1. INTRODUCTION

In the Λ-cold dark matter (Λ-CDM) paradigm, larger galaxies are hierarchically assembled by merging of small CDM fragments (Diemand et al. 2007; Springel 2005), as also recently confirmed by the high-resolution simulations “Aquarius” (Lunnan et al. 2012; Springel et al. 2008). The idea is attractive when applied to our Galaxy, since it echoes the pioneering scenario suggested by Searle & Zinn (1978, hereafter SZ), in which the Milky Way (MW) was successively built up from small substructures. Indeed, first attempts to link the SZ scenario with the cosmological simulations foresaw the assembling of the Galactic halo starting from a number of satellites, and producing a number of tidal streams that should be (and are in fact) observed (Bullock et al. 2001). The survivors of such a process should have the observational characteristics of the present-day dwarf spheroidal galaxies (dSphs), which are old, metal-poor, and gas deficient systems.

However, according to the Λ-CDM theory, the expected number of surviving fragments of the accretion process is one or two orders of magnitude larger than the observed number of MW “bright” dSph companions. It was also pointed out that the present-day “bright” dwarfs may be the wrong remnants, as they could instead be tidal dwarf galaxies, with a non-primordial origin (e.g., Metz et al. 2008). In any case this so-called missing satellites problem (Moore et al. 1999; Klypin et al. 1999) has represented, so far, a major issue of the comparison between theoretical expectations and observational evidence. The discrepancy was partially alleviated in the past few years by the discovery of several “ultra-faint” dwarf (UDF) galaxies surrounding the MW, on the basis of the analysis of the Sloan Digital Sky Survey (SDSS) data (e.g., Koposov et al. 2009 and references therein). The UFDs bring the number of known MW dSph satellites to ≈27 (e.g., Mateo 1998; Belokurov et al. 2010, and references therein). Since the sky coverage of the SDSS is only ~1/4 of the celestial sphere, basic statistical arguments suggest that tens of these faint MW satellites are still undiscovered, thus further narrowing the gap between theoretical expectations and observational evidence unless, as suggested by Metz et al. (2009), the distribution of these faint systems is not uniform and follows instead a disk around the MW.

ABSTRACT

We present a $B$, $V$ color–magnitude diagram (CMD) of the Milky Way dwarf satellite Ursa Major II (UMa II), spanning the magnitude range from $V \sim 15$ to $V \sim 23.5$ mag and extending over an $18 \times 18$ arcmin$^2$ area centered on the Galaxy. Our photometry goes down to about 2 mag below the Galaxy’s main-sequence turnoff that we detected at $V \sim 21.5$ mag. We have discovered a bona fide RR Lyrae variable star in UMa II, which we use to estimate a conservative dereddened distance modulus for the galaxy of ($m - M)_0 = 17.70 \pm 0.04 \pm 0.12$ mag, where the first error accounts for the uncertainties of the calibrated photometry, and the second reflects our lack of information on the metallicity of the star. The corresponding distance to UMa II is $34.7^{+0.6}_{-0.5}(^{+12.0}_{-9.1})$ kpc. Our photometry shows evidence of a spread in the Galaxy’s subgiant branch, compatible with a spread in metal abundance in the range between $Z = 0.0001$ and $Z = 0.001$. Based on our estimate of the distance, a comparison of the fiducial lines of the Galactic globular clusters M68 and M5 ($(Fe/H) = -2.27 \pm 0.04$ dex and $-1.33 \pm 0.02$ dex, respectively), with the position on the CMD of spectroscopically confirmed Galaxy members, may suggest the existence of stellar populations of different metal abundance/age in the central region of UMa II.

Key words: galaxies: dwarf – galaxies: individual (Ursa Major II) – stars: distances – stars: variables: RR Lyrae – techniques: photometric

Online-only material: color figures, machine-readable table

* Based on data collected at the 1.52 m telescope of the INAF-Osservatorio Astronomico di Bologna, Loiano, Italy, at the 2.3 m telescope of the Wyoming Infrared Observatory (WIRO) at Mt. Jelm, WY, USA, and at the 1.8 m Perkins telescope of the Lowell Observatory, at Anderson Mesa, Flagstaff, AZ, USA.
Whatever the case, in order to be “proper” remnants of the primordial Galactic halo contributors the observed satellites should host old stellar populations with properties compatible with those of the MW halo. In particular, they should contain stars as metal-poor as [Fe/H] < −3.0 or −4.0 dex ("extremely metal-poor stars"); Beers & Christlieb 2005 and RR Lyrae stars with pulsation properties conforming to the Oosterhoff dichotomy (Oosterhoff 1939) observed for field and cluster MW RR Lyrae variables (Catelan 2009 and references therein). Regarding both aspects the “bright” MW dSph satellites do not seem to be the possible primordial contributors to the Galactic halo, as spectroscopic studies (e.g., Helmi et al. 2006) show that there are very few extremely metal-poor stars in most of the “bright” MW dSph satellites (Tolstoy et al. 2009 and reference therein) and, on the other hand, these galaxies are generally classified as "Oosterhoff-intermediate" (e.g., Carina: Dall’Ora et al. 2003; Fornax: Bersier & Wood 2002) because their fundamental-mode RR Lyrae stars have average periods (⟨Pab⟩) intermediate between the Oosterhoff I (OoI; ⟨Pab⟩ = 0.55 days) and II (OoII; ⟨Pab⟩ = 0.65 days) types observed for the MW field and cluster variables. The Ursa Minor dSph (⟨Pab⟩ = 0.638 days) and the Sagittarius (⟨Pab⟩ = 0.574 days) are the only exceptions to this generally accepted “rule” among the “bright” dwarfs (Smith et al. 2009 and references therein).

The UFDs, instead, seem to possess both proper metal abundances, as shown by a number of spectroscopic studies (e.g., Simon & Geha 2007; Kirby et al. 2008; Frebel et al. 2010), as well as compatible properties of stellar populations and variable stars, as shown by our long-term project to monitor the UFD variable stars (see Moretti et al. 2009 for a summary). In brief, the five galaxies we have studied so far, namely, Bootes I (Dall’Ora et al. 2006), Canes Venatici I (CVn I; Kuehn et al. 2008), Canes Venatici II (CVn II; Greco et al. 2008), Coma Berenices (Coma; Musella et al. 2009), and Leo IV (Moretti et al. 2009), contain RR Lyrae stars with pulsation periods suggesting an Oo II classification, with the exception being CVn I, which appears to be Oosterhoff-intermediate. In this respect, we remark that both total luminosity and global metallicity of CVn I make this object more likely a “classical” dSph than a UFD (see, e.g., Figure 5 of Kirby et al. 2008). Continuing our study of variable stars in the Galactic UFDs in this paper we present results for Ursa Major II (UMa II).

UMa II (RA. = 08h51m30s, decl. = +63°07’48”, J2000; Zucker et al. 2006) was initially discovered as a candidate star cluster in the Galactic halo by Grillmair (2006), and only afterward recognized as a dwarf galaxy by Zucker et al. (2006). According to Simon & Geha (2007) and Muñoz et al. (2010), UMa II appears to be a very elongated and extended object, likely undergoing tidal disruption. This suggestion is supported by the existence of a velocity gradient along the major axis of 8.4 ± 1.4 km s⁻¹ between eastern and western sides of the Galaxy (Simon & Geha 2007). This gradient shows the same direction of elongation as discussed in Muñoz et al. (2010).

The Galaxy was proposed to be the progenitor of the so-called Orphan Stream (Fellhauer et al. 2007). Zucker et al. (2006) derived a half light radius of r₅₀ ∼ 13' for the galaxy, and highlighted that the central part of UMa II breaks up into three distinct clumps. Subsequently, Muñoz et al. (2010) on the basis of deep, wide-field Canada–France–Hawaii Telescope (CFHT) photometry, showed that this apparent clumping is due to the poor statistics of the bright stars, and disappears when deeper data are used. Moreover, they showed that UMa II is more extended than previously thought. The same conclusion was reached by Newberg et al. (2010), from the analysis of the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009) spectroscopic and SDSS/SEGUE photometric data. These findings seem to rule out the link between UMa II and the Orphan Stream. Spectroscopic studies disclosed the presence of very metal-poor stars in the galaxy, with [Fe/H] ∼ −3.0 dex, and detailed abundance patterns consistent with those observed in the Galactic halo (Kirby et al. 2008; Frebel et al. 2010). Martin et al. (2008) derived new structural parameters for UMa II, adopting a slightly different position for the Galaxy center and a flatter shape with a slightly larger r₅₀, compared to Zucker et al. (2006). In the following, we use the structural parameters derived by Zucker et al. (2006). However, our conclusions would not be affected if we used Martin et al.’s parameters instead.

### 2. OBSERVATIONS AND DATA REDUCTION

Time-series observations of UMa II were obtained between 2007 January and March with three different telescopes. At the Wyoming Infrared Observatory (WIRO) 2.3 m telescope, using the WIRO Prime Focus Camera, we obtained 40 images in Johnson V, 12 images in Johnson B, and 22 images in Cousins I. At the 1.8 m Perkins telescope of the Lowell Observatory, we used the Perkins Re-Imaging SysteM (PRISM) instrument in photometry mode to obtain 12 V, 4 B, and 4 I images of UMa II. Five nights at the Loiano Observatory 1.5 m telescope provided 14 B and 15 V images using the Bologna Faint Object Spectrograph and Camera (BFOSC). The WIRO observations cover the largest area with a field of view (FOV) of 17.8 × 17.8 at the pixel scale of 0.55 arcsec pixel⁻¹, pointed on the center coordinates of UMa II derived by Zucker et al. (2006). The FOVs at the Lowell and Loiano telescopes are slightly smaller, 13.65 × 13.65 (0.39 arcsec pixel⁻¹) and 13’ x 12.6 (0.58 arcsec pixel⁻¹), respectively. The total area covered by our observations is 18.38 × 18.26. This corresponds to the central clump of UMa II, while the other two clumps reported by Zucker et al. (2006) are both slightly outside the field covered by our observations. The log of observations is provided in Table 1.

| Night       | Instrument | Filter | Exposure (s) | No. of images | Median Seeing (arcsec) |
|-------------|------------|--------|--------------|---------------|------------------------|
| 2007 Jan 16 | WIRO       | V      | 10           | 4             | 3.4                    |
| 2007 Jan 17 | WIRO       | V      | 20           | 30            | 2.6                    |
| 2007 Jan 17 | WIRO       | V      | 60           | 6             | 2.6                    |
| 2007 Jan 17 | WIRO       | B      | 30           | 12            | 2.2                    |
| 2007 Feb 22 | PRISM      | V      | 300          | 12            | 2.0                    |
| 2007 Feb 22 | PRISM      | B      | 600          | 4             | 2.1                    |
| 2007 Mar 12 | BFOSC      | V      | 1200         | 3             | 1.6                    |
| 2007 Mar 12 | BFOSC      | B      | 1200         | 3             | 1.6                    |
| 2007 Mar 13 | BFOSC      | V      | 1200         | 3             | 1.4                    |
| 2007 Mar 13 | BFOSC      | B      | 1200         | 3             | 1.4                    |
| 2007 Mar 14 | BFOSC      | V      | 1200         | 2             | 1.6                    |
| 2007 Mar 14 | BFOSC      | B      | 1200         | 2             | 1.3                    |
| 2007 Mar 15 | BFOSC      | V      | 1200         | 2             | 1.5                    |
| 2007 Mar 15 | BFOSC      | B      | 1200         | 3             | 1.5                    |
| 2007 Mar 16 | BFOSC      | V      | 1200         | 3             | 1.6                    |
| 2007 Mar 16 | BFOSC      | B      | 1200         | 2             | 1.4                    |

**Note.** See the text for details on the individual instruments.
3. IDENTIFICATION OF VARIABLE STARS AND DISTANCE TO THE GALAXY

For each star, calibrated time-series photometry was obtained first by shifting the instrumental magnitudes to the WIRO instrumental photometric system, and then calibrating the WIRO-aligned data to the Johnson photometric system. We omitted the relative color term dependence since the relative color terms were small enough in the observed color range of the RR Lyrae stars (0.2 < \(B - V\) < 0.5 mag) to be considered negligible for our purposes. Search and identification of candidate variable stars were performed with two different methods: (1) the Stetson (1993) variability index, which compares the spread of individual measurements with the intrinsic photometric error and (2) an ad hoc procedure in which we first computed the Fourier transforms (in the Schwarzenberg-Czerny 1996 formulation) of the stars having at least 12 measurements in each photometric band.

Data sets from each observatory were pre-reduced using standard IRAF\(^{12}\) techniques (bias subtraction and flat fielding). Since we lack a photometric calibration of the \(I\)-band data, observations in this band were not considered in the subsequent analysis and only the \(B, V\) data are presented in the paper. Point-spread function (PSF) photometry was performed with the DAOPHOT IV/ALLFRAME (Stetson 1987, 1994) package. After an accurate evaluation of the PSF of each individual frame, a reference image was built by averaging all the available frames and a source catalog was extracted from the stacked image. The source list was then passed to ALLFRAME, which performed homogeneous PSF photometry simultaneously on all images, thus producing \(b\) and \(v\) instrumental magnitude catalogs for each telescope. Typical internal photometric errors were of the order of 0.01–0.02 mag at the horizontal branch (HB) level, on the averaged catalog, while the signal-to-noise ratio (S/N) greatly changes between the individual exposures, due to the different telescope sizes and very different exposure times adopted at the various sites.

To calibrate our photometry, additional \(B, V\) observations of UMa II, along with standard fields centered on the open clusters NGC 188 and NGC 7790, selected from the publicly available standard stars archive maintained by P. B. Stetson\(^{13}\), were obtained on a photometric night in 2008 January, at the 3.5 m Telescopio Nazionale Galileo (TNG) in La Palma, Canary Islands. We used the standard La Palma extinction coefficients\(^{14}\) to derive the following calibration equations:

\[
B = b + (0.058 \pm 0.007)(B - V) + (26.400 \pm 0.020)
\]

\[
V = v + (0.082 \pm 0.014)(B - V) + (26.141 \pm 0.010),
\]

where \(B, V\) and \(b, v\) are the standard and the instrumental magnitudes, respectively.\(^{15}\) The rms of these equations is of \(\sim 0.02\) mag in both bands. These calibrations were used to define secondary standards in the field of UMa II. In particular, we selected 25 isolated local standards with photometric errors less than 0.05 mag which were visually inspected to remove any non-stellar objects. The remaining stars cover a range in color of 0.1 < \(B - V\) < 1.7 mag. Since the three telescopes define slightly different photometric systems, the individual data sets were calibrated separately, and for each filter a final master catalog was obtained by averaging the measurements of the individual telescopes. Typical uncertainties in calibrating our data set on the TNG local standards were in the range of 0.01–0.03 mag. Figure 1 shows the photometric internal error as a function of the calibrated magnitude, both in the \(B\) and \(V\) bands.

\(^{12}\) IRAF is distributed by the National Optical Astronomical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

\(^{13}\) http://www4.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/community/STETSON/standards/

\(^{14}\) http://www.ast.cam.ac.uk/~dwe/SRF/camc_extinction.html

\(^{15}\) The instrumental magnitude for a generic band \(X\) is defined as \(m_X = -2.5 \log(F_X) - K_X X\), where \(F_X\) is the flux normalized to 1 s, \(K_X\) is the extinction coefficient, and \(X\) is the airmass.
band, and then we averaged these transforms to estimate the noise and calculated the S/Ns. Results from B and V photometries were cross-correlated, and all stars with S/N > 4 in both photometric bands were visually inspected, for a total of ~200 candidates. In particular, we checked all the stars around the Galaxy’s HB and some of the stars in the blue stragglers region of the color–magnitude diagram (CMD) which might be pulsating variables of the SX Phoenicis type. The light curves of the candidate variables were inspected by eye. We confirmed only one candidate variable, whose multiband light curves were analyzed with the Graphical Analyzer of Time Series (GRaTiS; Clementini et al. 2000) package, obtaining a classification as RR Lyrae with pulsation period of 0.6593 days.\footnote{See note added in proof on p. 8.} We note that, selecting a brighter zero point of a metallicity of \([\text{Fe}/\text{H}] = -2.12\text{ mag}\) appears to be slightly too blue for the star pulsation period. We will discuss this further at the end of the section.

We have estimated the distance to UMa II from its RR Lyrae, by adopting the calibration of the absolute V magnitude of the RR Lyrae stars as a function of the metallicity provided by Clementini et al. (2003) and Gratton et al. (2004), who derived \(\Delta M_V = \frac{\Delta [\text{Fe}/\text{H}]}{0.047}\text{ mag}\) from a sample of 100 RR Lyrae stars in the Large Magellanic Cloud (LMC) spanning the metallicity range from \([\text{Fe}/\text{H}] = -2.12\text{ to } -0.27\text{ dex}\), and the RR Lyrae zero point \(M_V = 0.047\text{ mag at } [\text{Fe}/\text{H}] = -1.5\text{ dex}\), proposed by Cacciari & Clementini (2003). We explicitly note that, selecting a brighter zero point of \(M_V = 0.047\text{ mag at } [\text{Fe}/\text{H}] = -1.5\text{ dex}\), which is in agreement with the LMC distance modulus of \((m - M)_0 = 18.52\) mag (Clementini et al. 2003), the kernel of our analysis is not changed. Adopting a metallicity of \([\text{Fe}/\text{H}] = -2.44 \pm 0.06\text{ dex for UMa II (Kirby et al. 2008), an average apparent magnitude of the UMa II HB of } (V_{\text{HB}}) = 18.39\text{ mag, as derived from the Galaxy RR Lyrae star, and a reddening of } E(B-V) = 0.096\text{ mag.}}

\begin{table}
\centering
\caption{\textit{B, V} Photometry of the RR Lyrae Star Detected in UMa II}
\begin{tabular}{lcc}
\hline
\textbf{HJD} & \textbf{B} & \textbf{V} \\
(\text{2454117}) & (mag) & (\text{2454116}) & (mag) \\
\hline
0.756437 & 18.27 & 0.900689 & 18.92 \\
0.757167 & 18.27 & 0.902199 & 18.81 \\
0.758047 & 18.28 & 0.902819 & 18.87 \\
0.758747 & 18.27 & 0.903249 & 18.91 \\
0.759427 & 18.29 & 0.903679 & 18.75 \\
0.761087 & 18.29 & 1.750797 & 17.97 \\
0.832037 & 18.69 & 1.752317 & 17.98 \\
0.832677 & 18.69 & 1.752877 & 17.98 \\
0.833317 & 18.70 & 1.753467 & 18.00 \\
0.834037 & 18.68 & 1.753997 & 18.00 \\
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{\textit{B, V} light curves of the lonely bona fide RR Lyrae variable, star V1, detected in the UMa II dSph (see the text for details).}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3}
\caption{Period–amplitude diagram in the \textit{V} band. The solid lines show the positions of the Oo I and Oo II Galactic GCs, according to Clement & Rowe (2000). Different symbols correspond to RR Lyrae stars identified in five of the ultra-faint SDSS dwarfs studied so far for variability (namely, Bootes I, CVn II, Coma, Leo IV, and UMa II, from the present study). For UMa II, we have plotted the amplitude of the truncated Fourier series best fitting the \textit{V} data (\(A_V = 1.22\text{ mag}\)). Results are unchanged if we use instead the amplitude corresponding to the difference of the observed minimum and maximum light data points (\(A_V = 1.09\text{ mag}\)). (A color version of this figure is available in the online journal.)}
\end{figure}
corresponding to 34.7 kpc (Simon & Geha 2007), Kirby et al. (2008), and Frebel et al. (2010), respectively. The cyan filled circle marks the galaxy’s bona fide RR Lyrae star found in our study, while the cyan filled triangle shows a suspected RR Lyrae in Simon & Geha (2007) study. This star falls outside the FOV of our observations, and its magnitudes are taken from Simon & Geha (2007) and correspond to random phase values. (A color version of this figure is available in the online journal.)

Figure 4. $V, B − V$ color–magnitude diagram of UMa II with superimposed the ridgelines of the Galactic globular clusters M68 (blue dashed line) and M5 (red dashed line). Large blue, red, magenta, and cyan open symbols identify spectroscopically confirmed members of UMa II according to Martin et al. (2007), Simon & Geha (2007), Kirby et al. (2008), and Frebel et al. (2010), respectively. The cyan filled circle marks the galaxy’s bona fide RR Lyrae star found in our study, while the cyan filled triangle shows a suspected RR Lyrae in Simon & Geha (2007) study. This star falls outside the FOV of our observations, and its magnitudes are taken from Simon & Geha (2007) and correspond to random phase values. (A color version of this figure is available in the online journal.)

Table 3
Identification and Properties of the RR Lyrae Star Detected in UMa II

| Name | $α$ (2000) | $δ$ (2000) | Type | $P$ (days) | Epoch ($−2450000$) | $(V)$ (mag) | $N_V$ | $(B)$ (mag) | $N_B$ | $A_V$ (mag) | $A_B$ (mag) |
|------|------------|------------|------|------------|-----------------|-----------|----------|-----------|----------|-------------|-------------|
| V1   | 08:50:37.43 | +65:10:10.0 | RRab | 0.6595     | 4153.8779       | 18.39     | 53       | 18.61     | 16        | $≥1.09(1.22)$ | $≥1.27(1.38)$ |

Note. Mean values are intensity-averaged mean magnitudes.

4. THE STELLAR POPULATION(S) OF THE UMa II UFD

Figure 4 shows our CMD of UMa II, where to minimize the contamination by non-point sources we only plot objects with DAOPHOT parameters $χ < 1.4$ and $-0.3 < sharpness < +0.3$ and also considered only stars within the Galaxy’s half light radius ($r_h ≈ 13$ arcmin, as worked out from the preliminary values of distance, $d ≈ 30$ kpc, and linear half light radius $r_h ≈ 120$ pc; published by Zucker et al. 2006). UMa II appears to be quite elongated with an ellipticity of $≈ 0.5$, therefore we adopted the azimuthally averaged value of the half light radius (Zucker et al. 2006). We explicitly note that UMa II shows a rapidly varying ellipticity, with values ranging from $ε = 0.40$ in the center to $ε = 0.73$ near its half light radius (Muñoz et al. 2010), but this does not affect our conclusions about the stellar populations present in the galaxy. The RR Lyrae star we have discovered in the galaxy is marked by a cyan filled circle, while the cyan filled triangle shows the position of star SDSSJ084947.6+630830, which was suspected to be an RR Lyrae variable by Simon & Geha (2007) on the basis of the observed radial velocity and spectral type variations. Unfortunately, this star falls outside our FOV. Nevertheless, we
show its position on our CMD, after transforming the SDSS g, r magnitudes to the Johnson standard system with the relations by Fukugita et al. (1996), as it appears to be consistent with the RR Lyrae instability strip, thus supporting the Simon & Geha (2007) hypothesis. Blue, red, magenta, and cyan open circles mark spectroscopically confirmed members of UMa II according to Martin et al. (2007), Simon & Geha (2007), Kirby et al. (2008), and Frebel et al. (2010), respectively. No correction for contamination by Galactic field stars was made, as our attempt to compare the Proper Motions Extended catalog (PPM-Extended; Roeser et al. 2010) entries of the spectroscopically confirmed UMa II members with all the other stars present in the field did not show a clear separation.

UMa II is characterized by a very low average metal abundance \([\text{Fe/H}] = -2.44 \text{ dex}\), an internal metallicity spread as large as \(\approx 0.6 \text{ dex}\) (Kirby et al. 2008), and \(\alpha\) element abundances in agreement with those observed in the Galactic halo \((\alpha/\text{Fe}) = 0.4 \text{ dex}(\text{Frebel et al. 2010 and references therein). In Figure 4, we have overplotted to the UMa II CMD the ridgelines of the Galactic globular clusters (GCs) M68 (blue dashed line; from Walker 1994) and M5 (blue solid line; from Sandquist et al. 1996), because these two GCs well encompass the metallicity range found in the Galaxy. Indeed, M68 is a metal-poor cluster, with \([\text{Fe/H}] = -2.27 \pm 0.04 \text{ dex}\) (Carretta et al. 2009), and more recent determinations claim an even lower metallicity of \([\text{Fe/H}] = -2.44 \pm 0.1 \text{ dex}\) (Simmons et al. 2011), hence very similar to the average metallicity of UMa II; M5 is a metal-intermediate cluster, with \([\text{Fe/H}] = -1.33 \pm 0.02 \text{ dex}\) (Carretta et al. 2009). The ridgelines were properly shifted to account for differences in distance and reddening. For M68, we used the RR Lyrae mean apparent V magnitude \((V(\text{RR})) = 15.60 \text{ mag}\) by Walker (1994) and a reddening of \(E(B-V) = 0.05 \text{ mag}\), as available in the compilation by Harris (1996). With these values we get an apparent distance modulus of 15.11 mag, by adopting the RR Lyrae magnitude–metallicity calibration as above. For M5, we have adopted \((m-M)_0 = 14.44 \text{ mag}\) from Coppola et al. (2011) and \(E(B-V) = 0.03 \text{ mag}\) (Harris 1996).

Our RR Lyrae based distance to UMa II is supported by the good match of the M68 ridgelines and the UMa II subgiant branch (SGB), and by the very satisfactory alignment, along both the M68 and M5 HBs, of three bona fide UMa II stars, one of them being a spectroscopically confirmed member. The good match between a few stars located at \(V\) in the range from 21.0 to 21.5 mag and the \(B-V\) color between 0.4–0.5 and 0.7–0.8 mag, two of which are spectroscopically confirmed members of UMa II with the M5 ridgeline, seems to suggest the presence of a second SGB. This is not surprising, since the quoted spectroscopic works clearly demonstrate the occurrence of stellar populations with different metallicities in this UFD. Moreover, the Galaxy bona fide main sequence appears to have an observed width of \(\approx 0.2 \text{ mag}\) in the range of luminosities between \(V \approx 22\) and \(V \approx 23 \text{ mag}\), while the width expected in that range due to the photometric errors alone would be of the order of \(\sigma_{V-B} \approx 0.1 \text{ mag}\) (see Figure 1). In the following, we will refer to the stars close to the M68 and M5 ridgelines as “blue” and “red” populations, respectively. To check if the blue and red population are also compatible with a spread in the age, we have compared in Figure 5 the CMD of UMa II with the BaSTI (Bag of Stellar Tracks and Isochrones) \(\alpha\)-enhanced isochrones by Pietrinferni et al. (2006). Following the recent \(\alpha\)-enhanced abundances measured by Frebel et al. (2010), we have adopted for the blue population the \(\alpha\)-enhanced models with \(Z = 0.0001\) and \([\alpha/\text{Fe}] = 0.4 \text{ dex}\), corresponding to an iron-over-hydrogen ratio of \([\text{Fe/H}] = -2.62 \text{ dex}\) and a global metallicity of \([\text{M/H}] = -2.27 \text{ dex}\), and ages of 12, 13, and 14 Gyr. For the red population, we have used the \(\alpha\)-enhanced models with \(Z = 0.001\) and \([\alpha/\text{Fe}] = 0.4 \text{ dex}\), corresponding to an iron-over-hydrogen ratio of \([\text{Fe/H}] = -1.62 \text{ dex}\) and a global metallicity of \([\text{M/H}] = -1.27 \text{ dex}\), with ages of 11, 12, 13 and 14 Gyr, since M5 is thought to be \(\sim 1 \text{ Gyr}\) younger than M68 (see Marín-Franch et al. 2009). We stress that our selection of the isochrones is entirely based on the measured metallicities. It is also important to note that UMa II hosts a very metal-poor stellar component with \([\text{Fe/H}] = -3 \text{ dex}\) (Frebel et al. 2010). Unfortunately, the BaSTI database does not contain such low metallicities. We also explicitly note that the spectroscopically confirmed member of UMa II at \(V \approx 19.8 \text{ mag}\) and \((B-V) \approx 1 \text{ mag}\) has a measured metallicity of \([\text{Fe/H}] = -1.8 \text{ dex}\) (SDSSJ085117.07+630347.3; Martin et al. 2007) and appears to be definitely too red for its metallicity, being redder than spectroscopically confirmed members close to the M5 ridgeline and the \(Z = 0.001\) isochrones. The star could be contaminated by a red companion, even if the values of its DAOPHOT structural parameters \(\chi\) and sharpness do not support this explanation. Strangely, this star is not present in the Two Micron All Sky Survey catalog, even if stars of similar luminosity are reported.

The isochrone fitting appears to be quite satisfactory (see Figure 5) but, as commented by the referee, the small statistics does not allow us to prove the existence of two distinct stellar populations, with different age and/or metallicity in UMa II. It is worth mentioning that Zucker et al. (2006) suggested the presence of an age/metallicity spread in UMa II that could be accounted for by an intermediate-metallicity stellar population with age of at least 10 Gyr. We do not recover such a spread, but our data marginally suggest a gap between the metal-poor and the metal-intermediate SGBs. If this gap is not due to the poor statistics, UMa II may have experienced
distinct bursts of star formation during its star formation history, similar to those found in the Carina dwarf galaxy (Monelli et al. 2003), for example. However, an alternative, intriguing explanation has been proposed by Frebel & Bromm (2010), who suggested that in the poor baryonic matter content of the UFDs, pristine (i.e., Population III) core collapse (and maybe pair-instability) supernova (SN) events may have suppressed further star formation and inhibited a homogeneous mixing of the interstellar medium. According to this model, stars born close to the core collapse SN progenitors would be chemically enriched from the SN yields, while more distant stars would not. Therefore, the stellar populations in UMa II could have the same age but different metallicity as arising from differently enriched material. Alternatively, several Population III SNe could have enriched the environment but, given the shallow potential well of the UFDs, part of the enriched gas was lost (Frebel 2011). In either the case, these kind of galaxies should be regarded as “one-shot events.” Our photometric data do not allow us to distinguish between the two possible scenarios since the red population is reasonably well described by isochrones in the range between 11 and 14 Gyr.

In order to verify whether the stellar populations show a different spatial distribution in the FOV covered by our observations, we have used the ridgelines of M68 and M5 to select stars possibly compatible with a blue and a red population, and plotted them on the Galaxy map with different colors. This is shown in Figures 6 and 7. In particular, Figure 6 illustrates our selection of the two components by displaying as blue and red filled circles the sources, within the UMa II half light radius, which lie within \( \pm 0.05 \) mag in \( B - V \) for \( V \leq 21.5 \) mag and \( \pm 0.10 \) mag in \( B - V \) for \( V > 21.5 \) mag from the ridgelines of M68 and M5, respectively. Green dots show the sources with \( V > 21.5 \) mag, which could belong to either populations. Large open circles identify spectroscopically confirmed members of UMa II according to Martin et al. (2007), Simon & Geha (2007), and Kirby et al. (2008). The filled triangle marks the galaxy’s bona fide RR Lyrae star we detected in our study.

Figure 6. \( V, B - V \) color–magnitude diagram of UMa II with the ridgelines of the Galactic GCs M68 (blue solid line) and M5 (red solid line) superimposed, which we have used to select stars belonging to the two different populations that we suggest to exist in UMa II. Blue and red dots mark the stars within \( \pm 0.05 \) mag in \( B - V \) for \( V \leq 21.5 \) mag, and \( \pm 0.10 \) mag in \( B - V \) for \( V > 21.5 \) mag from the ridgelines of M68 and M5, respectively. Green dots show the sources with \( V > 21.5 \) mag, which could belong to either populations. Large open circles identify spectroscopically confirmed members of UMa II according to Martin et al. (2007), Simon & Geha (2007), and Kirby et al. (2008). The filled triangle marks the galaxy’s bona fide RR Lyrae star we detected in our study.

Figure 7. Upper panel: map of sources with \( V \leq 21.5 \) mag, within the UMa II half light radius, which we consider to belong to the galaxy according to the comparison with the ridgelines of M68 (blue filled circles) and M5 (red filled circles), or with spectroscopically confirmed membership (black open circles). The symbol sizes are proportional to the star’s brightness. Lower panel: map of all sources within the UMa II half light radius, which we consider to belong to the Galaxy either according to the comparison with the ridgelines of M68 (blue filled circles) and M5 (red filled circles), or with spectroscopically confirmed membership (black open circles). Marked in green are sources with \( V > 21.5 \) mag which could belong to either populations. In both panels, the RR Lyrae star is marked by a cyan filled triangle.
shows that sources brighter than $V = 21.5$ mag lying closer to the M68 ridgeline (blue filled circles) are larger in number and seem to be more concentrated toward the center of UMa II than sources closer to the M5 ridgeline (red filled circles), but this could be an effect due to the poor statistics. On the other hand, the lower panel of Figure 7 shows that sources fainter than $V = 21.5$ mag, which could belong either to the M68-like or to the M5-like population (green filled circles), do not show any obvious pattern.

5. CONCLUSIONS

We have presented the first Johnson $V$, $B - V$ CMD of the UMa II UFD galaxy and reported the detection of a bona fide RR Lyrae star in the galaxy, from which we have derived a true distance modulus of $(m - M)_0 = 17.70 \pm 0.04(\pm 0.12)$ mag ($d = 34.7^{+0.0}_{-0.1}(^{+2.0}_{-1.5})$ kpc). The error quoted in the brackets takes into account our lack of knowledge of the metallicity of the RR Lyrae star. The pulsation period of this variable ($P = 0.6593$ days) and its position in the period–amplitude (Bailey) diagram suggest the similarity of UMa II with Oosterhoff type II systems. A comparison of the observed CMD with the location of UMa II spectroscopically confirmed member stars (taken from the catalogs of Martin et al. 2007; Simon & Geha 2007; Kirby et al. 2008; Frebel et al. 2010) and with the fiducial lines of the Galactic GCs M68 and M5 is compatible with a spread in age/metallicity of the stellar content of the Galaxy. The inner brightness profile of UMa II, as suggested by Muñoz et al. (2010) on the basis of deep CFHT photometry, could be due to the presence of multiple stellar generations, as also postulated in McConnachie et al. (2007). However, the comparison with the isochrones gives only a coarse estimate of the age of the stellar populations, and no definite conclusion can be reached about a possible spread in age. On the other hand, when only the comparison with the M68 and M5 ridgelines is considered, the hypothesis of an age difference of $\sim 1$ Gyr is favored. Since the field covered by our photometry is smaller than the fields observed by the Martin et al. (2007), Simon & Geha (2007), Kirby et al. (2008), and Frebel et al. (2010) studies, our conclusions apply mainly to the central part of UMa II monitored by our data. A deeper, more accurate and more spatially extended photometry is therefore strongly desired to unveil all the secrets of the UMa II UFD.

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Note added in proof. Our colleague P. Wils (2012, private communication) warned us that, on the basis of the Catalina Sky Survey and the Linear Near-Earth Asteroid Research data, the period of the variable could be 0.56514 days. However, our data mostly support our quoted period, and we adopt throughout the paper. This difference has a negligible impact on our analysis.
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