THE DRACO AND URSA MINOR DWARF SPHEROIDAL GALAXIES: A COMPARATIVE STUDY

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ABSTRACT
We present ($V, I$) photometry of two wide ($\simeq 25 \times 25$ arcmin$^2$) fields centered on the low surface brightness dwarf spheroidal galaxies Draco and Ursa Minor. New estimates of the distance to these galaxies are provided ($M_{\odot}(\text{UMi}) = 19.41 \pm 0.12 \text{ and } M_{\odot}(\text{Dra}) = 19.84 \pm 0.14$), and a comparative study of their evolved stellar population is presented. We detect for the first time the red giant branch (RGB) bump in the luminosity function of UMi ($V_{\text{bump}} = 19.40 \pm 0.06$), while the feature is not detected in Draco. Photometric metallicity distributions are obtained for the two galaxies, and an accurate analysis to determine the intrinsic metallicity spread is performed by means of artificial star experiments. The adopted method is insensitive to stars more metal poor than [Fe/H] $\sim -2.5$, and it rests on the assumption that the age spread in the considered populations is small (i.e., the impact of the actual age spread on the colors of the RGB stars is negligible). We find that while the average metallicity of the two galaxies is similar ([Fe/H]$_{\text{UMi}} = -1.8$ and [Fe/H]$_{\text{Dra}} = -1.7$), the metallicity distributions are significantly different, having different peak values ([Fe/H]$^{\text{mod}}_{\text{UMi}} = -1.9$ and [Fe/H]$^{\text{mod}}_{\text{Dra}} = -1.6$) and different maximum metallicities. We suggest that such differences may be partly responsible for the difference in horizontal-branch morphology between the two galaxies. The intrinsic metallicity 1 $\sigma$ spread is $\sigma_i = 0.10$ in UMi and $\sigma_i = 0.13$ in Draco. We demonstrate that the inner region of UMi is significantly structured, at odds with what is expected for a system in dynamical equilibrium. In particular, we show that the main density peak of UMi is off-center with respect to the center of symmetry of the whole galaxy and shows a much lower ellipticity with respect to the rest of the galaxy. Moreover, UMi stars are shown to be clustered according to two different characteristic clustering scales, as opposed to Draco, which instead has a very symmetric and smooth density profile. The possible consequences of this striking structural difference on our ideas about galaxy formation are briefly discussed. Combining our distance modulus with the more recent estimates of the total luminosity of UMi, we find that the mass-to-light ratio ($M/L$) of this galaxy may be as low as $M/L \sim 7$, a factor of 5–10 lower than current estimates.

Key words: dark matter — galaxies: dwarf — galaxies: fundamental parameters — galaxies: individual (Draco, Ursa Minor) — galaxies: stellar content — galaxies: structure — Local Group

On-line material: machine-readable tables

1. INTRODUCTION

The Draco ($\alpha = 17^h 20^m 19^s$, $\delta = 57^\circ 54/8$ [J2000.0]) and Ursa Minor ($\alpha = 15^h 00^m 11^s$, $\delta = 67^\circ 12/9$ [J2000.0]) dwarf spheroidal (dSph) galaxies are the faintest known members of the Local Group of galaxies and are among the lowest surface brightness members of the group (Mateo 1998).

The Draco appear to be dominated by very old (age greater than 8–10 Gyr) and metal-deficient ([Fe/H] $\sim -2$) stellar populations (see Mateo 1998; Carney & Seitzer 1986; Aparicio, Carrera, & Martinez-Delgado 2001; Grillmair et al. 1998; Mighell & Burke 1999; Dolphin 2002); thus, they may represent a very early and elementary stage of the evolution of the building blocks that may have had a primary role in the assembly of the Milky Way galaxy (see Bellazzini, Ferraro, & Pancino 2001b). Furthermore, they are reported to have the highest mass-to-light ratio ($M/L$) of any other known galaxy (e.g., up to $M/L = 300–1000$ for Draco and $M/L \sim 50–100$ for UMi; see Kleyka et al. 2001; Armandroff, Olszewski, & Pryor 1995). Hence, their stellar content may just represent the handful of baryons trapped in a system whose true nature is that of a huge dark halo. All these exceptional properties have made these galaxies classi-
Draco and UMi are twin galaxies under many aspects: they have a similar distance from the center of the Galaxy, similar masses and luminosities, and similar metal content and are both devoid of gas (see Table 3 for a summary of their physical parameters). In this context, a comparative study performed with strictly homogeneous observational material and with the same data reduction and data analysis techniques may reveal interesting features. Here we present the results of a comparative analysis, performed by obtaining well-calibrated \((V, I)\) photometry of the evolved stars of UMi and Draco over a field of view of \(~25 \times 25\) arcm\(^2\), under strictly homogeneous conditions (see Bellazzini et al. 2001c for a discussion of the possible problems associated with the comparison of inhomogeneous photometries).

The structure of the paper is as follows: in § 2, we describe the observational material, the data reduction process, and the photometric calibration; in § 3, we present the color-magnitude diagrams (CMDs) and the results of artificial star experiments; § 4 is devoted to the estimate of the distance to Draco and UMi; in § 5, we study the properties of the red giant branch (RGB) of the two galaxies. In § 6, we compare the structures of Dra and UMi and demonstrate that the inner region of UMi is significantly structured and that its stars are clustered according to two different characteristic scale lengths. Section 7 is dedicated to the discussion of our results.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Observations

The data were obtained at the 3.52 m Italian telescope Telescopio Nazionale Galileo (TNG; Roque de los Muchachos, La Palma, Canary Islands, Spain) using DoLoRes, a focal reducer imager/spectrograph equipped with a 2048 \(\times\) 2048 pixel thinned and back-illuminated Loral CCD array (gain = 0.97 \(e^-/\)ADU \(-1\), readout noise = 9.0 ADU rms). The pixel scale is 0\(^\prime\)275 pixel\(^{-1}\); thus, the total field of view of the camera is 9.4 \(\times\) 9.4 arcmin\(^2\). The observations were carried out during three nights (2001 March 19, 20, and 21) under average seeing conditions (FWHM \~1.0\(^{\prime\prime}\)–1.4\(^{\prime\prime}\)). The first and third nights of the run were photometric. The scientific exposures taken during the second night were calibrated indirectly by using the data acquired in the photometric nights.

Each galaxy was sampled with a square mosaic of nine partially overlapping fields, covering a total field of view of \(25 \times 25\) arcmin\(^2\). For each field, two \(V\) and two \(I\) exposures (\(t_{\text{exp}} = 120\) s in each filter for Dra and \(t_{\text{exp}} = 90\) s for UMi) were secured.

2.2. Data Analysis

All the raw images were corrected for bias and flat field, and the overscan region was trimmed using standard IRAF\(^4\) procedures. Each pair of images in each band has been averaged, so the final analysis was performed on averaged \(V\) and \(I\) images.

The point-spread function (PSF)-fitting procedure was performed independently on each \(V\) and \(I\) average image, using a version of DoPhot (Schechter, Mateo, & Saha 1993) 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 catalog listing the instrumental \(V, I\) magnitudes for all the stars in each field has been obtained by cross-correlating the \(V\) and \(I\) catalogs. Only the sources classified as stars by the code have been retained. The spurious sources erroneously fitted by DoPhot (as cosmic rays, bright background galaxies, etc.) have been removed by hand from the catalogs.

Nine different catalogs (one for each subfield of the mosaic) were obtained for each galaxy. These catalogs were converted to a homogeneous photometric system using the large sets of stars in common among the various fields. The magnitudes of the stars in common among adjacent fields were averaged. A homogeneous total catalog of instrumental magnitudes and positions was finally obtained for each mosaic field.

2.3. Photometric Calibration

The absolute calibration has been obtained from several repeated observations of Landolt (1992) standard fields, including all the stars listed in the extended catalog of calibrators provided by Stetson (2000). The coefficients of atmospheric extinction \((C_{\text{ext}})\) were directly obtained by repeated observations of the same standard field at different air masses. Accurate estimates of the aperture correction were obtained with a large number of bright and isolated stars. The final calibration equations and \(C_{\text{ext}}\) are shown in Figure 1.

The accuracy of the photometric calibration was checked by comparison with the independent \(V, I\) photometry of the Draco dSph (kindly provided by P. Stetson 2002, private communication) and with the \(V\) photometry of UMi from Stetson (2000). The results of this test are shown in Figure 2, where the difference between our photometry \((V_{\text{tw}}\) and \(I_{\text{tw}})\) and that of Stetson \((V_{\text{St}}\) and \(I_{\text{St}})\) is plotted as a function of magnitude for both galaxies. Unfortunately, no previous \(I\)-band photometry of UMi is available. The comparison suggests that the global uncertainty in the calibration is lower than \(\pm 0.02\) mag in each passband over the whole range of \(V-I\) color sampled. The equations shown in Figure 1 were applied to the catalogs described in § 2.2 to produce the final calibrated catalogs that are reported in Tables 1 and 2. In each table, we report the identification number (col. [1]), the \(V\) magnitude and its error as estimated by DoPhot (see § 3.1 below) (cols. [2] and [3]), \(I\) magnitude and error (cols. [4] and [5]), the position in the mosaic in pixels (cols. [6] and [7]), the position in the sky in equatorial coordinates at the equinox J2000.0 (cols. [8] and [9]), the classification of the identified variable stars, if available (col. [10]), and the name of the identified variable stars according to the nomenclature indicated in the table note (col. [11]). The photometric errors as estimated from artificial stars experiments will be shown and discussed in § 3.1.

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\(^4\) 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.
Fig. 1.—Difference between calibrated (upper-case letters, e.g., $V, I$) and instrumental (lower-case letters, e.g., $v, i$) magnitudes for the Landolt standard stars observed on March 19 (triangles) and March 21 (circles). The calibration relations (upper panel: $V$; lower panel: $I$) are plotted (solid lines) and the corresponding equations are reported along with the rms error of the linear fits and the measured extinction coefficients.

Fig. 2.—Difference between independently calibrated photometry from this work (tw) and by Stetson (2000), for Draco (upper panel: $V$; middle panel: $I$) and UMi (lower panel: $V$).

### TABLE 1

PHOTOMETRY AND POSITIONS OF STARS IN URSA MINOR

| ID    | $V$/C15 | $I$/C15 | X(px) | Y(px) | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | Variable Star Type | Variable Star Number |
|-------|---------|---------|-------|-------|---------------------|---------------------|---------------------|---------------------|
| 10018 | 16.858  | 15.342  | 246.08| 365.12| 15 08 27.2          | 67 10 07.7          | 0                   | 0                   |
| 10019 | 17.018  | 15.628  | 399.38| 462.34| 15 08 34.4          | 67 10 34.2          | 0                   | 0                   |
| 10020 | 16.542  | 15.717  | 754.09| 801.17| 15 08 51.2          | 67 12 07.0          | 0                   | 0                   |
| 10021 | 16.579  | 15.620  | 1959.44| 817.81| 15 09 48.4          | 67 12 09.3          | 0                   | 0                   |
| 10023 | 16.928  | 15.679  | 838.95| 1488.32| 15 08 55.4         | 67 15 15.9          | 0                   | 0                   |
| 10024 | 16.458  | 15.569  | 873.74| 1918.16| 15 08 57.2          | 67 17 14.2          | 0                   | 0                   |
| 10025 | 17.714  | 15.689  | 548.78| 65.36  | 15 08 41.5          | 67 08 44.9          | 0                   | 0                   |
| 10026 | 17.459  | 15.467  | 102.13| 160.05 | 15 08 20.4          | 67 09 11.5          | 0                   | 0                   |
| 10028 | 18.090  | 15.754  | 1399.35| 279.70| 15 09 21.7          | 67 09 42.5          | 0                   | 0                   |

Note.—Table 1 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. The variable stars are numbered after the nomenclature by N88 (col. [11]) and classified according the same authors (col. [10]: 1 = RRab; 2 = RRc; 3 = anomalous Cepheids; 4 = unclassified variables).

### TABLE 2

PHOTOMETRY AND POSITIONS OF STARS IN DRACO

| ID    | $V$/C15 | $I$/C15 | X(px) | Y(px) | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | Variable Star Type | Variable Star Number |
|-------|---------|---------|-------|-------|---------------------|---------------------|---------------------|---------------------|
| 10069 | 16.744  | 15.963  | 1295.30| 338.62| 17 20 34.3          | 57 51 56.4          | 0                   | 0                   |
| 10085 | 17.510  | 15.628  | 399.38| 462.34| 17 20 37.2          | 57 54 58.2          | 0                   | 0                   |
| 10086 | 16.478  | 15.802  | 1145.29| 1051.62| 17 20 52.9          | 57 55 43.5          | 0                   | 0                   |
| 10090 | 16.989  | 15.710  | 505.79 | 1158.47| 17 20 52.9          | 57 55 43.5          | 0                   | 0                   |
| 10091 | 17.313  | 15.744  | 1828.06| 1218.93| 17 20 52.9          | 57 55 43.5          | 0                   | 0                   |
| 10097 | 17.112  | 15.816  | 463.32 | 1303.23| 17 20 52.9          | 57 55 43.5          | 0                   | 0                   |
| 10100 | 17.212  | 15.799  | 1456.76| 1651.69| 17 20 52.9          | 57 55 43.5          | 0                   | 0                   |
| 10109 | 16.948  | 15.746  | 279.70 | 15 09 21.7| 67 09 42.5          | 0                   | 0                   | 0                   |

Note.—Table 2 is presented in its entirety in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content. The variable stars are numbered after the nomenclature from Baade & Swope 1961 (col. [11]). In col. (10), only the known anomalous Cepheid V141 is flagged with variable type = 3.
3. THE COLOR-MAGNITUDE DIAGRAM

The final \((V, V-I)\) color-magnitude diagrams (CMDs) of the two galaxies are shown in Figure 3. In both cases, our photometry reaches the base of the RGB at \(V \approx 22.5\).

The RGBs are well defined and steep, typical of metal-poor stellar systems. The RGB of UMi appears to be narrower than that of Draco, suggesting a smaller metallicity spread or a similar metallicity spread but a lower mean metal content. In the CMD of UMi, a hint of the asymptotic giant branch (AGB) bump (see Ferraro et al. 1999, hereafter F99) can be noted (at \(V \sim 19, V-I \approx 0.9\)), while the corresponding feature of Draco is probably hidden by the larger extent of contamination by foreground and background stars. Note the sharp color cutoff of the distribution of field stars at \(V-I = 0.8\), corresponding to the main-sequence turnoff (MSTO) of the Galactic halo/thick-disk stars (Morrison et al. 2000). Both Eskridge & Schweitzer (2001) and Shetrone, Coté, & Stetson (2001b) found that some stars lying to the red of the upper RGB are members of the respective galaxy, in either Draco or UMi. The same authors have also demonstrated that all of these stars are not first-ascent red giants but carbon stars instead.

Most of the horizontal-branch (HB) stars lie in the range \(19.5 \leq V \leq 20.5\) in UMi and \(20.0 \leq V \leq 21.0\) in Draco. We have counteridentified 65 variable stars in UMi from the catalog of Nemec, Wohlau, & Mendes de Oliveira (1988, hereafter N88) that cover our whole field of view. In Figure 3, we indicate the type ab RR Lyrae with open squares, the type c RR Lyrae with open triangles, and the anomalous Cepheids with open circles, after the classification by the same authors. In Draco, 56 variable stars were counteridentified in the central \(\sim 10 \times 10\) arcmin\(^2\) field, from the study by Baade & Swope (1961). Since an explicit classification is not provided by Baade & Swope (1961), we marked all the RR Lyrae variables with stars, while the only anomalous Cepheid identified is plotted as an open circle, as in the previous case. However, it is important to note that, according to Baade & Swope (1961), the large majority of RR Lyrae variables in Draco are of type ab (see also Nemec 1985).

As already noted by other authors, the morphology of the two HBs is very different. UMi has only a handful of HB stars to the red of the instability strip, a significant number of RR Lyrae variables of both Bailey’s types, and a well-populated blue tail reaching \(V \approx 20.5\) and \(V-I \approx 0.0\). On the other hand, the HB of Draco is well populated in its red

![Fig. 3.](image-url)
part and has a sparse blue tail, reaching \( V \approx 21.0 \). As can be seen in Figure 3, there is a large number of stars in the red part of the instability strip (see also Fig. 4), suggesting that the census of RR Lyrae variables in this galaxy is far from complete. A modern CCD search for variables over a wide field of view is urged Kinemuchi et al. 2002.

Finally, at \( 21 \leq V \leq 22.5 \) and \( 0.0 < V-I < 0.6 \), the upper part of a blue plume is evident in both CMDs. This is a well-known feature of the CMD of these galaxies and has been preferentially interpreted as a sequence of genuine blue stragglers stars, e.g., the result of the evolution of binary stars (Carney & Seitzer 1986; Grillmair et al. 1998; Mighell & Burke 1999; Carrera et al. 2002; Aparicio et al. 2001).

3.1. Artificial-Stars Experiments

We have performed extensive artificial-stars experiments in the central field of each mosaic, i.e., the fields with the highest stellar density. We take the results from these fields as representative of the whole mosaics. More than 5000 stars per field have been extracted from a luminosity function (LF) similar to the observed one and with colors lying on the observed RGB ridge line of the galaxies, following the methods described in detail in Bellazzini et al. (2002a, 2002b). The artificial stars have been simultaneously added to the \( V \) and \( I \) frames, \(~400 \) at a time, with a minimum distance among them of \(~40 \) pixels to avoid undesired interference among artificial stars (see Bellazzini et al. 2002b for details and references). The stars are simulated with the observed PSF, and the complete data reduction process has been repeated for all the frames “enriched” with the artificial stars.

In the present context, we performed the artificial-stars experiment to obtain the following:

1. A realistic estimate of the photometric error as a function of magnitude, by comparing the a priori known input magnitudes with the measured (output) magnitudes. This result is shown in Figure 4. The average error is lower than 0.05 mag in both passbands for \( V \leq 20.0 \) and \( \leq 0.1 \) for fainter magnitudes.

2. The effect of the “observation plus data reduction” process on the measured magnitudes and colors of stars lying along the RGB of a simple stellar population (SSP; i.e., a population of stars all having the same age and chemical composition; see Renzini & Fusi Pecchi 1988). This result (shown in the upper panels of Fig. 5) will be very useful to discriminate the color spread due to the intrinsic metallicity dispersion from the observational scatter.

3. The completeness factor \( (C_f = N_{rec}/N_{inp}; \) i.e., the ratio between the artificial stars correctly recovered and measured and the total number of simulated stars) as a function of magnitude. The lower panels of Figure 5 show that in both mosaics, the completeness is very high \( (C_f > 90\%) \) down to \( I \sim 20.5 \).

4. THE DISTANCE TO UMI AND DRA

4.1. Relative Distance

As a first step, we determine the relative distance modulus of the two galaxies. Since the two are affected by the same amount of interstellar extinction \( [E(B-V)] = 0.03 \); Mateo 1998; Schlegel, Finkbeiner & Davis 1998 \) and share a similar metal content (Mateo 1998), such an estimate can be obtained by finding the best match between the HBs. The upper panel of Figure 6 shows a zoomed view of the HB of UMi. The RR Lyrae variables are plotted as open stars. The stars not recognized as variables by N88 but lying in the range of color and magnitude covered by the RR Lyrae sampled at random phase are plotted as dots, while the stars to the red and to the blue of this region are plotted as solid circles. The solid line in the instability strip is the mean RR Lyrae level \( (\langle V_{RR} \rangle = 19.86 \pm 0.07) \) according to N88. The solid heavy line is the ridge line tracking the mean of the HB distribution of UMi. The dashed lines are displaced by \( \Delta V = \pm 0.1 \) mag from the ridge line and roughly bound all the nonvariable HB stars of UMi.

In the lower panel of Figure 6, the HB ridge line of UMi has been shifted to match the HB of Draco, which has been plotted with the same symbols used above. The fit is made difficult by the different HB morphology, but the solution obtained here with a shift of \( +0.42 \) mag in \( V \) and \( +0.02 \) in \( V-I \) appears as the best possible match. The derived relative distance modulus is \( \delta_{(m-M)} = 0.42 \pm 0.10 \). The result is in good agreement with the difference of moduli that can be obtained from Table 2 of Mateo (1998); i.e., \( \delta_{(m-M)} = 0.47 \pm 0.18 \).

4.2. Comparison with Template Clusters

An indirect estimate of \( \langle V_{RR} \rangle \) and of the distance modulus can be obtained by finding a match with the HB of well-studied template clusters of similar metallicity, for which a robust direct estimate of \( \langle V_{RR} \rangle \) is available (see, e.g., Montegriffo et al. 1998 and references therein).

In Figure 7, we report the results of the comparison with the photometry of M68 \( ([Fe/H] = -2.09) \) by Walker (1994). The HBs of UMi (upper panel) and Draco (lower panel) are plotted with the same symbols as in Figure 6, while the stars of M68, shifted to match the HBs of UMi and Dra, are represented by open circles. The solid line is the mean level of the RR Lyrae variables in M68
A good match is found between the HBs of M68 and UMi by applying a shift of 4.24 mag in $V$ to the stars of M68. Using the above-quoted $\langle V_{RR} \rangle$ of M68 and propagating all the uncertainties, $\langle V_{RR} \rangle (\text{UMi}) = 19.88 \pm 0.10$ is inferred, in excellent agreement with the estimate by N88.

We derive also the level of the zero-age horizontal branch ($V_{ZAHB}$, a quantity that is best suited for comparison with theoretical models) by applying the same $D_V$ to the $V_{ZAHB}$ value of M68 reported by F99, $V_{ZAHB} = 15.75 \pm 0.05$. We obtain $V_{ZAHB}(\text{UMi}) = 19.99 \pm 0.11$. Finally, taking into account the difference in reddening and adopting $(m-M)_0(\text{M68}) = 15.11 \pm 0.1$ from F99, we obtain the following estimate for the distance modulus of UMi: $(m-M)_0 = 19.38 \pm 0.16$, inclusive of all the uncertainties.

The HB morphology of Draco has no counterpart among the galactic globular clusters of similar metallicity. Hence, the fit with the HB of M68—shown in the lower panel of Figure 7—is worse than that found for UMi and does not provide a well-constrained solution. However, with the adopted shift we obtain results that are in full agreement with the differential distance between UMi and Draco derived in § 4.1. With the same procedure described above, we obtain for Draco $\langle V_{RR} \rangle = 20.30 \pm 0.12$, $V_{ZAHB} = 20.41 \pm 0.13$, and $(m-M)_0 = 19.80 \pm 0.18$.

Figure 8 reports the results of the comparison with the Hubble Space Telescope (HST) photometry of M92 ([Fe/H] = −2.24) by Ferraro and coworkers (F. Ferraro et al. 2003, in preparation), which is also in good agreement with the well-calibrated ground-based photometry by Johnson & Bolte (1998). The symbols and the procedure are the same adopted in Figure 7 for the comparison with M68.

In this case, a good match is also obtained for UMi (upper panel), with the shifts reported in the figure. We adopt larger uncertainties in the derived quantities, with respect to the case of M68, since M92 is slightly more metal poor than UMi (and Draco). Adopting $\langle V_{RR} \rangle (\text{M92}) = 15.08 \pm 0.01$ from Kopacki (2001), we obtain $\langle V_{RR} \rangle (\text{UMi}) = 19.84 \pm 0.12$, again in excellent agreement with N88 as well as with the results from Figure 7. Adopting $V_{ZAHB}(\text{M92}) = 15.30 \pm 10$ from F99, we obtain $V_{ZAHB}(\text{UMi}) = 20.06 \pm 0.14$, in agreement with that found above. Finally, adopting $(m-M)_0(\text{M92}) = 14.74 \pm 15$ from F99, we obtain $(m-M)_0(\text{UMi}) = 19.47 \pm 0.20$. 

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**Fig. 5.**—Upper panels: Input and output CMDs of the artificial stars for UMi (left pair of panels) and Dra (right pair of panels). These plots show the effects of the observation + data reduction process on the RGB stars of a simple stellar population. Lower panels: Completeness factor ($C_f$) as a function of $I$ magnitude for UMi (left panel) and Dra (right panel).
M92 appears to provide a better match to the HB of Draco, with respect to M68 (Fig. 8, lower panel). With the same assumptions as above, we obtain for Draco $h_{VRI} = 20.26 \pm 0.12$, $V_{ZAHB} = 20.48 \pm 0.14$, and $(m-M)_0(Dra) = 19.89 \pm 0.20$. The overall agreement with the results obtained from the comparison with M68 is fully satisfying.

In conclusion, we adopt the weighted mean of the results obtained above for $h_{VRI}$, $V_{ZAHB}$, and $(m-M)_0$. The final results are $(V_{RR}) = 19.86 \pm 0.09$, $V_{ZAHB} = 20.02 \pm 0.09$ for UMi, and $(V_{RR}) = 20.28 \pm 0.10$, $V_{ZAHB} = 20.44 \pm 0.10$ for Draco. The adopted distance moduli are $(m-M)_0(UMi) = 19.41 \pm 0.12$ and $(m-M)_0(Dra) = 19.84 \pm 0.14$.

4.3. A Consistency Check: The RGB Tip

The use of the tip of the red giant branch (TRGB) as a standard candle is a powerful technique to estimate the distances to galaxies that host old stellar populations (see Madore & Freedman 1998 and references therein). Bellazzini et al. (2001a) have recently provided a new robust calibration of the zero point of the relation between the absolute $I$ magnitude of the tip ($M_{TRGB}^I$) and the metallicity that is independent of the distance scale based upon classical standard candles (RR Lyrae, Cepheids). This new calibration prompted us to start a large observational program aimed at a reassessment of the distances to Local Group galaxies based on the TRGB technique. The present study is the first of a series describing the results of this program. Unfortunately, despite the large field sampled, UMi and Draco have too few stars (and a too low surface brightness) to allow an individual safe application of the TRGB technique (see Sakai, Madore, & Freedman 1996; Madore & Freedman 1995, hereafter MF95). However, it is of great interest for the final scope of the project to check if the distance of these galaxies is consistent with the new TRGB distance scale.
To do this check, we adopt the shift derived in § 4.1 to move Draco at the distance of UMi, and we try to detect the TRGB from the merged sample, having now a number of stars nearly double with respect to each individual case. In the left panel of Figure 9, we report the composite \((I, V-I)\) CMD of the two galaxies together, after the application of the quoted shift to Draco. The right panels of Figure 9 report the actual detection of the TRGB using the standard technique, as defined by Sakai et al. (1996). The sharp cutoff of the LF of the RGB (which is the actual observational marker of the TRGB) is clearly visible in the histograms shown in the upper and middle-right panels. The edge-detector Sobel filter shows the TRGB as the most pronounced peak at \(I = 15.57 \pm 0.05\). The considered sample has 100 stars in the upper 1 mag bin; however, from the CMD of field stars, we estimate that \(\approx 20\%\) of them are likely foreground sources. Hence, the actual number of stars in the uppermost 1 mag bin is in fact \(N_\star \approx 80\). By means of numerical simulations, MF95 showed that a reasonably safe detection of the TRGB can be made only if \(N_\star > 100\), thus it is likely that our detection overestimates the actual \(I\) magnitude of the tip. To quantify this systematic error, we repeat the MF95 numerical experiment. We adopted the ridge line of M68 as an RGB template and a model RGB LF of the same form as the one used by MF95, imposing a cutoff at \(M_I = -4.00\). Then we randomly generated 100 synthetic RGBs for each of the following cases: \(N_\star = 20, 40, 60, 80, 100, 150, 200\), and we detected the tip of each synthetic RGB with the standard technique. Observational errors extracted from a Gaussian distribution with \(\sigma_V, \sigma_I\) similar to those of the observed stars were added to each synthetic star before the TRGB detection. The average \(M_I(\text{TRGB})\) of the 100 simulated RGBs and the corresponding standard deviations are plotted as a function of \(N_\star\) in Figure 10. The results by MF95 are confirmed: for \(N_\star \geq 100\), the estimate from the standard technique is within \(\leq 0.02\) mag of the true TRGB and the standard deviation is \(< 0.04\) mag. The efficiency of the method drops suddenly for \(N_\star \leq 80\), and the associated uncertainty becomes \(\approx 0.1\) or larger. The difference between the true luminosity of the tip and the observed one can be modeled with a first-order polynomial as a function of \(N_\star\) for \(N_\star < 100\):

\[
\delta I_{\text{TRGB}} = I_{\text{true}}^{\text{TRGB}} - I_{\text{obs}}^{\text{TRGB}} = 0.0022N_\star - 0.236.
\]

In the present case, with \(N_\star \approx 80\), \(\delta I_{\text{TRGB}} = -0.07 \pm 0.08\).
thus our final estimate for the TRGB location is $M_{\text{TRGB}} = 15.50 \pm 0.14$, where we have considered also the uncertainties associated with the correction and with the Dra-UMi shift we have applied to obtain the considered merged sample. The galaxies are dominated by a metal-poor population quite similar to that of the template used by Bellazzini et al. (2001a), which obtained $M_{\text{TRGB}} = -4.04 \pm 0.12$ at [Fe/H] = -1.7 for the globular cluster ω Centauri. Adopting $E(B-V) = 0.03$, we obtain $(m-M)_0 = 19.50 \pm 0.20$ and $(m-M)_0 = 19.92 \pm 0.27$ for UMi and Draco, respectively, in good agreement with the results of § 4.2.

Hence, we conclude that the distance moduli derived in § 4.2 are fully consistent with the TRGB distance scale as calibrated by Bellazzini et al. (2001a).

5. THE STELLAR CONTENT OF UMI AND DRACO

5.1. The RGB Bump

The RGB bump is an evolutionary feature occurring along the RGB that flags the point where the H-burning shell crosses the chemical discontinuity left by the maximum penetration of the convective envelope. Theoretical models predict that the position of the RGB bump is driven mainly by metallicity, with a mild dependence on age (see F99 and references therein).

From an observational point of view, the feature was observed for the first time in a globular cluster by King, Da Costa, & Demarque (1985) and was only recently identified in a significant number of clusters (Fusi Pecci et al. 1990; Zoccali et al. 1999; F99). The first detection of the RGB bump in a galaxy is very recent as well. Majewski et al. (1999) identified a double RGB bump in the Sculptor dwarf spheroidal and took this evidence as indicative of the presence of two populations of different metallicities. A very similar feature has been revealed also in the Sextans dSph by Bellazzini et al. (2001b). At present, these are the only two detections of the RGB bump ever obtained in stellar systems other than globulars.

The change in the slope of the cumulative LF and the excess of star counts in the differential LF of the RGB are the main tools with which to identify the RGB bump. In particular, Fusi Pecci et al. (1990) suggest that the change in the slope of the cumulative LF is the safest indicator of the RGB bump. In Figure 11, the differential and cumulative LFs of the RGB in the region of the bump are shown for both galaxies.

The RGB bump is clearly detected in UMi at $V_{\text{bump}} = 19.40 \pm 0.06$. This is the first single RGB bump ever detected in a galaxy. On the other hand, there is no sign of this feature in the LF of Draco. We argue that a larger spread of metallicity and/or age in the stellar population of Draco, with respect to UMi, is responsible for the smearing of the RGB bump feature in this galaxy (see § 5.2). This suggests that these dSphs—which are quite similar under many aspects (see Bellazzini et al. 2001b and references therein)—had different evolutionary histories at early times.

The magnitude difference between the RGB bump and the HB level ($\Delta V_{\text{bump}}$) has been used by Fusi Pecci et al. (1990), and later by F99 and Zoccali et al. (1999), to compare the observations with the theoretical predictions. The $\Delta V_{\text{bump}}$ parameter is mainly a function of the metallicity and has only a mild dependence on age. Adopting the ZAHB levels obtained in § 4.2, we obtain for UMi $\Delta V_{\text{bump}} = -0.62 \pm 0.11$. Since it has been shown that UMi is dominated by a very old population that formed in a rather short timescale (Carrera et al. 2002; Mighell & Burke 1999; Feltzing, Gilmore, & Wyse 1999; Dolphin 2002) we can safely use the $\Delta V_{\text{bump}}$ parameter as an indicator of the mean metal content of the old stars. We use the data by F99 to obtain a fit of [Fe/H] as a function of $\Delta V_{\text{bump}}$, adopting the metallicity scales by Zinn & West (1984, hereafter ZW) and Carretta & Gratton (1997, hereafter CG). We find

$$[\text{Fe/H}]_{\text{ZW}} = 1.426 \Delta V_{\text{bump}} - 1.233 \quad (\text{rms} = 0.08)$$

$$[\text{Fe/H}]_{\text{CG}} = -0.430 \Delta V_{\text{bump}}^2 + 1.183 \Delta V_{\text{bump}} - 1.046 \quad (\text{rms} = 0.07).$$

With these relations, we obtain for UMi $\langle [\text{Fe/H}]_{\text{ZW}} \rangle = -2.1 \pm 0.2$ and $\langle [\text{Fe/H}]_{\text{CG}} \rangle = -1.95 \pm 0.2$, in good agreement with the estimates obtained with other methods (see Mateo 1998; Carrera et al. 2002; Shetrone, Coté, & Sargent 2001a).

5.2. The Metallicity Distributions

In Figure 12, the $(I, V-I)$ distribution of the upper RGB of UMi (left panel) and Draco (right panel) are compared with the ridge lines of the template globular clusters NGC 6341, NGC 6205, and NGC 288, from left to right, taken from the homogeneous set by Saviane et al. (2000). In the ZW metallicity scale, the templates have [Fe/H] = -2.24, -1.65, and -1.40, respectively, while in the CG scale their metallicities are [Fe/H] = -2.16, -1.39, and -1.07, respectively. The metallicities, distance moduli, and reddening of the templates are taken from F99. For the two galaxies, we adopted the estimates of § 4. The meaning of the horizontal lines and of the large open symbol will be discussed in § 5.2.1.
The large majority of the UMi RGB stars are enclosed between the ridge lines of NGC 6341 and NGC 6205, implying a mean metallicity around \([\text{Fe/H}]_{\text{ZW}} \approx -2.0\), in good agreement with the result found in § 5.1 as well as with previous estimates, either photometric or spectroscopic (see Carrera et al. 2002; Shetrone et al. 2001a, and references therein). The RGB of Draco seems slightly redder than the one of UMi, suggesting a mean metallicity \([\text{Fe/H}]_{\text{ZW}} \approx -1.7\), also in agreement with previous estimates (see Aparicio et al. 2001; Shetrone et al. 2001a and references therein). Both galaxies appear significantly more metal rich (by \(\sim 0.3\) dex) if the CG metallicity scale is adopted, as a natural consequence of the higher metallicity value of all the adopted templates in this scale. Independently of the assumed scale, it is clear that the color spread along the RGB of both galaxies is significantly larger than the photometric scatter (see Fig. 4), thus we confirm the presence of an intrinsic metallicity spread (Shetrone et al. 2001a; Carrera et al. 2002; Aparicio et al. 2001).

The RGB color of old populations is driven mainly by the metal content of the stars. Based on this principle, photometric metallicity distributions (MDs) can be obtained by suitable interpolation between a grid of metallicity templates, a technique that has been widely applied in recent years (see, e.g., Holland, Fahlman, & Richer 1996; Harris & Harris 2000; Saviane et al. 2000, and references therein). Here we obtained the MDs shown in Figures 13 and 14 by interpolating in color between the RGB ridge lines of the adopted templates (see Fig. 12) for the stars in the magnitude range \(-2.9 \leq M_I \leq -3.9\). While the accuracy of the single-metallicity estimate is low, the main characteristics of the distribution as a whole (for instance, its mean and dispersion) are quite robust, being based on a large number of stars. This technique is particularly appropriate in the present case since we know that both galaxies are dominated by very old stellar populations (Mighell & Burke 1999; Grillmair et al. 1998; Dolphin 2002; Aparicio et al. 2001; Carrera et al. 2002). However, the actual metallicity spread derived with this technique is the convolution of the intrinsic metallicity spread with the color spread due to observational scatter, and the impact of this latter factor depends on the mean metallicity, since the same observational scatter should produce a larger (apparent) metallicity spread in the low-metallicity regime, where the RGB ridge lines are steeper, with respect to the high-metallicity regime. In fact, \(\Delta[\text{Fe/H}] / \Delta(V-I)\) decreases with increasing metallicity. To
deal with this problem, we compare the observed photometric MDs with those of the recovered artificial stars shown in Figure 4, which closely model the CMD of an SSP observed and reduced under the same conditions as real stars.

In Figure 13, the MD of Draco (right panels) and the MD of the corresponding synthetic SSP (left panels; see Fig. 5) are compared. All the MDs are normalized to their maximum value. The upper panels show the histograms in the ZW scale. The total number of included stars is reported in the upper right corner. The middle and lower panels show the generalized histograms (solid lines) in the ZW scale and in the CG scale, respectively (see Holland et al. 1996; Laird et al. 1988, and references therein). The measured standard deviation ($\sigma$) is reported in the upper right corner of each panel. The MD of the synthetic SSP represents the response of the whole procedure to the pure observational scatter or, in other words, the observed version of a true metallicity distribution having the form of a Dirac $\delta$-function. The plots in the left panels of Figure 13 demonstrate that the observational scatter produce a sizeable (spurious) metallicity spread. To obtain a sensible measure of the true intrinsic metallicity spread, we have to deconvolve this “response function” from the observed distributions shown in the right panels of Figure 13. The dotted lines are the Gaussian distributions obtained by deconvolving the response function from a Gaussian distribution having the same mean and standard deviation of the observed distributions. The standard deviation of the dotted curves is a good estimate of the true intrinsic metallicity spread $\sigma_i$.

In the ZW scale, the MD of Draco spans more than 0.6 dex. The mean and median metallicities are $\langle [Fe/H] \rangle = -1.7 \pm 0.1$, while the mode is $\langle [Fe/H] \rangle_{\text{mod}} = -1.6 \pm 0.1$. The intrinsic 1 $\sigma$ scatter is $\sigma_i = 0.13$ dex. There is a marginal indication of a secondary peak at lower metallicity, but the statistical significance of this feature is low, thus we do not comment further on it. These estimates are in good agreement with the results of the spectroscopic analysis by Lehnert et al. (1992) and Shetrone et al. (2001a). The detailed comparison between our photo-

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**Fig. 12.** $(I, V-J)$ distribution of the upper RGB of UMi (left panel) and Draco (right panel) are compared with the ridge lines of the templates globular clusters NGC 6341 ($[Fe/H]_{\text{ZW}} = -2.24; [Fe/H]_{\text{CG}} = -2.16$), NGC 6205 ($[Fe/H]_{\text{ZW}} = -1.65; [Fe/H]_{\text{CG}} = -1.39$), and NGC 288 ($[Fe/H]_{\text{ZW}} = -1.40; [Fe/H]_{\text{CG}} = -1.07$), from left to right. The long-dashed line is the expected level of the TRGB with the adopted distance moduli (from § 4.2) and the TRGB calibration by Bellazzini et al. (2001a). The dotted lines enclose the full range of uncertainty in the expected magnitude of the TRGB. The large open symbols marks the stars observed by Shetrone et al. (2001) according to the metallicity estimated by these authors. Circles: $[Fe/H] \leq -2.10$; pentagons: $-2.10 < [Fe/H] \leq -1.8$; squares: $-1.8 < [Fe/H] \leq -1.5$; triangles: $-1.5 < [Fe/H] \leq -1.3$. 

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**Fig. 13.** (I, V−I) distribution of UMi (left panel) and Draco (right panel) are compared with the ridge lines of the templates globular clusters NGC 6341 ([Fe/H]_{ZW} = -2.24; [Fe/H]_{CG} = -2.16), NGC 6205 ([Fe/H]_{ZW} = -1.65; [Fe/H]_{CG} = -1.39), and NGC 288 ([Fe/H]_{ZW} = -1.40; [Fe/H]_{CG} = -1.07), from left to right. The long-dashed line is the expected level of the TRGB with the adopted distance moduli (from § 4.2) and the TRGB calibration by Bellazzini et al. (2001a). The dotted lines enclose the full range of uncertainty in the expected magnitude of the TRGB. The large open symbols marks the stars observed by Shetrone et al. (2001) according to the metallicity estimated by these authors. Circles: [Fe/H] ≤ -2.10; pentagons: -2.10 < [Fe/H] ≤ -1.8; squares: -1.8 < [Fe/H] ≤ -1.5; triangles: -1.5 < [Fe/H] ≤ -1.3.
metric estimates and the study of Shetrone et al. (2001a) is discussed in § 5.2.1. Our method is insensitive to very metal poor stars \([\text{[Fe/H]}]_{\leq 2.5}\), so they are obviously not represented in our metallicity distribution. However, from Figure 12 it may be concluded that the number of possible RGB stars bluer (i.e., more metal poor) than the NGC 6341 template (at \([\text{[Fe/H]}] = 2.24\)) should be small in both galaxy (see § 5.2.1 for further details).

In Figure 14, the MDs of UMi and of its synthetic SSP are reported in the same way as in Figure 13. It can be appreciated that although the photometric scatter is very similar for Draco and UMi (see Fig. 4), the response function has a larger \(\sigma\) in the case of UMi. This is due to larger sensitivity of metallicity to color at the most metal poor regime described above. In the ZW scale, the MD of UMi spans a range nearly as wide as that of Draco. The mean and median metallicities are \(\langle [\text{Fe/H}] \rangle = -1.8 \pm 0.1\), while the mode is \([\text{Fe/H}]_{\text{mod}} = -1.9 \pm 0.1\). The intrinsic scatter is \(\sigma_f = 0.10\) dex. Also, in this case the agreement with results of other studies (Shetrone et al. 2001a; Aparicio et al. 2001) and with the constraints obtained in § 5.1 is quite good.

From the comparison of the MDs of the two galaxies, we can conclude that Draco is slightly less metal deficient than UMi, on average, and it presents a slightly larger metallicity spread. The parameters obtained from the photometric MDs (for Draco and UMi and for both metallicity scales) are summarized in Table 3.

The MDs in the CG scale are remarkably similar to the MDs in the ZW scale described above but, as expected, are shifted to higher metallicities and show a slightly larger spread; thus, the conclusions drawn above are unchanged. On the other hand, it is important to remark that the comparison of the observed distributions with chemical evolution models would lead to different conclusions depending on the assumed metallicity scale. In particular, by adopting the CG scale, one should conclude that the first stars in Draco and UMi formed from an interstellar medium already relatively enriched and reached a more advanced stage of chemical evolution than suggested by the ZW scale. This kind of uncertainty in the metallicity scales may have other dangerous drawbacks, hampering our interpretation of astrophysical data in several cases (see, e.g., Catelan et al. 2001).

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**Fig. 13.**—Photometric metallicity distribution of Draco (right panels) are compared with the distribution obtained with the same technique from the synthetic SSP we adopted for the artificial stars experiments (left panels). Upper panels: Ordinary histograms in the ZW metallicity scale. Middle panels: Generalized histograms in the ZW metallicity scale. Lower panels: Generalized histograms in the CG metallicity scale. The adopted smoothing length of the generalized histograms is equal to the measured \(\sigma\) of the response function, i.e., the natural smoothing length.
5.2.1. Comparison with Spectroscopic Estimates

A detailed comparison with the recent results by Shetrone et al. (2001a) may be useful to check the consistency between high-resolution spectroscopic abundances and photometric metallicity estimates. The stars observed by Shetrone et al. (2001a) are plotted in Figure 12 as large open symbols. Different symbols are adopted according to the metallicity estimates by Shetrone et al. (2001a). Circles are stars with \( [\text{Fe/H}] / C_{20} / C_{0} > 2.10 \), pentagons have \( 2.10 < [\text{Fe/H}] / C_{20} / C_{0} < 1.8 \), squares have \( 1.8 < [\text{Fe/H}] / C_{20} / C_{0} < 1.5 \), and triangles have \( 1.5 < [\text{Fe/H}] / C_{20} / C_{0} < 1.3 \) (actually, there are only two stars in this latter bin, both with \( [\text{Fe/H}] / C_{0} = 1.45 \)). In both panels of Figure 12, the dashed line is the expected level of the TRGB with the adopted distance moduli (from \( x \)). The dotted lines enclose the full range of uncertainty in the expected magnitude of the TRGB, including observational and calibration uncertainties.

First of all, we note that all the considered stars have \( I > I_{\text{TRGB}} \), to within the uncertainties. This is compatible with the hypothesis that they are first-ascent RGB stars, as suggested by Shetrone et al. (2001a). Second, the metallicity rank derived from spectroscopy is correctly reproduced by our photometry: stars with higher spectroscopic metallicity estimates lie on redder RGB loci. Finally, the zero point of the spectroscopic scale is in good agreement (within the uncertainties) with that derived from our photometry if the CG metallicity scale is adopted. Three out of four of the stars in the more metal-poor metallicity bin (circles) have \( -2.36 \pm 0.09 \leq [\text{Fe/H}] \leq -2.17 \pm 0.12 \) and lie around the ridge line of NGC 6341 ([Fe/H]_CG = -2.16 \pm 0.10). The two more metal-rich stars (triangles, \( [\text{Fe/H}] = -1.45 \pm 0.07 \)) are slightly bluer than the ridge line of NGC 6205 ([Fe/H]_CG = -1.39 \pm 0.10). Hence, both the metal-rich and metal-poor zero points seem to agree quite well. The only exception is the star 119 in Draco, which is slightly redder than the ridge line of NGC 6341 and, according to Shetrone et al. (2001a), has \( [\text{Fe/H}] = -2.97 \pm 0.15 \). We have no suggestion to reconcile such a large discrepancy between color and spectroscopic metallicity, except for trying to repeat both measures.

If the ZW scale is adopted for the templates shown in Figure 12, the consistency in the metal-poor zero point is preserved ([Fe/H]_ZW = -2.24 \pm 0.20 for NGC 6341), but a serious problem emerges at the metal-rich end, where the two stars with \( [\text{Fe/H}] = -1.45 \) lie to the blue of the \( [\text{Fe/H}] = -1.65 \) template, and the \( [\text{Fe/H}] = -1.4 \) template...
(NGC 288) is more than 0.1 mag redder than these stars. The problem with star 119 is not mitigated by the assumption of the ZW metallicity scale. Thus, it appears that the adoption of the GC metallicity scale provides a much higher degree of consistency between spectroscopic and photometric metallicity estimates, at least in the present case. The above comparison may suggest that the metallicities by Shetrone et al. (2001a) are consistent with the CG scale, which is also based on high-resolution measures.

Finally, another possible source of uncertainty in the photometric metallicity estimates is the small difference in the average abundance of $\alpha$-elements between Dra and UMi and the template clusters (see Shetrone et al. 2001a and discussion therein).

5.3. Populations Gradients

Radial population gradients are ubiquitous in dwarf galaxies (see Harbeck et al. 2001; Saviane et al. 2001; Hopp et al. 2000; Tosi et al. 2001, and references therein). In almost all cases, old/metal-poor stars are found to be more abundant in the outer regions of dwarf galaxies, while more metal rich and/or younger stars are preferentially found near the centers of galaxies (Harbeck et al. 2001). Here we look for population gradients by using the fraction of blue HB stars (i.e., those with $V-I < 0.4$) in different concentric radial annuli. The small number of available HB stars limits the spatial resolution to just 3 annuli. The results are shown in Figure 15. In UMi (upper panel), the fraction of BHB stars appears to rise slightly in the inner 4'. However, the effect is at least 1 $\sigma$, and the data are consistent with no population gradient, in agreement with what Carrera et al. (2002) found. The opposite effect is found in Draco (lower panel): the BHB fraction drops by a factor of 2 in the inner 4', i.e., the classical gradient described above, with more metal rich and/or younger stars clustered in the central region. The significance of the result is just marginal (2 $\sigma$), thus not in disagreement with the null detection reported by Aparicio et al. (2001).

6. STRUCTURE

We take advantage of our well-defined CMDs to select likely members of UMi and Draco with which reliable

![Image](image-url)
density contour maps can be obtained. The upper panels of Figure 16 show the adopted selections, while in the lower panels of the same figure the isodensity contour maps of the selected members of UMi and Draco are shown. Our maps cover the inner regions of the galaxies, within 1–2 core radii ($r_c$), and are obtained by computing the stellar density on an uniform grid with points spaced by 100 pixels. At each point of the grid, the density is computed over a circle of radius $r = 3'. This choice provides a suitable degree of smoothing and minimizes the effects of possible small empty regions (for instance, saturated stars or dead CCD columns). The continuous lines are isodensity contours starting from 1 star arcmin$^{-2}$ and spaced by 0.5 stars arcmin$^{-2}$. The innermost contour corresponds to 4.5 stars arcmin$^{-2}$ for UMi and to 6.0 stars arcmin$^{-2}$ for Draco. To give a term of comparison, Kleyna et al. (1998), using a sample with similar limiting magnitude, found a very similar value for the maximum density of UMi (~4 stars arcmin$^{-2}$) and estimated the density of the background to be 0.31 star arcmin$^{-2}$ at a distance of ~30′ from the center of UMi, much farther out than our outermost isodense.

The structure of the two galaxies, as shown in Figure 16, is in excellent agreement with previous results (Irwin & Hatzidimitriou 1995; Kleyna et al. 1998; Piatek et al. 2002; Odenkirchen et al. 2001): the ellipticity, position angle, and ratio between the central surface brightnesses are the same as reported in the review by Mateo (1998). Draco is more dense and has a much smoother profile with respect to UMi. Its isodensity contours are quite regular, showing just a marginal trend toward more boxy shapes in the outer parts. On the other hand, the inner contours of UMi appear quite structured and asymmetrical and deserve a deeper analysis and discussion.

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The detection of small-scale clustering and asymmetric structures in the inner parts of UMi has been claimed by many different authors since the early 1980s (see, e.g.,

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**Fig. 16.** Upper panels: CMDs of the two galaxies. The stars selected as members (bold dots) are used to derive the density contour maps shown in the lower panels. The outermost contour corresponds to a density of 1 star arcmin$^{-2}$; the contours are plotted in steps of 0.5 stars arcmin$^{-2}$ (i.e., 1.0, 1.5, 2.0, . . . etc.). The innermost contour corresponds to a density of 4.5 stars arcmin$^{-2}$ for UMi and 6.0 stars arcmin$^{-2}$ for Draco. The dotted contour in the map of UMi corresponds to a density of 3.2 stars arcmin$^{-2}$. It has been reported to show the low contrast structures in the northeastern region of the galaxy that have already been noted by Irwin & Hatzidimitriou 1995. The dotted contour shows also that the symmetry seen in the outer isodense curves breaks just above the density of 3 arcmin$^{-2}$. The density is estimated over a 100 pixel spaced grid. At each point of the grid, the density is estimated in a circle with radius = 3'.

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Olszewski & Aronson 1985; Irwin & Hatzidimitriou 1995; Kleyna et al. 1998; Battinelli & Demers 1999; Demers & Battinelli 2001; Eskridge & Schweitzter 2001), but a clear-cut demonstration of the statistical significance of such structures is still lacking. In Figure 16, the isodensity contours up to 3.0 stars arcmin$^{-2}$ appear quite elongated but similar in shape and symmetrical. On the other hand, the peak of density ($X \simeq 1.8; Y \simeq 3$) is clearly off-centered with respect to the center of symmetry of the outer contours ($X \simeq 4.3; Y \simeq 5.3$). We note that the density contrast between the density peak and the last symmetric contour is larger than 4 $\sigma$, i.e., quite significant. It is also remarkable that the off-centered main density peak displays a much rounder shape with respect to the rest of the galaxy. On the other hand, the dotted contour (corresponding to a density of 3.2 stars arcmin$^{-2}$) is reported to show that the substructures in the northeast region of the galaxy that are clearly visible in the maps by Irwin & Hatzidimitriou 1995 and Kleyna et al. (1998) are present also in our sample but have a low-density contrast with respect to the last symmetric contour, thus low statistical significance, as concluded also by Kleyna et al. (1998).

It is important to remark that the only other spheroidal galaxy of the Local Group that has a clearly off-centered density peak is the Sagittarius dSph, whose structure is greatly strained by the Galactic tidal field (see Ibata et al. 1997; Newberg et al. 2002). Independent evidence of the effects of the Galactic tidal fields on UMi has been reported by Martinez-Delgado et al. (2001).

Kleyna et al. (1998) found significant asymmetry in the distribution of stars along the major axis. Here we concentrate on the clustering properties of UMi stars. We define $d_n$ as the distance of a given star to its $n$th nearest neighbor. In the following, we will show the results obtained with $d_{200}$, i.e., the distance to the 200th nearest neighbor, but we remark that the results are preserved for a very wide range of $n$ ($50 \leq n \leq 500$). In the upper panel of Figure 17, the distributions of $d_{200}$ are shown for three template samples having the same dimensions of the observed ones ($\sim 2500$ member stars per galaxy). The dotted curve is the $d_{200}$ distribution of a sample randomly drawn from a uniform distribution. The continuous and dashed lines are the $d_{200}$ distributions of samples drawn from an elliptical Gaussian distribution having $\sigma_r = r_c$ (UMi) and $\sigma_r/\sigma_y = (a/b)$ UMi, and $\sigma_r = r_c$ (Dra) and $\sigma_r/\sigma_y = (a/b)$ Dra, respectively, where $a$ and $b$ are the semimajor and semiminor axes of the galaxies, as listed by Mateo (1998). It can be easily appreciated that (1) more concentrated (denser) systems have $d_{200}$ distributions peaked at shorter lengths and (2) independently of the assumed density profile, the $d_{200}$ distributions of symmetric and smooth systems show a single major peak, marking the characteristic clustering scale, followed by a very sharp cutoff. In these systems, there are no stars having $d_{200}$ shorter than the cutoff value.

In the middle panel of Figure 17, the $d_{200}$ distribution of Draco is presented. The observed distribution is very well reproduced by its template: the characteristic clustering scale is $\sim 500$ pixels $\simeq 2/3$ and no star with clustering scale shorter than the cutoff ($\sim 480$ pixels) is observed. On the other hand, the $d_{200}$ distribution of UMi (Fig. 17, lower panel) is quite different from that of Draco and from the smooth/symmetric templates. The major peak and the cutoff are well reproduced by the corresponding template but there is a clear secondary peak at shorter scale lengths with respect to the main cutoff. The presence of this secondary peak shows that there are two characteristic scales of clustering in UMi, a longer one ($\sim 700$ pixels $\simeq 3/2$) associated with the general properties of the system and a shorter one ($\sim 600$ pixels $\simeq 2/7$) associated with the more compact structures corresponding to the off-centered density peak.

Can the observed $d_{200}$ distribution of UMi arise by chance (i.e., small-number fluctuations) from an intrinsically smooth and unstructured system? To answer this question, we extracted 1000 random samples from the model assumed for the UMi template shown in the upper panel of Figure 17 and, for each of them, we computed the fraction of stars having $d_{200}$ lower than the observed cutoff $F(d_{200} < d_{200}^{\text{cutoff}})$ (hereafter $F_d$ for brevity), fixed at $d_{200} = 630$ pixels. The distribution of the $F_d$ of the simulated samples is shown in Figure 18. The observed fraction ($F_d = 0.12$) is indicated by a dotted line. Figure 18 shows that (1) in no case a sample having $F_d$ equal or greater than the observed value has been extracted from the unstructured model, (2) the highest $F_d$ value reached by a simulation ($F_d \simeq 0.08$) is significantly lower than the observed one, and (3) 95% of the simulated samples have $F_d \leq 0.04$. We conclude that the observed presence of two characteristic clustering scales is a real and statistically significant property of UMi.

Finally, we find that the spread in magnitude of the blue HBs of Draco and UMi is small and compatible with the observational scatter at that magnitude. Thus, we cannot see any sign of the significant elongation along the line of sight that was required in the model by Klessen & Kroupa (1998) to explain the large velocity dispersion observed in dSph galaxies without the need of massive dark matter halos (see also Aparicio et al. 2001).
shows that the second peak in the times larger than the largest value obtained in these simulations. This test line marks the value of \( F \) unstructured model of UMi shown in the upper panel of Fig. 17. The dotted chance from a smooth and symmetrical model.

V derived a distance modulus to Draco by (1) estimating \((2000)\) obtained \( V_{RR} = 19.84 \pm 0.07 \) and \((m-M)_0 = 19.40 \pm 0.10\), in excellent agreement with our results.

Indepenently of the above considerations, it is important to remark that the actual uncertainty on state-of-the-art distance estimates to Draco and UMi remains approximately \( \pm 25\% \), in spite of all efforts. It is clear that classical distance indicators are inefficient in this context and valid alternatives are certainly needed. The search for detached double-lined eclipsing binaries (DD-EB) is now possible with new-generation instruments and may be very rewarding, given the high binary fraction that has been reported for these two galaxies (Olszewski, Pryor, & Armandroff 1996).

7. DISCUSSION

The distance estimates to Draco and UMi derived in § 4 are tied to the distance scale introduced by F99 and compatible with the TRGB scale introduced by Bellazzini et al. (2001a). The F99 scale is fully consistent with the scale based on the revised \textit{Hipparcos} parallaxes by Carretta et al. (2000). F99 showed that their distance moduli of globular clusters are typically \( \sim 0.2 \) mag larger than those tied to the traditional \( M_V(\text{RR})-[\text{Fe}/\text{H}] \) calibration relation. This is probably the main reason why we find distance moduli for UMi and Draco that are larger by 0.2–0.3 mag than what is generally found in the literature (see, e.g., Mateo 1998 and references therein). We note also that, independently of the distance scale, our procedure of HB matching leads to results that are in excellent agreement with works based on the RR Lyrae (e.g., N88; Nemec 1985), while a sensible mismatch is noticed with respect to the main-sequence fitting technique adopted by Mighell & Burke (1999) using \textit{HST} data. We argue that the problems with the absolute photometric calibration of \textit{HST} WFPC2 data may be at the origin of the observed differences.

The comparison with the recent distance estimates by Aparicio et al. (2001) (for Draco) and Carrera et al. (2002) (for UMi) is of particular interest. Aparicio et al. (2001) derived a distance modulus to Draco by (1) estimating \( V_{RR} \) from the observed HB and (2) adopting the classical \( M_V(\text{RR})-[\text{Fe}/\text{H}] \) relation by Lee et al. (1999). They obtain \( V_{RR} = 20.14 \pm 0.12 \), compatible with our estimate within the uncertainties, but their final distance modulus \([m-M]_0 = 19.5 \pm 0.2\) is 0.34 mag smaller than ours. However, if the above-quoted systematic difference of \( \sim 0.2 \) mag between the F99 distance scale and the scale by Lee et al. (1999) is taken into account, the consistency between the two estimates is clearly recovered. On the other hand, Carrera et al. (2002) derived the mean level of RR Lyrae in UMi by a comparison with template globular cluster of similar metallicity, i.e., the same method adopted here. Moreover, the distance moduli of the template clusters were taken from Reid (1999), who derived them from main-sequence fitting to \textit{Hipparcos} subdwarfs. With this approach, Carrera et al. (2002) obtained \( V_{RR} = 19.84 \pm 0.07 \) and \((m-M)_0 = 19.40 \pm 0.10\), in excellent agreement with our results.

The metallicity distributions presented here confirm (with larger samples, with respect to existing spectroscopic surveys) that the stellar populations of both galaxies have a sizeable spread in metal content. Since they are dominated by very old stars, we conclude that significant self-enrichment took place in these systems in quite a short timescale (i.e., a few Gyr) at very early epochs. The same conclusions have been previously reached for Sculptor (Majewski et al. 1999) and Sextans (Bellazzini et al. 2001b). Shetrone et al. (2001a) have shown that some of the stars of UMi, Dra, and Sex show abundance patterns significantly different from those typical of Galactic halo stars. In particular, it has been suggested (Ikuta & Arimoto 2002) that the transition from an \( \alpha \)-enhanced regime to nearly solar \([\alpha/\text{Fe}] \) ratios occurred at a much lower \([\text{Fe}/\text{H}] \) value than in our own Galaxy. This evidence led Shetrone et al. (2001a) to conclude that it is unlikely that systems such as UMi and Draco gave a significant contribution to the assembly of the Galactic halo. We remark here that this conclusion is correct only for satellites that would have been accreted by the Milky Way in an advanced stage of their chemical evolution. A very early accretion (i.e., within \( \sim 1 \) Gyr of the onset of star formation) or simply a very early stripping of the gaseous component by the Galaxy would not leave any peculiar chemical signature in a Galactic halo largely composed by building blocks such as Draco, UMi, or Sextans (as they were in their first Gyr of “stellar” life).

Our results show also that, while the average metallicity of the two galaxy is similar, the difference in the MDs is significant. The MD of UMi peaks at \([\text{Fe}/\text{H}] \approx -1.9\) and barely reaches \([\text{Fe}/\text{H}] \approx -1.6\), while that of Draco peaks at \([\text{Fe}/\text{H}] \approx -1.6\) and reaches \([\text{Fe}/\text{H}] \approx -1.3\). This fact has to be taken into account, in particular in the interpretation of the great difference in HB morphology between the two galaxies. Dra and UMi are not a good “second parameter.
pair” (see Bellazzini et al. 2001c and references therein); a sizeable part of the HB morphology difference may be due to the differences in the actual MD. The large population of binaries (and blue stragglers) hosted by the galaxies (Olszewski et al. 1996) may also be have some impact on the observed HB morphology, especially in the case of Draco (see Fusi Pecci et al. 1992; Bellazzini et al. 2001c, 2002a; Carney et al. 2001, and references therein).

7.2. A Striking Structural Difference: Not Such Twins after All?

Draco and UMi have similar distance from the center of the Galaxy, similar luminous mass, and similar star formation histories. Both are thought to have high \( M/L \) and probably also similar orbits, since they have similar radial velocities and (possibly) proper motions (see Mateo 1998; Scholz & Irwin 1994; Schweitzer, Cudworth, & Majewski 1997). In spite of that, while Draco shows a very symmetrical and smooth profile out to a very large distance from the center (Odenkirchen et al. 2001; Piatek et al. 2002), we have demonstrated that even the innermost regions of UMi are strongly structured and asymmetrical. The presence of a massive and extended CDM halo should have inhibited the formation of any significant substructure in the stellar component of UMi. The star formation activity cannot be responsible for the disturbed structure of this galaxy since significant star formation episodes ceased many Gyr ago. Furthermore, we accurately checked for possible differences in the stellar populations between the off-centered (and nearly round) density peak of UMi and its outer regions and found none.

Ferraro, Bellazzini, & Pancino (2002) showed that a small self-gravitating stellar system is embedded into the main body of the peculiar globular cluster \( \omega \) Cen. This stellar system has likely managed to preserve its individuality over many Gyr while orbiting into the stellar halo of the cluster. A similar possibility could be envisaged also to explain the origin of the peculiar density peak of UMi. The process of hierarchical merging is expected to be scale-free, thus the records of the formation of a galaxy such as UMi from smaller fragments may be still detectable today (see Fellhauer & Kroupa 2000), possibly favored by the fact that the putative fragment we are considering is much denser than the stellar medium in which it is embedded. The main argument against this hypothesis is the already-reported observational evidence that the stellar population in the density peak does not differ from the average UMi population (as opposed to the \( \omega \) Cen case; see Ferraro et al. 2002, and references therein). Large high-resolution spectroscopic surveys may possibly provide more stringent indications on the viability of this scenario.

While we were writing, a new preprint was posted (Palma et al. 2002, hereafter P02) in which our results about the structure of UMi are fully confirmed. Furthermore, P02 were able to follow the structure of UMi out to a distance of \( \sim 1.7 \) from the center and demonstrated that (1) the galaxy is elongated along the direction of its proper-motion vector and (2) the outer isodensity contours of UMi have the typical S-shape of tidally disturbed stellar systems. If it will be spectroscopically confirmed that the stars in the S-shaped structures are unbound or the signature of apparent rotation will be found, this would directly disprove a specific prediction of the CDM simulations (Hayashi et al. 2002). In any case, the strongly disturbed structure of UMi provides a severe challenge to standard CDM scenarios, above all if the comparison with Draco is considered. Moreover, P02 showed that previous estimates of the total luminosity of UMi had missed a significant amount of light that is found at large distances from the center of the galaxy. Their estimate of total luminosity is 2.7 times larger than previous ones. Taking this into account and considering the (possible) effects of anisotropic velocity dispersions, they were able to reduce the mass-to-light ratio of UMi down to \( M/L \sim 16 \). If we include in this computation the effects of our larger distance modulus [and assuming \( M_{00}(UMi) = 2.3 \times 10^7 M_\odot \), after Mateo 1998], we obtain \( M/L \sim 7 \), just a factor of \( \sim 7 \) larger than the typical \( M/L \) of ordinary globular clusters.

From the above discussion, it appear that further observational and theoretical efforts are still needed to fully understand the nature of UMi and Draco. It is quite possible that we have some fundamental lesson to learn from these faint and unassuming stellar systems.

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5 However the clustering properties of UMi stars are not considered in that work.

6 In fact, the presently available observations of Draco are very well fitted by the predictions of CDM models (Hayashi et al. 2002).

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