The Red Giant Branch Tip and Bump of the Leo II dwarf spheroidal galaxy

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1 INTRODUCTION

Leo II (Harrington & Wilson 1954) is one of the most distant dwarf spheroidal (dSph) satellites of the Milky Way ($D \approx 205$ Kpc, according to Mateo 1998). From deep HST photometry (Mighell & Rich 1996) determined a mean age of $9 \pm 1$ Gyr for the main stellar population of this galaxy, with a Star Formation History (SFH) started $\approx 14$ Gyr ago and lasted for $\approx 7$ Gyr. According to these authors, after this epoch the SF in Leo II has been very low and, at most, sporadic (see also Bosler et al. 2004) that reached similar conclusions following a different path. The presence of a significant fraction of old stars (e.g., age $\gtrsim 10$ Gyr) in this galaxy is witnessed by a conspicuous population of RR Lyrae variables (see Siegel & Majewski 2003 and references therein) and Blue Horizontal Branch (BHB) stars (Demers & Irwin 1993, Mighell & Rich 1996).

The observed color of the Red Giant Branch (RGB) is typical of a metal poor population, and most of the existing photometric studies (Demers & Harris 1983; Lee 1995; Demers & Irwin 1993) agree in deriving an average metallicity $[\text{Fe}/\text{H}] \approx -1.9$ in the Zinn & West (1984) hereafter ZW) metallicity scale, with a metallicity dispersion of $\approx 0.3$ dex, while Mighell & Rich (1996) obtained $[\text{Fe}/\text{H}] \approx -1.6$. During a recent low-resolution spectroscopic survey, Bosler et al. (2004) determined the metallicity of 41 RGB stars in Leo II, in the Carretta & Gratton (1997, hereafter CG) metallicity scale. The metallicity of the stars studied by Bosler et al. (2004) ranges from $[\text{Fe}/\text{H}]_{CG} = -2.32$ to $[\text{Fe}/\text{H}]_{CG} = -1.26$; the average metallicity is $\langle [\text{Fe}/\text{H}]_{CG} \rangle = -1.57$, in good agreement with the photometric estimates described above, once the differences in the metallicity scales are taken into account. A global mass-to-light ratio $M/L \approx 11.1 \pm 3.8$ (Vogt et al. 1993) suggests that the Dark Matter (DM) is the main contributor to the total mass of the galaxy, as in most of the other dSphs of the Local Group.

As a part of a large programme aimed at obtaining homogeneous distances for most of the galaxies of the Local Group (see Bellazzini et al. 2002; Galleti, Bellazzini & Ferraro 2003; Bellazzini et al. 2004a, Monaco et al. 2004), we present here the results of the V,I photometry (reaching $V \approx 23$) of a $9.4' \times 9.4'$ field centered on Leo II. We provide a new estimate of the distance to this galaxy using the Tip of the Red Giant Branch (TRGB) as a standard candle (see Lee et al. 1993a; Sakai, Madore & Freedman 1998).
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 x 2048 pixels CCD array. The pixel scale is 0.275 arcsec/pix. The observations were carried out during three nights (March 19, 20 and 21, 2001), under average seeing conditions (FWHM ≃ 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 those papers.

We acquired five exposures in I (two with $t_{ex} = 600\ s$, and three with $t_{ex} = 300\ s$), and eight exposures in V (two with $t_{ex} = 600\ s$, and six with $t_{ex} = 300\ s$), centered on the center of Leo II. 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 images was registered, flux-normalized and combined into one single master frame (per filter) using the tasks interp.csh and ref.csh of the ISIS-2.1 package (Alard 1999). 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 1999, 2004\footnote{See also the on-line tutorial \url{http://www2.iap.fr/users/alard/tut.html} for details and references about the method}).

The PSF-fitting procedure was performed independently on each V and I master image, using a version of DoPhot (Schechter, Mateo & Sahia 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-σ threshold, and the spatial variations of the PSF were modeled with a quadratic polynomial. The adopted threshold corresponds to the limiting magnitudes $I \simeq 22.2$ and $V \simeq 23.2$. 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 ±0.02 mag level (see Bellazzini et al. 2002). The astrometric solution to transform the original reference frame (X,Y in pixels) to equatorial coordinates at the 2000.0 Equinox have been obtained from 58 stars in common with the GSC2.2 catalogue\footnote{See \url{http://www-gsss.stsci.edu/gsc/gsc2/GSC2home.htm} for further details (from 58 stars in common with the GSC2.2 catalogue\footnote{See \url{http://www-gsss.stsci.edu/gsc/gsc2/GSC2home.htm} for further details} and 111 RR Lyrae and 2 anomalous cepheids from the catalog of Siegel & Majewski (2000). The final catalogue is available in electronic form from the CDS.

$$E(B-V) = 0.02 \pm 0.01$$, according to Mateo (1998) (and in agreement with Schlegel, Finkbeiner & Davis (1998) and $A_r = 1.76 E(B-V)$, according to Dean, Warren & Cousins (1978), are adopted throughout the following analysis.

2.1 Color-Magnitude Diagram

The Color Magnitude Diagram (CMD) obtained from our catalogue is displayed in Fig. 1. The morphology of the CMD is fully consistent with those presented and described in previous studies that attained sufficiently deep and accurate photometry to unveil the morphology of the entire Horizontal Branch (Demers & Irwin 1993; Mighell & Rich 1993; Momany 2000).

The CMD is dominated by the steep RGB of Leo II and three with $t_{ex} = 300\ s$), 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 images was registered, flux-normalized and combined into one single master frame (per filter) using the tasks interp.csh and ref.csh of the ISIS-2.1 package (Alard 1999). 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 1999, 2004\footnote{See also the on-line tutorial \url{http://www2.iap.fr/users/alard/tut.html} for details and references about the method}).

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The CMD is dominated by the steep RGB of Leo II
extending from the limiting magnitude to $I \approx 17.8$. A handful of bright AGB stars, most of which are also detected in the infrared by 2MASS (marked by open circles in Fig. 1), are also present at $I < 18.0$ and $V - I \geq 1.4$. Most of the identified carbon stars are included in this family. The star detected by 2MASS at $I \approx 19.0$ and $V - I \approx 1.4$ may be an unknown carbon star but a check of the membership should be performed to obtain a firm classification. This star has $J - K \approx 1.2$, similar to that of the recognized carbon stars.

The majority of He-burning stars are clustered in a Red Clump around $I \approx 21.3$ and $V - I \approx 0.9$, but a significant number of RR Lyrae is also present and a sparse tail of BHB stars is clearly visible at $V - I \leq 0.4$. The sparse plume of stars between $I \approx 21$ and $I \approx 19.5$, at $V - I \approx 0.8$ probably hosts the high-mass tail of He-burning stars of the galaxy. One of the two Anomalous Cepheid contained in our catalogue lies at the tip of this feature, in agreement with the above hypothesis. According to the Galactic model by Robin et al. (2003) the total number of foreground Milky Way stars sampled by our field in the color and magnitude ranges displayed in Fig. 1 is $\sim 21$, with only three foreground stars falling into the region of the CMD populated by the above described plume.

2.1.1 A new RR Lyrae variable

The package we used to produce the above described master frames (ISIS Alard 1999) is aimed at the search of variable stars by mean of a very efficient image subtraction technique (see, for example, Cacciari, Bellazzini & Colucci 2002; Kaluzny et al. 2001; Clementini et al. 2004). Just to verify the performance of the code in difficult conditions (i.e., very sparse time series and typical target just $\sim 1$ mag brighter than the limiting magnitude of the photometry) we applied the whole image subtraction process to the eight $V$ images from which we obtained our master frame. We identified a list of 14 bona-fide variables with detected variations larger than 0.1 mag in the considered lapse of time. Thirteen of them were variables included in the catalogue of Siegel & Majewski (2000). 12 ab type RR Lyrae and 1 RRc. The fourteenth identified variable is not included in Siegel et al.’s catalogue but the partial light curve we obtained (Fig. 2, upper panel) indicates that it is a real variable star. The large amplitude ($> 0.5$ mag) and its position in the CMD (shown in the lower panel of Fig. 2) suggest a preliminary classification as a RRab. Following the numbering by Siegel & Majewski (2000) we dub this variable V173. Its coordinates are $(RA_{2000}; Dec_{2000}) = (11^h 13^m 23.7^s; 22^\circ 07' 21.7'')$.

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. We followed exactly the procedure described 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. We limited the artificial stars experiments to RGB stars with $I \leq 22.0$. 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. A total of \( \gtrsim 10^4 \) artificial stars have been added and processed on the V and I master frames.

The difference between input and output magnitudes, shown in the upper panels of Fig. 3, confirms that the photometric errors are quite small and the degree of blending cannot affect our analyses. The total completeness of the sample (Fig. 3, lower panels) is larger than 80\% for \( I(V) \lesssim 20.0(21.0) \) and drops below 50\% for \( I(V) \gtrsim 21.0(22.0) \). The increasing of stellar crowding toward the center of the galaxy produces a significant radial variation of the completeness. The two curves plotted in the lower panels of Fig. 3 show the behaviour of \( C_f(V) \) and \( C_f(I) \) in the regions within 3’ from the center (filled circles) and outside 3’ from the center (empty circles). The spatial variation of the completeness cannot affect any of the results and analyses reported in the following, with the only possible exception of the radial population gradient presented in Sect. 5, below (see the same Sect. 5 for discussion).

3 THE DISTANCE TO LEO II

3.1 Detection of the TRGB

The use of Tip of the Red Giant Branch (TRGB) as a standard candle is now a mature and widely used technique to estimate the distance to galaxies of any morphological type (see Lee et al. 1993, Madore & Freedman 1995, 1998, Walker 2003 for a detailed description of the method, recent reviews and applications). The underlying physics is well understood (Madore & Freedman 1998, Salaris, Cassisi & Weiss 2003) and the observational procedure 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 edge-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. 2002). The present sample is at the limit of this requirement, having \( N_\star = 106 \) stars within one magnitude from the detected TRGB (see below). In Sect. 3.3 we will provide additional evidence supporting the robustness of our TRGB detection.

The detection of the TRGB is displayed in Fig. 4. The cut-off of the RGB LF is clearly evident and it is easily detected by the Sobel’s filter at \( I^{\text{TRGB}} = 17.83 \pm 0.03 \), where the reported uncertainty is the Half Width at Half Maximum of the peak of the filter response. The only previous published estimate of \( I^{\text{TRGB}} \) for Leo II is from Lee (1995, hereafter L95) who found \( I^{\text{TRGB}} = 17.7 \pm 0.2 \). While formally consistent with our measure, within the errors, the CMD shown in the left panel of Fig. 4 suggests that the TRGB level identified by L95 is too bright, probably due to the influence of the AGB population on his
LF. In this regard, it has to be considered that our field cover an area that is double with respect to L95 and that our sample collects 30% more stars than that of L95, down to \( I = 22.0 \).

### 3.2 Metallicity

In Fig. 5 the observed RGB of Leo II is compared with the template ridge lines of the globular clusters NGC 6341, NGC 6205 and NGC 288, taken from the set adopted by Bellazzini et al. (2003). It is immediately clear that the bulk of Leo II RGB stars is enclosed within the ridge lines of NGC 6341 ([Fe/H]_{CG} = −2.16; [Fe/H]_{ZW} = −2.24; [M/H] = −1.95) and of NGC 6205 ([Fe/H]_{CG} = −1.39; [Fe/H]_{ZW} = −1.65; [M/H] = −1.18)^4.

We derived individual photometric estimates of the metallicity in the different scales for 165 RGB stars having \( M_I < −2.5 \) by interpolating on the grid of templates, as done in Bellazzini et al. (2002, 2003) and Galleti, Bellazzini & Ferraro (2004). From the obtained distributions we derived robust estimates of the average metallicity and of the standard deviation. The median and the average of all the considered distributions differ by just \( \lesssim 0.03 \) dex, indicating that the average values are not driven by few outlier points but are truly representative of the bulk of the distributions. The final estimates of the mean metallicity and of the distance modulus (see Sect. 3.3, below) have been obtained by an iterative process, adopting \( M_I^{\text{TRGB}} = −4.05 \) as initial guess (see Galleti, Bellazzini & Ferraro 2004). The process converged immediately to the final values because the dependence of \( M_I^{\text{TRGB}} \) on metallicity is essentially null in the range of metallicity around \([M/H] \sim −1.5\). In the following of this section we shortly compare our average metallicities with previous estimates found in the literature.

- **ZW scale:** we obtain \( \langle [\text{Fe}/H]_{ZW} \rangle = −1.91 \) and \( \sigma = 0.22 \) dex in excellent agreement with Lee (1995); Demers & Irwin (1993) and Siegel & Majewski (2000). The agreement with Mighell & Rich (1996) is less satisfying but the difference of their estimate to all the others (0.3 dex) is not a reason of serious concern. Moreover, these authors sampled the very central region of the galaxy, where the average metallicity of the stars may be intrinsically higher with respect to outer regions (see Sect. 5, below).

- **CG scale:** we obtain \( \langle [\text{Fe}/H]_{CG} \rangle = −1.74 \) and \( \sigma = 0.30 \) dex, within 0.2 dex of the spectroscopic estimate by Bolster et al. (2004). Our metallicity distribution is also broadly similar to that obtained by these authors (for instance, the range is −2.4 \( \lesssim [\text{Fe}/H]_{CG} \lesssim −1.2 \) while Bolster et al. find −2.32 \( \lesssim [\text{Fe}/H]_{CG} \lesssim −1.26 \)), suggesting that our photometric metallicities are quite reliable in the present case.

- **Global metallicity scale:** \( \langle [M/H] \rangle \approx −1.53 \) and \( \sigma = 0.30 \) dex.

\(^4\) [M/H] is the **global metallicity**, a parameter that includes the contribution of Iron and of 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, e.g., Salari, Chieffi & Straniero 1992; Ferraro et al. 1992; Bellazzini et al. 2004a,b; for discussion and references).

#### 3.3 The distance modulus of Leo I

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

\[
M_I^{\text{TRGB}} = 0.258[M/H]^2 + 0.676[M/H] − 3.629 \pm 0.12 \tag{1}
\]

At the mean metallicity \([M/H] = −1.53\) (as derived in Sect. 3.2, above), the resulting distance modulus is \((m − M)_0 = 21.84\). This estimate is affected by the combination of uncertainties coming from different sources, i.e.: the estimate of apparent magnitude of the TRGB (\(σ = 0.03\) mag, plus the \(σ = 0.02\) mag uncertainty on the zero-point of the absolute photometric calibration), the calibration relation (\(σ = 0.12\) mag, see Bellazzini et al. 2004a), the reddening (\(σ = 0.01\) mag), and the assumed global metallicity (\(σ = 0.3\) dex). Properly propagating all these uncertainties we finally obtain \((m − M)_0 = 21.84 ± 0.13\), corresponding to a heliocentric distance \(D = 233 ± 15\) Kpc.

This result is consistent with all previous estimates within the uncertainties quoted by the various authors, typically \(±0.2\) mag, but is outside of their formal range \(21.55 \lesssim (m − M)_0 \lesssim 21.78\). However it has to be considered...
that (a) all previously determined distance moduli are tied to different RR Lyrae-based distance scales and (b) the uncertainty in the absolute magnitude of the adopted standard candle was taken as null in all cases. Hence (a) part of the difference may be due to systematic differences between the adopted distance scales and (b) the true $1 - \sigma$ uncertainties of previous estimates should be of order $\pm 0.25/0.3$ mag, to compare with our $\pm 0.13$ which includes all the possible sources of errors.

As said in Sect. 3.1, the number of bright RGB stars of Leo II contained in our sample is just above the limit for a safe detection of the TRGB. To verify the robustness of the above derived distance modulus to sampling effects we compare the luminosity of the BHB of Leo II with that of the cluster that provide the fundamental zero-point of our calibration of the TRGB method (e.g. $\omega$ Centauri, see Bellazzini, Ferraro & Pancino 2001; Bellazzini et al. 2004a). For a favorable circumstance the metallicity of the main population of $\omega$ Cen ($[M/H] \simeq -1.4$, see Sollima et al. 2004) is very similar to the average metallicity of Leo II. In the upper panel of Fig. 6 we show the ridge line of the mean level of the BHB of Leo II (continuous line) as well a the lines enclosing the whole BHB distribution (dotted lines). In the lower panel of Fig. 6 these ridge lines are compared to the observed BHB of $\omega$ Cen (from Pancino et al. 2004), adopting $(m-M)_{B}^{\omega \text{Cen}} = 13.70$, $E(B-V)^{\omega \text{Cen}} = 0.11$, according to Bellazzini et al. (2004a). It can be readily appreciated that the TRGB distance modulus carries the HBs of Leo II and $\omega$ Cen essentially to a perfect match, providing further support to the reliability of our distance estimate.

4 THE RGB BUMP(S)

The RGB bump is the effect of a well known phase of the RGB evolution of low mass stars (see Iben 1963; Fusi Pecci et al. 1990, and references therein). When the H-burning shell of a RGB star encounters the chemical discontinuity left behind by the maximum penetration of the convective envelope, the luminosity of the star has a slight drop. When the shell adapts at the new environment the luminosity grows again, but at a different pace than before. As a result the stars pile-up at this stage, producing a bump in the RGB LF and the slope of the LF changes above the bump, because of the change in the evolutionary rate. The RGB bump has been extensively studied in globular clusters (see Fusi Pecci et al. 1990; Zoccali et al. 1999; Ferraro et al. 1999 - hereafter F99 - and references therein), but it has been detected in dwarf galaxies only in recent times (Majewski et al.1999, Bellazzini et al. 2001, 2002; Monaco et al. 2002; Lee et al. 2003, Monaco et al. 2002 and Bellazzini 2004) provided direct evidence that significant constraints on the age and metal content of dSph galaxies can be obtained from the study of this observational feature.

Majewski et al. (1999) and Bellazzini et al. (2001) interpreted the detection of two bumps on the RGB LF as indication of the presence of two distinct populations in Sculptor and Sextans, respectively. A preliminary detection of a double RGB bump in Leo II, from the same dataset studied here, has been presented in Bellazzini (2004). Lee et al. (2003) argued against this interpretation, proposing that the brightest of the two bumps found in these galaxies is due to the AGB clump instead Gallart & Bertelli 1995).

In the attempt of minimizing the effects of any possible AGB Clump on the RGB LF we carefully selected our sample of RGB stars. The adopted selection is shown in the upper-right panel of Fig. 7. Note that the sparse cluster of stars located at $V \simeq 21.3$ and $V - I \simeq 0.9$ that may be identified with the AGB clump of the main population of Leo II has been excluded from the selection, as well as the bluest stars of the whole sequence, which may presumably have the highest degree of contamination from AGB stars. In spite of that, the right-panels of Fig. 7 show that two significant bumps are detected on the RGB of Leo II. The main bump (B1) is at $V_{\text{bump}} = 21.76 \pm 0.05$, the less pronounced one (B2) is at $V_{\text{bump}} = 21.35 \pm 0.05$. While B1 can be straightforwardly interpreted as the RGB bump of the dominant stellar population of Leo II, the nature of B2 is more uncertain. We combined Eq. 7 and Eq. 6.6 of F99 (obtained from well studied galactic globulars) to derive a relation for the difference in V magnitude of the AGB clump and the RGB Bump ($\Delta V_{\text{bump}}^{\text{AGB}}$) as a function of the global metallicity:

$$\Delta V_{\text{bump}}^{\text{AGB}} = -0.360[M/H]^2 - 1.772[M/H] - 2.283 \pm 0.09. \quad (2)$$

The difference in magnitude between B2 and B1 ($\Delta V_{B2-B1} = -0.41 \pm 0.07$) is in excellent agreement with the predictions of Eq. 2 for $[M/H] \simeq -1.5$, i.e. $\Delta V_{\text{bump}}^{\text{AGB}}$
−0.43±0.09\(^5\). This result seems to favor the interpretation of B2 as a feature associated with the AGB clump of the same population that generated the RGB bump B1. On the other hand, as shown in Fig. 7, our RGB selection should have removed most of the AGB clump stars from the considered sample. Hence the possibility that B2 is a genuine secondary RGB Bump cannot be excluded at the present stage. Given this uncertain interpretation we drop any further discussion of B2 in the following analysis, which is focused on B1 instead. Larger photometric samples and dedicated theoretical modeling of the luminosity functions in the AGB phase are needed to achieve a clearer view of the problem of double bumps in the context of composite stellar populations.

In the lower-left panel of Fig. 7 we compare the absolute V magnitude of B1 with three isochrones in the \(M_V\) vs. \([M/H]\) plane obtained from Eq. 3 of F99 (see Monaco et al. 2002; Bellazzini 2004). According to F99, the bulk of the Galactic globular clusters is comprised between the 16 Gyr and the 12 Gyr isochrones, in this plane. Hence, the position of B1 indicates that the main population of Leo II is more than 4 Gyr younger than the typical Galactic globular, in excellent agreement with the results of Mighell & Rich (1996), obtained from the analysis of the Main Sequence Turn Off (MSTO) of Leo II. The inclusion in the plot of the main RGB bump of \(\omega\) Cen (see S04) provides again a real case to compare with: the difference in \(M_V\) between this cluster and Leo II(B1) is at the \(\geq 2 - \sigma\) level. It has to be recalled that the age difference between the Main Population (MP) of Leo II and classical globular clusters would be lower than what read from the lower-left panel of Fig. 7 if the Helium abundance of Leo II - MP is higher than that of the clusters (see S04 and references therein).

5 A POPULATION GRADIENT IN LEO II

Population gradients are a common feature in dSph galaxies (see Harbeck et al. 2001, hereafter H01 - and references therein). In all the cases in which a radial gradient has been found, the sense is invariably that the most metal-rich/young populations are more centrally concentrated than the metal-poor/older ones. Since the HB is the evolutionary phase in which low-mass stars display the maximum sensitivity to metallicity and age (as well as to a number of other physical parameters, see Fusi Pecci et al. 1993), in most cases the gradients have been detected using HB stars as tracers (H01; Bellazzini et al. 2002).

In Fig. 8 the cumulative radial distributions of Red Clump (RC) stars and of BHB+RR Ly stars are compared. The plot shows that the usual kind of radial gradient is present also in Leo II: RC stars are significantly more centrally concentrated the BHB+RR Ly stars. A Kolmogorov-Smirnov test quantify the probability that the two samples are extracted from the same parent radial distribution - according to a Kolmogorov-Smirnov test - is reported in the lower right angle of the plot.

![Figure 8. Cumulative radial distributions of Red Clump stars (continuous line), RR Lyrae and Blue Horizontal Branch stars (dotted line), and RGB stars fainter than the RC (long dashed line, adopted as a control sample). The probability that the samples are extracted from the same parent radial distribution - according to a Kolmogorov-Smirnov test - is reported in the lower right angle of the plot.](image)

\(^5\) At odds with the results of the preliminary analysis shown in Bellazzini (2004), the difference is entirely due to the fact that in that analysis we assumed \([M/H] \simeq -1.7\), instead of \([M/H] \simeq -1.5\), as adopted here.

In I, hence the BHB+RR Ly sample may be slightly less complete than the RC one. Is it possible that this fact, coupled with the radial variation of the completeness discussed in Sect. 2.2, has originated a spurious difference in the distribution of BHB+RR Ly and RC stars? To test this hypothesis we plot in Fig. 8 also the distribution of RGB stars fainter than the RC (Faint RGB). Note that this sample should be less complete than the BHB+RR Ly one since its members are fainter in V while having I magnitudes similar to BHB+RR Ly. Hence, if the detected population gradient is due to the radial variations of the completeness, the Faint RGB sample should display a radial distribution even more extended than the BHB+RR Ly. Fig. 8 shows that this is not the case: the distribution of Faint RGBs is much more similar to that of RC stars than to the distribution of BHB+RR Ly. Therefore, the observed difference between the radial distributions of RC and BHB+RR Ly stars is not due to completeness effects but it traces a real population gradient.

It is very likely that both age and metallicity variations are at the origin of the effect. However, since RC stars dominates the HB population of Leo II it is reasonable to associate them with the main population of the galaxy, whose mean age is \(\simeq 9\) Gyr, according to Mighell & Rich (1996), while RR Lyrae and BHB stars should be associated with older populations (up to age=14 Gyr) Mighell & Rich (1996). In this framework the age would be the main driver of the gradient.
6 CONCLUSIONS

We have provided a clean and accurate detection of the I magnitude of the TRGB of Leo II. Adopting the average metallicity we derived from the same data by comparison with templates RGB ridge lines, and the calibration of $M^I_{TRGB}$ as a function of the global metallicity ($[M/H]$) provided by Bellazzini et al. (2004a) we have obtained a new estimate of the distance modulus of Leo II, $(m-M)_0 = 21.84 \pm 0.13$, corresponding to a distance $D = 233 \pm 15$ Kpc.

The effects of all the possible sources of uncertainty have been taken into account.

Two significant bumps have been detected in the LF of the RGB of Leo II. The fainter bump (B1) has been identified as the RGB bump of the main population of the galaxy, while the brighter one (B2) may be due to stars belonging to the AGB clump of the same population or may be a secondary RGB bump, associated with another population of the galaxy. The luminosity of the main bump (B1) indicates that the main population of Leo II is several ($\gtrsim 4$) Gyr.
younger than the typical Galactic globular clusters, in good agreement with the estimates obtained from the photometry of the MSTO by Mighell & Rich (1996). This result suggests that useful indications on the age may be obtained from the RGB bump also for distant stellar systems whose MSTO is out of the reach of currently available telescopes (see also Monaco et al. 2002, Bellazzini 2004).

A significant population gradient has been detected for the first time in this galaxy: the BHB and RR Lyrae stars have a more extended radial distribution with respect to stars in the Red Clump. Age differences are proposed as the main driver of the observed gradient.

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