The distance to the Leo I dwarf spheroidal galaxy from the Red Giant Branch Tip *

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\section*{ABSTRACT}

We present V and I photometry of a 9.4' × 9.4' field centered on the dwarf spheroidal galaxy Leo I. The I magnitude of the tip of the Red Giant Branch is robustly estimated from two different datasets (\(I_{\text{TRGB}} = 17.97^{+0.05}_{-0.03}\)). From this estimate, adopting \([M/H] \approx -1.2\) from the comparison of RGB stars with Galactic templates, we obtain a distance modulus \((m - M)_0 = 22.02 \pm 0.13\), corresponding to a distance \(D = 254^{+16}_{-19}\) Kpc.

\textbf{Key words:} stars: Population II - galaxies: distances and redshifts - Local Group

\section{INTRODUCTION}

Leo I is one of the brightest \((M_V = -11.9)\) dwarf spheroidal galaxies of the Local Group and is the most distant Galactic satellite presently known \((D = 250 \pm 30\) Kpc, according to Mateo 1998). Recent accurate studies based on HST photometry (Caputo et al. 1999; Gallart et al. 1999) have firmly established that the large majority of Leo I stars have an age comprised between 7-10 Gyr and 1 Gyr, but the dominance of intermediate-age population is known since the early CCD analyses (see Reid & Moni 1991; Lee et al. 1993a; Demers, Irwin & Gambui 1994, for an overview of pre-HST studies). The presence of (a sparse) old population \((\text{age} \gtrsim 10\) Gyr) has been confirmed only very recently, with the detection of Blue Horizontal Branch stars (Held et al. 2000) and RR Lyrae variables (Held et al. 2001). The available estimates of the mean metallicity range from \([Fe/H] = -2.1\) to \([Fe/H] = -1.0\) (see Caputo et al. 1994, for a review). The uncertainties are large but there is a general consensus on the metal-poor nature of the dominant stellar population.

Given its large distance from the Milky Way and its large radial velocity, this system has a crucial role in the estimate of the mass of the Galaxy at large radii (Zaritsky et al. 1994; Zaritsky et al. 1999) and of the Local Group as a whole, via the \textit{Local Group Timing} technique (Lynden-Bell 1999). The uncertainty on its actual distance is the major contributor to the error budget in this kind of studies (see Zaritsky 1999, Lynden-Bell 1999, for discussion and references).

In this paper we provide a new estimate of the distance to the Leo I galaxy using the Tip of the Red Giant Branch (TRGB) as a standard candle (see Lee et al. 1993a; Sakai, Madore & Freedman 1996; Madore & Freedman 1998; Salaris, Cassisi & Weiss 2003, for details and references about the method). We obtain a robust estimate of the apparent magnitude of the TRGB in the I passband and we derive the distance modulus of Leo I adopting our recent calibration of the method (Bellazzini, Ferraro & Pancino 2001; Bellazzini et al. 2004, hereafter B04) whose zero-point is fully independent from the RR-Lyrae distance scale (that is still affected by sizeable uncertainties, see Cacciari 1999; Walker 2003). The uncertainty on the final distance modulus is estimated by mean of a Monte Carlo simulation taking into account all the possible sources of error. This work is part of a large programme to obtain homogeneous distances for most of the galaxies of the Local Group (see Bellazzini et al. 2002; Galleti, Bellazzini & Ferraro 2004).

The plan of the paper is the following: in Sect. 2 we describe the observational material, the data reduction process, the artificial stars experiments, and we briefly discuss the Color Magnitude Diagrams; in Sect. 3 we report on the detection of the TRGB, and on our estimate of the distance modulus. Finally, the main results are summarized in Sect. 4.
2  OBSERVATIONS, DATA REDUCTION AND COLOR MAGNITUDE DIAGRAMS

The data were obtained at the 3.52 m Italian telescope TNG (Telescopio Nazionale Galileo - Roque de los Muchachos, La Palma, Canary Islands, Spain), using DoLoRes, a focal reducer imager/spectrograph equipped with a 2048 $\times$ 2048 pixels CCD array. The pixel scale is 0.275 arcsec/px, thus the total field of view of the camera is $9.4' \times 9.4'$. The observations were carried out during three nights (March 19, 20 and 21, 2001), under average seeing conditions ($FWHM \simeq 1.0'' - 1.4''$). The data have been acquired during the same observational run already described in Bellazzini et al. (2002): any further detail may be found in that paper.

We acquired five 300s exposures in I, and two 600 s and three 300s exposures in V, centered on the center of Leo I. All the raw images were corrected for bias and flat field, and the overscan region was trimmed using standard IRAF\footnote{IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.} procedures. Each set of five images (per filter) was registered, flux-normalized and combined into one single master frame using the tasks interp.csh and ref.csh of the ISIS-2.1 package (Alard 2000). ISIS is able to combine images into a master frame having the seeing of the best image in the set, without any loss of flux (Alard 2000). The PSF-fitting procedure was performed independently on each V and I master image, using a version of DoPhot (Schecter, Mateo & Sahai 1992) modified by P. Montegriffo at the Bologna Observatory to read images in double precision format. The frames were searched for sources adopting a 5-$\sigma$ threshold, and the spatial variations of the PSF were modeled with a quadratic polynomial. A final catalogue listing the instrumental V, I magnitudes for all the stars in each field has been obtained by cross-correlating the V and I catalogues. Only the sources classified as stars by the code have been retained. Aperture corrections have been determined on a sample of bright and isolated stars in each of the master frames and applied to the catalogues.

The transformation to the standard Johnson-Cousins photometric system has been achieved using the calibrating relation obtained and described in Bellazzini et al. (2002). The absolute calibration has been checked against independent photometries (Stetson 2000; Momany 2000) and it has been found to be accurate at the $\pm 0.02/0.03$ mag level (see Bellazzini et al. 2002).

Leo I is one of the best studied local dwarf spheroidals. Hence it is worth to check if there are other available datasets that may provide support to the present analysis. The search of the ESO archive has been successful. We retrieved from the ESO archive one V and one I 90 s frames centered on Leo I taken with the FORS 1 imager at the VLT-Antu telescope, at Cerro Paranal, Chile, on the night of December 2, 1999. The field of view is $6.7' \times 6.7'$ and the pixel scale is 0.200 arcsec/px. The images were taken under excellent seeing conditions ($FWHM \simeq 0.6''$). The images were reduced in the same way described above and were calibrated directly on the calibrated catalogues obtained from the TNG data. In the following we will refer to the TNG and VLT dataset as to the TNG sample and VLT sample, respectively.

2.1 Color-Magnitude Diagrams

The Color Magnitude Diagrams (CMD) of both the considered samples are displayed in Fig. 1. The two diagrams are very similar but the higher accuracy of the VLT relative photometry may be appreciated at a first glance, and it is probably due to the combination of the larger collecting area of the telescope and the much better seeing conditions. The morphology of the CMDs shown in Fig. 1 is fully consistent with those presented and described in previous studies (Reid & Mould 1991; Lee et al. 1993a; Demers, Irwin & Gamborini 1994; Caputo et al. 1999; Gallart et al. 1999; Held et al. 2001). The CMDs are dominated by the steep RGB of Leo I extending from the limiting magnitude to $I \simeq 18.0$. A handful of bright AGB stars (see Lee et al. 1993a; Menzies et al. 1994) are also present above this luminosity, in the range $1.2 \lesssim V - I \lesssim 3.0$. Among these stars we have marked with open circles (in the TNG sample) the carbon stars identified by Demers & Battinelli (2002). The compressed color scale of the CMDs, that has been adopted to include the reddest stars at $V - I \sim 3.0$, prevents a clear view of the Red Clump (RC) of Helium-burning stars that is quite evident in enlarged CMDs, peaking at $I \simeq 21.45$, slightly bluer than the

![Figure 1. I,V-I CMDs of Leo I obtained from TNG data (left panel) and VLT data (right panel). The characteristic photometric uncertainties are plotted in the two panels as errorbars aligned at $V - I = -0.2$. The open circles in the TNG CMD mark the carbon stars we have identified from Demers & Battinelli (2002).](image-url)
The completeness of the sam-
tometric errors are quite small and the degree of blending
shown in the lower panels of Fig. 2 confirms that the pho-
process of data reduction was repeated at any run.

crowding conditions) to the master frames and the whole
at a time to avoid any spurious modification of the actual

can not affect our analyses. The difference between input and output magnitudes as a function of $I_{out}$. The excess of stars in the half-part of the diagram of positive magnitude difference is due to blended stars that are recovered with as brighter sources with respect to their input counterparts.

The distance to the Leo I dwarf spheroidal galaxy

The use of Tip of the Red Giant Branch (TRGB) as a standard candle is now a mature and widely used tech-
nique to estimate the distance to galaxies of any mor-
phological type (see Lee et al. 1993a; Madore & Freedman
1995; 1998; Walker 2003, for a detailed description of the
method, recent reviews and applications). The underly-
ing physics is well understood (Madore & Freedman 1995;
Salaris, Cassisi & Weiss 2003) and the observational pro-
cedure is operationally well defined (Madore & Freedman
1995). The key observable is the sharp cut-off occurring
at the bright end of the RGB Luminosity Function (LF)
that can be easily detected with the application of an
dge-detector filter (Sobel filter; Madore & Freedman 1995;
Sakai, Madore & Freedman 1996) or by other (generally
parametric) techniques (see, for example; Mendez et al 2002;
McConnachie et al. 2004). The necessary condition for a
safe application of the technique is that the observed RGB
LF should be well populated, with more than $\sim$ 100 stars
within 1 mag from the TRGB (Madore & Freedman 1995;
Bellazzini et al. 2003). This criterion is clearly fulfilled in
the present analysis since there are $N_s = 346$ and $N_a = 298$
stars within one magnitude from the detected TRGB in the
TNG and VLT samples, respectively.

The detection of the TRGB is displayed in Fig. 3 and
4 for the TNG sample and the VLT sample, respectively. In
both cases, the cut-off of the RGB LF is clearly evident
and it is easily detected by the Sobel’s filter. We take the position
of the main peak of the filter response as our estimate of
$I_{TRGB}$ and the Half Width at Half Maximum of the peak
as the associated uncertainty ($I_{TRGB} = 17.98 \pm 0.09$
for the TNG sample, and $I_{TRGB} = 17.97 \pm 0.06$
for the VLT sample). The higher photometric precision of the VLT sample allows
a more accurate location of the Tip, with respect to the TNG
sample. As our final estimate we take the weighted mean of
the two detections, $I_{TRGB} = 17.97 \pm 0.03$.

Our estimate of $I_{TRGB}$ is in excellent agreement with
the results by Momany (2000) and (Caputo et al. 1994). The
estimate by Lee et al (1993a) $I_{TRGB} = 18.25 \pm 0.10$ is
$\sim 1.9\sigma$ larger than our value. Part of the difference may
be due to insufficient sampling of the RGB LF, since their
field is significantly smaller than ours ($5.7' \times 5.7'$, 2.6 times
smaller than the TNG field and 1.4 times smaller than the
VLT field). This conclusion is also supported by the
comparison with Mendez et al (2002) which states that in
their $5.5' \times 7.3'$ field they barely collect 100 RGB stars
in the upper 1 mag from the TRGB. These authors find
$I_{TRGB} = 18.14 \pm 0.11$, within one $\sigma$ of our estimate, but still
appreciably fainter. Also in this case, problems of sampling
and/or of absolute photometric calibration may be at the
origin of the difference with our result. We regard our result
as the most robust since (a) the sampling of the upper-RGB
LF is excellent in both datasets and, (b) our photometric
 calibration has been successfully compared with various in-
dependent photometries.

3 THE DISTANCE TO LEO I

3.1 Detection of the TRGB

RGB sequence at that magnitude. The sparse plume of stars
around $I \sim 20$ and $0.0 \lesssim V - I \lesssim 0.8$ has been identified
by Caputo et al. (1999) as the high-mass tail of He-burning
stars of Leo I.

2.2 Artificial Stars Experiments

To quantify the effects of the data reduction process on our
photometry we performed a set of artificial stars experiments
on the TNG dataset. We followed exactly the procedure de-
scribed in Bellazzini et al. (2002) and we refer the interested
reader to that paper for any detail. The artificial stars were
extracted from a LF similar to the observed one, with the
additional requirement that they must lie on the average
ridge line representing the observed RGB (see Fig. 2, up-
per left panel). We limited the artificial stars experiments
to RGB stars with $I \leq 21.0$. The stars were added ($\sim 100$
at a time to avoid any spurious modification of the actual
crowding conditions) to the master frames and the whole
process of data reduction was repeated at any run.

The difference between input and output magnitudes
shown in the lower panels of Fig. 2 confirms that the pho-
tometric errors are quite small and the degree of blending
cannot affect our analyses. The completeness of the sam-
ple (not shown) is larger than 80% in the whole range of
magnitude considered by our experiments.
3.2 The distance modulus of Leo I

To obtain the distance modulus of Leo I we adopt the calibration of \( M_{TRGB} \) as a function of the global metallicity \((M/H)\) recently provided by Bellazzini et al. (2004)

\[
M_{TRGB} = 0.258[M/H]^2 + 0.676[M/H] - 3.629 \pm 0.12
\]  

The global metallicity includes the contribution of Iron and the α-elements (O, Mg, Ti, Si, etc.), hence it is a more suitable indicator of the global metal content to relate with the observed properties of stars and stellar populations and for comparisons with theoretical models (see Salaris, Chieffi & Straniero 1993; Ferraro et al. 1999; Bellazzini et al. 2004, for discussion and references). The parameter is defined as

\[
[M/H] = \log([Fe/H] + log(0.638 \times [\alpha/Fe] + 0.362)
\]  

Salaris, Chieffi & Straniero (1993). We also adopt \( E(B-V) = 0.01 \pm 0.01 \) according to Mateo (1998) and \( A_I = 1.76E(B-V) \), according to Dean, Warren & Cousins (1978).

At the mean metallicity \( [M/H] = -1.2 \) (as derived in Sect. 3.3, below), the resulting distance modulus is \( (m-M)_0 = 22.02 \).

This estimate is affected by the combination of uncertainties coming from different sources, i.e. the estimate of apparent magnitude of the TRGB, the calibrating relations, the reddening and the assumed global metallicity. To properly account for all these uncertainty factors we recur to a Monte Carlo simulation. We compute the final true distance modulus (and its uncertainty) as the mean (and standard deviation) of 100000 random realizations of the \( (m-M)_0 \) estimate obtained by allowing all the relevant ingredients to vary within their error bars. In particular:

- The apparent TRGB magnitude was randomly extracted from two gaussian distributions with mean equal to the observed value. 50000 positive deviations were extracted from a gaussian with \( \sigma = 0.05 \) and 50000 negative deviations were extracted from a gaussian with \( \sigma = 0.03 \). To account for the uncertainty in the absolute photometric calibration we add to each realization of \( I_{TRGB} \) a component extracted from a gaussian distribution having zero mean and \( \sigma = 0.02 \) mag.
- We added to the absolute TRGB magnitude (from the calibrating relation by B04) a random component extracted from a gaussian distribution having zero mean and standard deviation equal to the uncertainty of the zero point of the calibrations as estimated by B04, i.e. \( \sigma = 0.12 \).
- The reddening values were extracted from a gaussian distribution with mean \( E(B-V) = 0.01 \) and \( \sigma_E(B-V) = 0.02 \) to account also for slightly different reddening estimates found in literature (for instance the reddening maps by Schlegel, Finkbeiner & Davis 1998, suggests E(B-V)=0.03). Negative values of the reddening are excluded from the simulation.
- The adopted metallicity values were extracted from a gaussian distribution with mean \( [M/H] = -1.2 \) and \( \sigma = 0.2 \).

For each simulated point \( (m-M)_0 \) was computed from the randomly extracted \( I_{TRGB} \), \( M_{TRGB} \), \( E(B-V) \) and \( [M/H] \). Finally, the mean \( <(m-M)_0> \) and \( \sigma \) of the 100000 realizations was obtained: \( (m-M)_0 = 22.02 \pm 0.13 \), corre-
the dependence of ever this is not a reason of serious concern for the present
the mean metallicity of Leo I. The age difference between $[\text{Fe}/\text{H}]$
Magnitude distribution is well represented by the ridge lines
Bellazzini et al. (2003). It is immediately clear that the bulk of Leo I RGB stars is enclosed within the ridge lines of NGC 6341 and NGC 5904.

result is in excellent agreement with the value tabulated in
Our result is broadly consistent with all previous photometric estimates of the mean metallicity of Leo I, all in the ZW scale. In terms of mean/median metallicity our estimation lie between the extremes provided by (1991) $(\text{[Fe}/\text{H}]_{ZW} = -1.6 \pm 0.3)$ and (1993) $(\text{[Fe}/\text{H}]_{ZW} = -2.1 \pm 0.1)$, in good agreement with the low-resolution spectral analysis by Suntzeff et al. (1984) and its revision reported by (1993) $(\text{[Fe}/\text{H}]_{ZW} \sim -1.8$, from 2 red giants) and, finally, in excellent agreement with Demers, Irwin & Gambui (1994) who finds $[\text{Fe}/\text{H}]_{ZW} = -1.6 \pm 0.4$

reported the first detailed abundance analysis of two Leo I red giants, based on high resolution spectroscopy (hence, presumably, in a scale equivalent to the CG one). They find $[\text{Fe}/\text{H}] = -1.5$ and $[\text{Fe}/\text{H}] = -1.1$ for the two considered stars. It is interesting to note that the same authors provide also an estimate of the $[\alpha/\text{Fe}]$ ratio for these stars, i.e. $[\alpha/\text{Fe}] \approx +0.05$ and $[\alpha/\text{Fe}] \approx 0.0$, respectively. From these values, using Eq. 2, we find that both stars have $[\text{M}/\text{H}] = -1.1$, in excellent agreement with our estimate.

4 CONCLUSIONS
We have provided a clean and accurate detection of the magnitude of the TRGB of Leo I from two independent datasets, tied to the same (well checked) photometric calibration. Adopting the median metallicity we derived from the same data with templates RGB ridge lines, and the calibration of $M_{\text{TRGB}}$ as a function of the global metallicity $(\text{[M}/\text{H}]$) provided by (2001) we have obtained a new estimate of the distance modulus of Leo I, $(m - M)_0 = 22.02 \pm 0.13$, corresponding to a distance $D = 254^{+16}_{-19} \text{Kpc}$.

The effects of all the possible sources of uncertainty have been taken into account by means of Monte Carlo simulations. The obtained distance modulus is in good agreement with the most recent distance estimates for this galaxy but it reduces the uncertainty by a factor $\sim 2$, with respect to previous applications of the TRGB method.

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