999; Gomez-Flechoso et al. 1999; Jiang & Binney 2000].

A fundamental ingredient of any realistic model of the dynamical history of Sgr is its distance, a key parameter that is not so well constrained, at present. The available estimates range from \((m - M)_0 = 16.90 \pm 0.15\) (Alard 1996) to \((m - M)_0 = 17.25^{+0.16}_{-0.20}\) (Bellazzini et al. 1998d). Other estimates have been provided, among the others, by Mateo et al. (1995c); Ibata et al. (1997); Marconi et al. (1998); Lavden & Sarajedini (2000). While all these distance moduli are formally compatible within the errors, they allow distances from \(D = 22.4\) Kpc to \(D = 29.5\) Kpc. It has also to be considered that, among the above analysis, the only one that was properly designed to obtain an accurate distance estimate is that by Lavden & Sarajedini (2000, hereafter LS00). These authors studied the RR Lyrae population of the globular cluster M 54, located in the core of the Sgr dSph. From a robust estimate of the average apparent magnitude of the ab type RR Lyrae of M 54 (< \(V_{RR} > = 18.17 \pm 0.01\)) they obtained \((m - M)_0 = 17.19 \pm 0.12\).

In this contribution we provide a new estimate of the distance to the Sgr galaxy using the Tip of the Red Giant Branch (TRGB) [see Lee, Freedman & Madore 1993; Sakai, Madore & Freedman 1998; Salaris, Cassisi & Weiss 2002, for details and references about the method]. We measured the apparent magnitude of the TRGB in the I passband and we derived the respective distance modulus adopting our recent calibration of the \(M_V(\text{RRLy})\) vs. \([Fe/H]\) relation [Bellazzini, Ferraro & Pancino 2001; Bellazzini et al. 2004], whose zero-point is fully independent from the RR-Lyrae distance scale (that is still affected by sizeable uncertainties, see Cacciari 1999; Walker 2003).

2 DETECTION OF THE TRGB

In order to measure the magnitude of the TRGB, we used the huge catalogue of \(\sim 490,000\) stars obtained in a \(1^\circ \times 1^\circ\) field centered on M 54 presented by Monaco et al. 2002 and plotted in Fig. X.

The Red Giant Branch (RGB) stars in Sgr can be...
more easily separated from the contaminating bulge and disc sequences (see, for example, Cole 2001) in the infrared Color Magnitude Diagram (CMD). Therefore, we used the infrared database from the 2MASS survey to select our RGB sample. We extracted Near Infrared (NIR) photometry of a $4^\circ \times 4^\circ$ field centered on M 54 from the Point Source Catalogue of the All Sky Data Release of 2MASS (Cutri et al. 2003). We selected only high quality sources, avoiding any possible blended stars and/or contaminants, as done in Bellazzini et al. (2003). The resulting sample of bona fide Sgr stars is shown in Fig. 2 enclosed in a box. In Fig. 3 we plotted the $I$ vs $V$ CMD zoomed in the RGB region. Stars selected in Fig. 2 and also measured in the optical bands are marked.

It is well known that the largely dominant stellar component of the Sgr dSph galaxy is a population of quite high mean metallicity ($-0.6 \lesssim [M/H] \lesssim -0.4$) and of age $\sim 6$ Gyr (Bellazzini et al. 1999b; Layden & Sarajedini 2000; Cole 2001; Monaco et al. 2002). Nevertheless the bona fide Sgr member in Fig. 3 show a large color spread in the CMD, witnessing the presence of stars of different ages and metallicity (Mateo et al. 1995; Bellazzini et al. 1999b; Layden & Sarajedini 2000; Monaco et al. 2003; Bonifacio et al. 2004). Since the absolute magnitude of the Tip is (weakly) dependent on metallicity, it would be safe to exclude stars not related to the Sgr dominant population from the sample used for the detection of the TRGB.

Therefore, we compared the optical CMD of Sgr with the RGB ridge lines of template globular clusters (see Monaco et al. 2002) and we finally adopted the selection shown in Fig. 3. According to our experiments with ridge lines, the adopted selection (the stars included between the two parallel thick lines in the plot) likely excludes stars with $[M/H] \lesssim -1.0$ and $[M/H] \gtrsim 0.0$. In this way the bulk of the dominant population (whose age and metallicity range is rather limited, see Monaco et al. 2002) is picked up by our selection.

The observable signature of the TRGB is the sharp cut-
We note that there are $N$ using the calibrating relations from Bellazzini et al. (2004, hereafter B04). In that paper we provided empirical relations for the absolute magnitude of the TRGB in I,J,H, and K as a function of the global metallicity of the considered stellar system. The global metallicity ($[M/H]$) is a parameter that takes into account not only the abundance of iron, but also of the α-elements (O, Mg, Si, etc.), making easier and more self-consistent the comparison between systems having different abundance patterns and with theoretical models (see Salaris, Chieffi & Straniero 1993; Ferraro et al. 1994, and B04 for definitions and details). The zero-point of the adopted calibration is based on the distance estimate to the globular cluster ω Centauri obtained by Thompson et al. (2001) from the double-line detached eclipsing binary OGLE-17 (see Bellazzini, Ferraro & Pancino 2001, B04), hence it is fully independent from the classical distance scale based on RR Lyrae and/or Horizontal Branch stars in general (see Tosi et al. 2001; Bellazzini et al. 2002; Maiz-Apellániz, Cieza & MacKenty 2002; Alves 2003; Walker 2003, for applications and discussions).

Assuming $E(B-V) = 0.14$ (see Lavden & Sarajedini 2000) and a mean metallicity of $[M/H]=-0.5$ (see Monaco et al. 2002) for the Sgr dominant population, the measured $I_{TRGB} = 13.44$ corresponds to $(m-M)_0 = 17.10$.

The final distance estimate is affected by the uncertainties in:

- the **calibrating relations**: the uncertainty of the zero point of the calibrations as estimated by B04 is $\sigma = 0.12$ mag for the I passband.
- the **metallicity** of the Sgr population: according to the relations in B04, a variation of $\pm 0.1$ dex in the mean metal content produce a change in the absolute I magnitude of the TRGB of about 0.045 mag.
- the estimate of the **apparent TRGB magnitude** which has an uncertainty of $\pm 0.06$ mag.
- the **reddening**: we adopt the direct reddening estimate obtained by LS00 from the color at the minimum of the light curve of ab RR Lyrae: $E(B-V) = 0.14 \pm 0.03$. This is in good agreement with the results from the reddening maps of Schlegel, Finkbeiner & Davis (1998), once the corrections provided by Dutra et al. (2001) are taken into account. Inspection of the reddening maps provided also strong indications that there is no serious variability of extinction in the considered field. The standard deviation of the reddening value, interpolated from the map at the position of each star in the 2MASS field, is just $\sigma E(B-V) = 0.03$, e.g. of the order of the uncertainty in the reddening estimate. Concerning the reddening laws, we adopt $A_I = 1.76 E(B-V)$ (Cousins’ I) from Dean, Warren & Cousins (1978).

All these uncertainty factors are independent each other. Therefore they can be quadratically summed to produce an average error of 0.15 mag, of the order of that obtained in other previous estimates of the distance to Sgr.

In summary, the derived distance modulus is $(m-M)_0 = 17.10 \pm 0.15$, corresponding to a heliocentric distance $D = 26.30 \pm 1.8$ Kpc.

In comparison to the infrared magnitudes, the I magnitude of the TRGB has a weaker dependence on metallicity. Moreover, the current calibrating relations suffer by a higher uncertainty at the infrared wavelengths. Therefore, it is certainly safer to use the I magnitude of the TRGB for the derivation of the distance. Nevertheless a comparison with

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**Figure 4.** Upper panel: Logarithmic LFs of the upper RGB for the stars selected in Fig. 3. The position of the TRGB is marked by a thick vertical line, the thin lines enclose the error bars. Middle panel: Logarithmic LF of the upper RGB as a generalized histogram. Lower panel: Sobel filter response to the LFs as a function of the I magnitude. The obvious peaks indicate the magnitude of the TRGB.
the infrared database can provide a useful consistency check for the derived distance modulus.

The 2MASS infrared photometry already introduced in section 4 is plotted in figure 5 in the K vs J-K (upper panel) and J vs J-K (lower panel) planes. We also plotted on each plane the predicted magnitude of the TRGB (middle continuous line) with the appropriate uncertainty (top and bottom lines). The predicted magnitude of the TRGB in the J and K passbands have been obtained from the derived distance modulus using the calibration provided in B04. The calibrations by B04 are in the same photometric system adopted by Ferraro et al. (2000, hereafter F00) and we used the empirical relations provided by Valenti et al. (2004) to convert the F00 into the 2MASS system: \( J_{\text{2MASS}} = J_{\text{F00}} - 0.06 \) and \( K_{\text{2MASS}} = K_{\text{F00}} - 0.05 \). We also adopted \( E(B-V) = 0.14 \) (LS00) and the reddening laws from Rich & Lebofsky (1985): \( A_J = 0.871E(B-V) \) and \( A_K = 0.346E(B-V) \).

We find that, by slightly adjusting the global metallicity to \([\text{M}/\text{H}] = -0.6\) (which is still consistent with the current estimates, see Monaco et al. 2002, Lavden & Sarajedini 2001), a fairly good agreement between the predicted and observed position of the TRGB is reached in the infrared passbands (see Fig. 5) which proves the internal consistency in the calibrating relations of B04.

4 DISCUSSION

We have provided a new estimate of the distance modulus to the Sgr dSph galaxy using the TRGB in the I passband as a standard candle. The obtained distance modulus is \((m-M)_0 = 17.10 \pm 0.15\) which corresponds to a heliocentric distance \(D = 26.30 \pm 1.8\) Kpc.

Due to the large uncertainties present in the various studies, this estimate is formally compatible with all existing measures. However, it is worth noting that most of existing distance estimates are often based on crude assumptions and many of them are likely affected by various kinds of systematics. In many cases the accuracy of these estimates was also hampered by the limited knowledge of the physical parameters (e.g. metallicity, age, etc.) of the main population of Sgr.

In the earliest studies the distance was derived by comparing the mean magnitude of the Red Clump of Sgr with that of template globular cluster or nearby galaxies (Bellazzini et al. 1999, Marconi et al. 1998, Ibata et al. 1995), e.g. neglecting the significant dependence of the RC on the age of the considered population (see Percival & Salaris 2003, and references therein). Other authors (Ibata et al. 1997, Sarajedini & Lavden 1993) extrapolated the mean magnitude of the RR Lyrae (\(M_V(\text{RR})\)) from the RC magnitude, adding a further source of uncertainty, and derived the distance modulus from a \(M_V(\text{RR}) vs. \text{[Fe/H]}\) relation, carrying its own uncertainty. The actual metallicity of the RR Lyrae stars of Sgr is poorly known (but see Csenerjes 2001). This fact limited the accuracy of distance estimates directly derived from the properties of the RR Lyrae (Mateo et al. 1995b). For example, Mateo et al. (1995a), Alard (1996), Csenerjes, Alard, & Guibert (2000) assumed a constant \(M_V(\text{RR})\), completely neglecting the variation of the RR Ly luminosity with metallicity. Fahlman et al. (1990) identified Sgr main sequence stars in the background of the globular cluster M 55. They derived a range of distance moduli by fitting the sequence with theoretical isochrones under different assumptions on the age and metallicity of Sgr. However too few stars were present to obtain an accurate fit and the age and metallicity adopted are quite different from what currently assumed for the dominant population of Sgr (see Monaco et al. 2002 and references therein). The result presented here is largely free from the systematics affecting the above described analysis.

The most accurate determination of the distance to Sgr available up to now is the one provided by LS00, based on the RR Lyrae of the globular cluster M 54. M 54 resides in the densest clump of Sgr stars (Sarajedini & Lavden 1995, Monaco et al. 2004) and it is part of the Sgr galaxy. From the mean magnitude of the ab RR Lyrae of M 54, LS00 derived \((m-M)_0 = 17.19 \pm 0.12\) as distance to M 54 and, hence, to Sgr. In particular they measured a \(<V_0^{\text{RR}} > = 17.74 \pm 0.03\) and assumed \([\text{Fe/H}] = -1.79\) for M 54 from their previous photometric study (Sarajedini & Lavden 1995). Then by considering the \(M_V(\text{RR}) vs. \text{[Fe/H]}\) relation of Chaboyer (1999) they derived the distance modulus. The error in the distance modulus, 0.12, reflects the uncertainty in the zero point of the \(M_V(\text{RR}) vs. \text{[Fe/H]}\) relation.

However, the high-resolution spectroscopic study of M 54 stars by Brown, Wallerstein, & Gonzalez (1999) pro-
vides a mean metallicity for the cluster of $[Fe/H] = -1.55$. This metallicity corresponds to $M_V(RR) = 0.61 \pm 0.07$ if we consider the most recent (Hipparcos based) calibration of the $M_V(RR)$ vs. $[Fe/H]$ relation (see Clementini et al. 2003, and references therein). Under this assumptions, the LS00 estimate of $<V_o^{RR}>$ corresponds to $(m - M)_0 = 17.13 \pm 0.09$, in excellent agreement with our result.

The analysis of the effects of the adoption of our distance estimate on dynamical models of the disruption of Sgr is clearly out of the scope of the present paper. Just to provide an idea of the impact on some relevant scale we note that (a) assuming the integrated apparent magnitude of Sgr estimated by Majewski et al. (2003, hereafter M03, $V = 3.63$) and our distance modulus, we obtain $M_V \simeq 13.47$, e.g. an increase in luminosity of 20% with respect to the results of M03 that assumed $(m - M)_0 = 16.90$; (b) the distances to stars in the Sgr Stream estimated by M03 from the photometric parallax to M giants are expanded by 10% adopting our distance modulus.

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