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THE LEO IV DWARF SPHEROIDAL GALAXY: COLOR–MAGNITUDE DIAGRAM AND PULSATING STARS*

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ABSTRACT

We present the first V, $B - V$ color–magnitude diagram of the Leo IV dwarf spheroidal galaxy, a faint Milky Way satellite recently discovered by the Sloan Digital Sky Survey. We have obtained B, V time-series photometry reaching about half a magnitude below the Leo IV turnoff, which we detect at $V = 24.7$ mag, and have performed the first study of the variable star population. We have identified three RR Lyrae stars (all fundamental-mode pulsators, RRab) and one SX Phoenicis variable in the galaxy. In the period–amplitude diagram the Leo IV RR Lyrae stars are located close to the loci of Oosterhoff type I systems and the evolved fundamental-mode RR Lyrae stars in the Galactic globular cluster M3. However, their mean pulsation period, $\langle P\mathrm{ab}\rangle = 0.655$ days, would suggest an Oosterhoff type II classification for this galaxy. The RR Lyrae stars trace very well the galaxy's horizontal branch, setting its average magnitude at $\langle V_{\mathrm{RR}}\rangle = 21.48 \pm 0.03$ mag (standard deviation of the mean). This leads to a distance modulus of $\mu_0 = 20.94 \pm 0.07$ mag, corresponding to a distance of 154 ± 5 kpc, by adopting for the Leo IV dSph a reddening $E(B - V) = 0.04 \pm 0.01$ mag and a metallicity of [Fe/H] $= -2.31 \pm 0.10$.

Key words: galaxies: dwarf – galaxies: individual (Leo IV) – stars: distances – stars: variables: other – techniques: photometric

1. INTRODUCTION

Dwarf Spheroidal (dSph) galaxies (Mateo 1998) provide important constraints on Λ cold dark matter (ΛCDM) theories of galaxy formation, which predict that several hundred small dark halo satellites should surround the halos of large galaxies like the Milky Way (MW) and M31 (Klypin et al. 1999; Moore et al. 1999), and that dSphs are the best candidates for the "building blocks" from which the MW and M31 were assembled (Searle & Zinn 1978). Indeed, there is a sizeable discrepancy between ΛCDM theory and observations, known as the "missing satellite problem" (Kauffmann et al. 1993; Tollerud et al. 2008), since the number of satellites predicted by theory is much higher than the number of dSphs actually observed surrounding the MW. Solving the "missing satellite problem" would require the discovery of many new dSph satellites of our Galaxy (e.g., Walsh et al. 2009).

The dSph galaxies surrounding the MW can be divided into two groups: "bright" dSphs, mainly discovered before 2005, and "faint" dSphs, discovered in the last couple of years primarily from the analysis of imaging obtained by the Sloan Digital Sky Survey (SDSS; York et al. 2000). Bright and faint dSphs lie in two separate regions in the absolute magnitude versus half-light radius plane (see Figure 8 of Belokurov et al. 2007, hereafter B07).

The bright dSphs include 10 systems (Draco, Ursa Minor, Fornax, Carina, Sculptor, Leo I, Leo II, Sextans, Sagittarius, and Canis Major; Mateo 1998; Ibata et al. 1995; Irwin & Hatzidimitriou 1995; Martin et al. 2004). These galaxies generally are found to contain stars exhibiting different chemical compositions than the stars in the Galactic halo (see Helmi et al. 2006, and references therein). Furthermore, they generally host RR Lyrae stars with pulsation properties that differ from the properties of the variables in the Galactic globular clusters (GCs), being "Oosterhoff-intermediate" (Oosterhoff 1939; Catelan 2009, and references therein). These two properties suggest that it is unlikely that the halo of the MW was formed from objects with properties similar to the bright dSphs that are observed today.

Since 2005, 15 new faint (effective surface brightnesses $\mu_V \gtrsim 28$ arcsec^{-2}) dSph satellites of the MW have been discovered, primarily from SDSS imaging: Willman I, Ursa Major I, Ursa Major II, Bootes I, Coma Berenices (Coma), Segue I, Canes Venatici I (CVn I), Canes Venatici II (CVn II), Leo IV, Hercules, Leo T, Bootes II, Leo V, Bootes III, and Segue II (Willman et al. 2005a, 2005b; Zucker et al. 2006a, 2006b; Grillmair 2006, 2009; Belokurov et al. 2006, 2007, 2008, 2009; Irwin et al. 2007; Walsh et al. 2007). These faint galaxies have high mass-to-light ratios and (often) distorted morphologies, probably due to tidal interactions with the MW.

* Based on data collected at the 2.5 m Isaac Newton Telescope, La Palma, Canary Island, Spain, at the 4.2 m William Herschel Telescope, Roche de los Muchachos, Canary Islands, Spain, and at the 4.1 m Southern Astrophysical Research Telescope, Cerro Pachón, Chile.
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They all host an ancient stellar population with chemical properties similar to that of external Galactic halo stars (Simon & Geha 2007; Kirby et al. 2008; Frebel et al. 2009). Several of the faint dSphs have mean metallicities as low or lower than the most metal-poor GCs and, generally, much lower than those of the bright dSphs.

Galactic GCs that contain significant numbers of RR Lyrae stars have fundamental-mode (RRab) pulsators with mean period ($\langle P\mathrm{ab}\rangle$) either around 0.55 days or around 0.65 days, and separate into the so-called Oosterhoff I (Oo I) and Oosterhoff II (Oo II) types (Oosterhoff 1939). Extragalactic GCs and field RR Lyrae stars in the bright dSph galaxies generally have, instead, $\langle P\mathrm{ab}\rangle$ intermediate between the two types (Catelan 2009 and references therein). Four of the faint dSphs have been searched for variable stars so far (namely, Bootes I, Dall'Ora et al. 2006, Siegel 2006; CVn I, Kuehn et al. 2008; CVn II, Greco et al. 2008; and Coma, Musella et al. 2009) and, with the exception of CVn I, were found to contain RR Lyrae stars with properties resembling those of the MW Oo II GCs.

All of the above characteristics suggest that a much larger population of objects similar to the presently observed faint dSphs may have been the "building blocks" of the halos of large galaxies such as the MW. The association is particularly clear with the outer halo of the MW, which Carollo et al. (2007) have demonstrated to exhibit a peak metallicity of [Fe/H] $= -2.2$, substantially lower than the inner halo (with a peak at [Fe/H] $= -1.6$), and which is the dominant population at Galactocentric distances beyond 15–20 kpc.

The Leo IV galaxy (R.A. $= 11^{\mathrm{h}}32^{\mathrm{m}}57^{\mathrm{s}}$, decl. $= -00^{\circ}32'00''$, J2000.0; $l = 265\overset{\circ}{.}4$, $b = 56\overset{\circ}{.}5$) is one of the newly discovered SDSS dSphs, with absolute magnitude $M_V = -5.1 \pm 0.6$ mag (B07) and surface brightness $\mu_V = 28.3$ mag arcsec^{-2} (Simon & Geha 2007). It is a low-mass ($M = (1.4 \pm 1.5) \times 10^6\ M_{\odot}$; Simon & Geha 2007) system, with half-light radius $r_h \sim 3.3$ arcmin (B07). It is located at heliocentric distance 160^{+15}_{-14} kpc with a position angle of 355° (B07). Its color–magnitude diagram (CMD) is more complex than the CMDs of other galaxies discovered by Belokurov et al., due to the presence of an apparently "thick" red giant branch (RGB) and a blue horizontal branch (HB). The RGB thickness suggests the presence of stellar populations of different age/metallicity (B07). There is no published CMD of Leo IV other than the i, $g-i$ CMD that reaches $i \sim 22$ mag obtained from the SDSS discovery data, nor has a study of the variable stars in the galaxy yet been performed. Simon & Geha (2007) obtained spectra for 18 bright stars in Leo IV from which they derived an average velocity dispersion of 3.3 ± 1.7 km s^{-1} and an average metallicity $\langle$[Fe/H]$\rangle = -2.31 \pm 0.10$ with a dispersion σ[Fe/H] $= 0.15$ dex, on the Zinn & West (1984) metallicity scale (hereafter ZW84). Kirby et al. (2008), using Keck DEIMOS spectroscopy coupled with spectral synthesis, measured the metallicity of a subset of 12 stars extracted from the Simon & Geha (2007) sample. They obtained an average metallicity $\langle$[Fe/H]$\rangle = -2.58 \pm 0.08$, with a dispersion σ[Fe/H] $= 0.75$ dex and individual metallicities as low as [Fe/H] ~ -3.0.

In this Letter, we present the first V, $B-V$ CMD of the Leo IV dSph, reaching a depth of $V \sim 25.5$ mag, sufficient to identify the galaxy's main-sequence turnoff at $V \sim 24.7$ mag. We carry out a search for variable stars, and identify three fundamental-mode RR Lyrae stars (RRab) and one SX Phoenicis (SX Phe) variable. We obtained B, V light curves for each variable star and use the average magnitude of the RR Lyrae stars to estimate the distance to the galaxy.

2. OBSERVATIONS AND DATA REDUCTION

Time-series B, V, I photometry of the Leo IV dSph galaxy was collected on 2007 April 20–23, with the Wide Field Camera (WFC), the prime focus mosaic CCD camera of the 2.5 m Isaac Newton Telescope (INT), on 2007 May 11–12, with the Prime Focus Imaging Platform (PFPI) of the 4.2 m William Hershel Telescope (WHT), and on 2007 March–May, with the SOAR Optical Imager (SOI) of the 4.1 m SOuthern Astrophysical Research telescope (SOAR). The fields of view (FOVs) covered by the three instruments are: 5.24×5.24 arcmin^2 for SOI at the SOAR telescope, 16.2×16.2 arcmin^2 for PFPI at the WHT, and 33×33 arcmin^2 for WFC at the INT. We needed two partially overlapping SOI fields to cover the galaxy, while just one PFPI field was sufficient, and from the INT data we could also infer additional information on stars outside the Leo IV half-light radius. We obtained a total number of 37 B, 42 V, and 12 I images of the galaxy. In this Letter, we present results from the analysis of the B and V data. Images were reduced following standard procedures (bias subtraction and flat-field correction) with IRAF. The INT and WHT data were corrected for linearity following recipes provided in the telescope's Web pages. We then performed PSF photometry using the DAOPHOT/ALLSTAR/ALLFRAME packages (Stetson 1987, 1994). Typical internal errors of the B, V single-frame photometry for stars at the HB level range from 0.02 to 0.03 mag for the INT and WHT data, and are of about 0.02 mag for the SOAR data. The absolute photometric calibration was obtained using observations of standard stars in the Landolt (1992) fields SA 101, SA 107, SA 110, and PG1323, as extended by P. B. Stetson,[12] which were observed at the INT during the night of 2007 April 22. Errors of the absolute photometric calibration are $\sigma_B = 0.01$ mag, $\sigma_V = 0.01$ mag, respectively.

3. IDENTIFICATION OF THE VARIABLE STARS

Variable stars were identified using the V and B time-series data separately. First we calculated the Fourier transforms (in the Schwarzenberg-Czerny 1996 formulation) of the stars having at least 12 measurements in each photometric band, then we averaged these transforms to estimate the noise and calculated the signal-to-noise ratios (S/Ns). Results from the V and B data sets were cross-correlated, and all stars with S/N> 5 in both photometric bands were visually inspected, for a total of about 2000 objects. We also checked whether some of the stars in the Blue Straggler Stars (BSSs) region might be pulsating variables of SX Phe type. The study of the light curves and period derivation were carried out using the Graphical Analyzer of Time Series package (GRaTiS; Clementini et al. 2000). We confirmed the variability and obtained reliable periods and light curves for 3 RR Lyrae stars, all fundamental-mode pulsators (stars: V1, V2, and V3), and for one SX Phe variable (star V4). The identification and properties of the confirmed variable stars are summarized in Table 1, their light curves are shown in Figure 1. The light-curve data of the variable stars and the photometric data of the galaxy CMD are available on request from the first author.

Stars V1, V2, and V4 lie inside the galaxy half-light radius, while V3 lies outside, at about 12 arcmin from the Leo IV center (see the lower panel of Figure 4). In the CMD, the SX Phe star is located in the region of the BSSs, while all the RRab stars (V3 included) fall near the galaxy's HB. We checked the

[12] See http://cadcwwwdao.nrc.ca/standards.

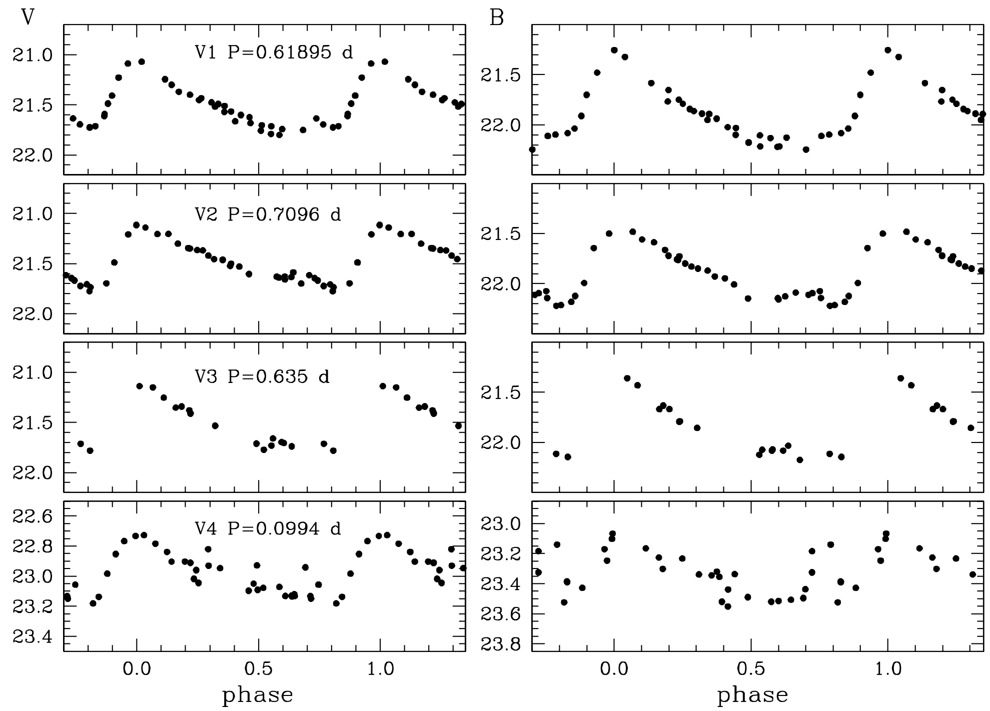

Figure 1. *V* (left panels) and *B* (right panels) light curves of the variable stars discovered in the Leo IV dSph galaxy. Three upper rows: fundamental-mode RR Lyrae stars; bottom row: SX Phe variable.

Table 1
Identification and Properties of Variable Stars in the Leo IV dSph Galaxy

Name	α (2000)	δ (2000)	Type	P (days)	Epoch (max) (−2450000)	$\langle V\rangle$ (mag)	$\langle B\rangle$ (mag)	A_V (mag)	A_B (mag)	[Fe/H]$_{ZW84}$[a]
V1	11 32 59.2	−00 34 03.6	RRab	0.61895	4212.453	21.47	21.82	0.73	0.99	−2.11
V2	11 32 55.8	−00 33 29.4	RRab	0.7096	4214.543	21.46	21.86	0.64	0.76	−2.03
V3	11 33 36.6	−00 38 43.3	RRab	0.635	4212.453	21.52	21.81	0.65	0.82	...
V4	11 32 45.4	−00 31 44.4	SX Phe	0.0994	4213.397	22.96	23.34	0.37	0.38	...

Notes.
[a] The metallicity of V1 was derived from the Fourier parameters of the *V*-band light curve. The metallicity of V2 is from Kirby et al. (2008).

position of V4 on the period–luminosity (PL) relation of the SX Phe stars. Using the star's period and the absolute magnitude inferred from the apparent magnitude and the distance provided by the RR Lyrae stars (see Section 4), we found that V4 lies very close to the Poretti et al. (2008) PL relation for SX Phe stars, thus confirming the classification as an SX Phe star.

So far, only four dSphs of Oosterhoff II type are known, namely, Ursa Minor among the bright companions of the MW, and Bootes I (Dall'Ora et al. 2006; Siegel 2006), CVn II (Greco et al. 2008), and Coma (Musella et al. 2009), among the faint SDSS dSphs. The average pulsation period of the Leo IV RRab stars, $\langle Pab\rangle = 0.655$ days, would suggest that Leo IV too is more similar to the Oosterhoff type II systems. However, in the *V*-band period–amplitude diagram (see Figure 2) the Leo IV RRab stars fall close to the locus of Oo I systems (from Clement & Rowe 2000), with V1 and V3 lying near the distribution of the bona fide regular variables, and V2 lying close to the locus of the well-evolved fundamental-mode RR Lyrae stars in the Galactic GC M3 (from Cacciari et al. 2005). Nevertheless, V2 does not appear to be overluminous in the CMD, as would be required if the star were evolved off the zero-age HB. The ambiguous behavior and the small number of variable stars make the conclusive assignment of an Oosterhoff type to the Leo IV dSph rather difficult.

We used the parameters of the Fourier decomposition of the *V*-band light curve, along with the Jurcsik & Kovács (1996) method

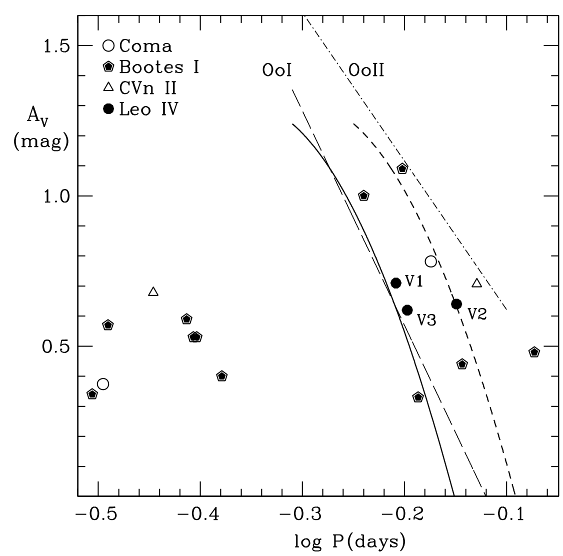

Figure 2. *V*-band period–amplitude diagram of RR Lyrae stars in the Coma, Bootes I, CVn II, and Leo IV dSphs. Variables with $\log P > -0.35$ days are RRab pulsators, those with $\log P < -0.35$ days are first-overtone (RRc) pulsators. Long-dashed and dot-dashed lines show the position of the Oo I and Oo II Galactic GCs, according to Clement & Rowe (2000). Period–amplitude distributions of the bona fide regular (solid curve) and well evolved (dashed curve) RRab stars in M3, from Cacciari et al. (2005), are also shown for comparison.

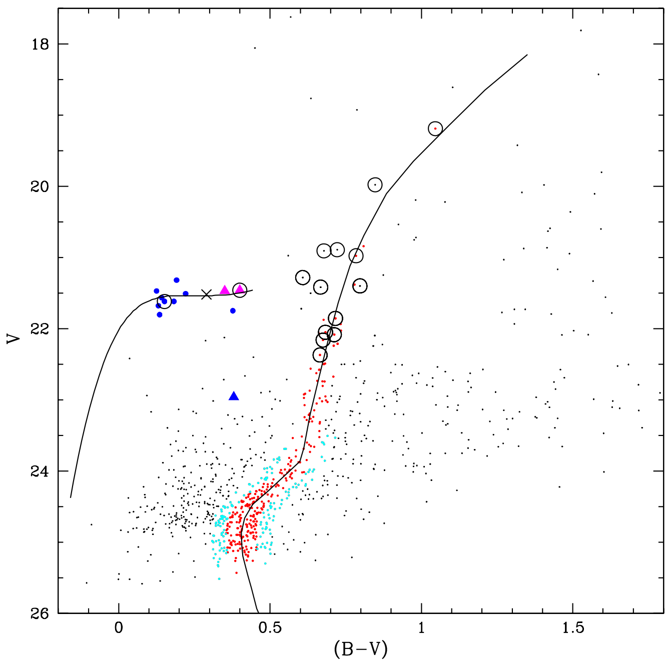

Figure 3. V, $B - V$ CMD of the Leo IV dSph obtained by plotting stellar-like objects located within the half-light radius of 3.3 arcmin. Variable stars V1, V2, and V4 are marked by triangles, star V3 by a cross, and nonvariable HB stars by (blue) filled circles. The solid line is the ridgeline of the Galactic GC M15. The red and cyan dots are stars respectively within $\pm$ 0.05 mag in $B-V$ and, for $V > 23.5$ mag, from $\pm$0.05 and $\pm$0.10 mag in $B-V$ from the ridgeline of M15. The open circles mark member stars of the Leo IV dSph according to Simon & Geha (2007) and Kirby et al. (2008).

for RRab stars, to estimate the metallicity on the ZW84 scale of V1, the only variable of our RR Lyrae sample which satisfies the Jurcsik & Kovács (1996) regularity conditions. The metallicity we derived for V1 is in good agreement with the spectroscopic metallicity derived for another RR Lyrae star (variable V2) by Kirby et al. (2008) (see the last column of Table 1).

4. THE CMD, STRUCTURE, AND DISTANCE OF LEO IV

Figure 3 shows the V, $B - V$ CMD of the Leo IV dSph obtained by plotting all stellar-like objects located within the half-light radius of 3.3 arcmin from the B07 center of Leo IV. The selection between stars and galaxies, for magnitudes brighter than $V = 22.5$ mag, was done with the software Source Extractor (SExtractor; Bertin & Arnouts 1996). Variable stars are plotted in the CMD according to their intensity-averaged magnitudes and colors (see Table 1), using filled triangles for stars V1, V2, and V4, and a cross for V3. Although well outside the Leo IV half-light radius, V3 appears to be perfectly located on the galaxy's HB, thus confirming its membership to the galaxy. Nonvariable HB stars are marked by (blue) filled circles. The CMD reaches $V \sim 25.5$ mag, and appears to be heavily contaminated at every magnitude level by field objects belonging to the MW. We used the mean ridgeline of the Galactic GC M15 (from Durrell & Harris 1993; solid line) properly shifted in magnitude and color, and selected as stars most likely belonging to the Leo IV galaxy the sources lying within $\pm$0.05 mag from the ridgeline of M15 (red dots). To allow for the larger photometric errors, for magnitudes fainter than $V = 23.5$ mag, we also considered as belonging to the galaxy stars with $B-V$ color in the range from $\pm$0.05 mag and $\pm$0.10 mag from the ridgeline of M15 (cyan dots). The HB

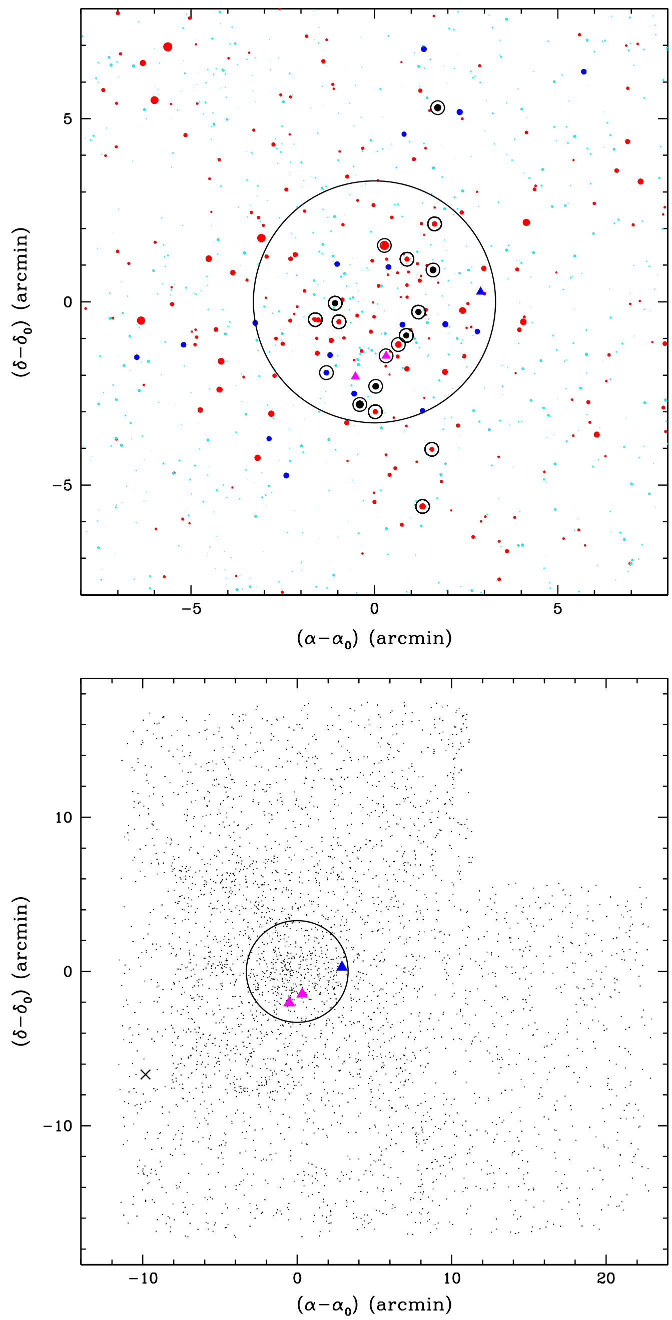

Figure 4. Upper panel: map of sources in the FOV of the WHT observations, which we consider to belong to the Leo IV galaxy according to the fit with the M15 ridgeline, or with membership spectroscopically confirmed by Simon & Geha (2007) (open circles). Symbols and color-coding are the same as in Figure 3 and, for nonvariable stars, the symbol sizes are proportional to the star's brightness. Lower panel: map of sources observed in the INT FOV which lie within $\pm$ 0.05 mag in $B-V$ (for $V > 23.5$ mag, within $\pm$ 0.10 mag in $B-V$) from the ridgeline of M15. The symbols and color-coding for the variable stars are the same as in Figure 3. In both panels the large circle shows the region corresponding to the half-light radius of Leo IV centered on the B07 coordinates for the galaxy.

of Leo IV shows up quite clearly and, along with the galaxy's RGB, is well reproduced by the ridgeline of M15, implying that Leo IV has an old and metal-poor stellar population with metallicity comparable to that of M15 ([Fe/H] = -2.15 ± 0.08, on the ZW84 scale). We also note that, by adopting for M15 a reddening value of $E(B - V)$= 0.10 $\pm$ 0.01 mag (Durrell & Harris 1993), the color shift needed to match the HB and RGB of Leo IV implies for the galaxy a reddening of $E(B-V) = 0.04 \pm 0.01$ mag. For comparison, the reddening in the direction of Leo IV obtained from the Schlegel et al. (1998) maps is 0.025 ± 0.026 mag. The objects marked by the open circles are stars within the Leo IV half-light radius, whose membership to the galaxy was confirmed spectroscopically by Simon & Geha (2007). They include the RR Lyrae star V2 and a number of HB and RGB stars which fall very close to the M15 ridgeline, thus supporting our identification of the Leo IV member stars.

The upper panel of Figure 4 shows a map of all sources observed in the FOV of the WHT observations that we consider to belong to the Leo IV galaxy, according to their position with respect to the M15 ridgeline, or with membership spectroscopically confirmed by Simon & Geha (2007) (open circles). Symbols and color-coding are the same as in Figure 3 and, for nonvariable stars, the symbol sizes are proportional to the star's brightness. The solid circle shows the region corresponding to the half-light radius of Leo IV centered on the B07 coordinates for the galaxy. The lower panel of Figure 4 shows a map of the sources observed in the INT FOV which lie within $\pm$ 0.05 mag in $B-V$ (for $V > 23.5$ mag, within $\pm$ 0.10 mag in $B-V$) from the ridgeline of M15. An overdensity of objects rather extended and irregular in shape is visible, corresponding to the region occupied by the Leo IV dSph. The black circle shows the half-light radius of Leo IV, according to B07. The peripheral location of V3 is remarkable, and provides further hints on the elongation and rather deformed morphology of the Leo IV dSph.

The average apparent magnitude of the galaxy's RR Lyrae stars is $\langle V_{\rm RR} \rangle = 21.48 \pm 0.03$ mag (standard deviation of the mean). Assuming $M_V = 0.59 \pm 0.03$ mag for the absolute luminosity of the RR Lyrae stars at [Fe/H] $= -1.5$ (Cacciari & Clementini 2003), $\Delta M_V/\Delta$[Fe/H] $= 0.214 \pm 0.047$ mag dex^{-1} for the slope of the luminosity–metallicity relation of RR Lyrae stars (Clementini et al. 2003), $E(B-V) = 0.04 \pm 0.01$ mag and [Fe/H] $= -2.31$ (Simon & Geha 2007), the distance modulus of Leo IV is $\mu_0 = 20.94 \pm 0.07$ mag which corresponds to a distance $d = 154 \pm 5$ kpc. The error includes uncertainties in the photometry, reddening, metallicity, and RR Lyrae absolute magnitude, but does not take into account evolution off the zero-age HB which might contribute an additional 0.05 mag uncertainty, bringing the total error budget to 0.09 mag. This new, precise distance estimate agrees very well with the distance of 160^{+15}_{-14} kpc derived by B07.

5. SUMMARY AND CONCLUSIONS

We have identified and obtained B, V light curves for three fundamental-mode RR Lyrae stars (V1, V2, and V3) and one SX Phe variable (V4) in the Leo IV dSph galaxy. In the period–amplitude diagram V1 and V3 fall close to the loci of Oo I Galactic GCs and bona fide regular variables in the Galactic GC M3, while V2 lies close to the loci of Oo II and well evolved M3 RRab stars. However, their average period, $\langle P{\rm ab} \rangle = 0.655$ days, would suggest an Oosterhoff II classification for the galaxy. From the average magnitude of the galaxy's RR Lyrae stars, the distance modulus of the Leo IV dSph is $\mu_0 = 20.94 \pm 0.07$ mag ($d = 154 \pm 5$ kpc). One of the RR Lyrae stars (V3) lies at about 12 arcmin from the galaxy center. Nevertheless, the mean magnitude places the star exactly on the galaxy HB and close to the other two RRab stars, thus suggesting a significant elongation of the Leo IV galaxy.

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