PULSATING VARIABLE STARS IN THE COMA BERENICES DWARF SPHEROIDAL GALAXY*

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ABSTRACT

We present B, V, I time-series photometry of the Coma Berenices dwarf spheroidal galaxy, a faint Milky Way (MW) satellite, recently discovered by the Sloan Digital Sky Survey. We have obtained V, B − V and V, V − I color–magnitude diagrams that reach V ∼ 23.0−23.2 mag showing the galaxy turnoff at V ∼ 21.7 mag, and have performed the first study of the variable star population of this new MW companion. Two RR Lyrae stars (a fundamental-mode, RRab, and a first overtone, RRc, pulsator) and a short period variable with period $P = 0.12468$ days were identified in the galaxy. The RRab star has a rather long period of $P_{\text{RRab}} = 0.66971$ days and is about 0.2 mag brighter than the RRc variable and other nonvariable stars on the galaxy horizontal branch (HB). In the period–amplitude diagram, the RRab variable falls closer to the loci of Oosterhoff type-II systems and evolved fundamental-mode RR Lyrae stars in the Galactic globular cluster M3. The average apparent magnitude of the galaxy HB, $\langle V_{\text{HB}} \rangle = 18.64 \pm 0.04$ mag, leads to a distance modulus for the Coma dSph $\mu_0 = 18.13 \pm 0.08$ mag, corresponding to a distance $d = 42^{+2}_{-1}$ kpc, by adopting a reddening $E(B−V) = 0.045 \pm 0.015$ mag and a metallicity $[\text{Fe/H}] = −2.53 \pm 0.05$ dex.

Key words: galaxies: distances and redshifts – galaxies: dwarf – galaxies: individual (Coma) – stars: horizontal-branch – stars: variables: other – techniques: photometric

1. INTRODUCTION

Over the past few years, the analysis of the Sloan Digital Sky Survey (SDSS) data led to the discovery of several ultrafaint companions of the Milky Way (MW). The new systems include two very faint globular clusters (GCs): Koposov 1 and 2 (Koposov et al. 2007), and 14 dwarf spheroidal (dSph) galaxies: Willman I, Ursa Major I, Canes Venatici I (CVn I), Ursa Major II (UMa II), Bootes I, Coma Berenices (Coma), Segue I, Canes Venatici II (CVn II), Leo IV, Hercules, Leo T, Bootes II, Leo V, and Bootes III (Willman et al. 2005a, 2005b; Zucker et al. 2006a, 2006b; Grillmair 2006; Belokurov et al. 2006, 2007; Irwin et al. 2007; Walsh et al. 2007; Belokurov et al. 2008; Grillmair 2009).

The new dSphs have half-light radii similar to those of the classical MW dSph companions, however, they are much fainter, with typical effective surface brightnesses in the range from 28 to 31 arcsec$^{-2}$ (Belokurov et al. 2007, hereafter B07). The new discoveries along with the 10 previously known MW dSph companions (Draco, Ursa Minor, Fornax, Carina, Sculptor, Leo I, Leo II, Sextans, Sagittarius, and Canis Major; Mateo 1998; Ibata et al. 1995; Martin et al. 2004), bring to 24 the number of dSph galaxies presently known to surround the MW. In the absolute magnitude versus half-light radius plane, the new dSphs are well separated from both GCs and traditional dSph galaxies, since they are generally more extended than GCs and much fainter than the old dSphs (see Figure 8 of B07). Only CVnI, the brightest of the new SDSS dSphs, lies on the faintest tail of the distribution for traditional dSphs. All the new SDSS dSphs host a metal-poor and ancient stellar component, with metallicity generally below $[\text{Fe/H}] \sim −2$ dex and down to as low as $[\text{Fe/H}] \sim −3$ dex (Munoz et al. 2006; Simon & Geha 2007; Geha et al. 2009; Kirby et al. 2008), and age as old as the stars in Galactic GCs like M92 (see B07). The density contours are irregular since most of these galaxies are in process of disruption. The closest ones (Bootes I, UMa II, and Coma) are more distorted owing to the tidal interaction with the MW (Belokurov et al. 2006, 2007; Zucker et al. 2006b); others appear to be connected with tidal streams. With the exception only of Leo T, the new systems all have globular-cluster-like color–magnitude diagrams (CMDs), showing main sequences, turnoffs, as well as hints of red giant and horizontal branches (RGBs and HBs, respectively). Variable stars have been identified so far in three of the new systems, namely, Bootes I, CVn I, and CVn II. Bootes I (Dall’Ora et al. 2006; Siegel 2006) and CVn II (Greco et al. 2008) both were found to contain RR Lyrae stars with properties resembling those of Oosterhoff-type II (Oosterhoff 1939) GCs in the MW. Confirming its similarity to the traditional dSphs, CVn II (Kuehn et al. 2008) hosts, instead, RR Lyrae stars with properties intermediate between the two Oosterhoff types, along with a few candidate Anomalous Cepheids.

The Coma galaxy (R.A. $= 12\h26\text{m}59\text{s}$, decl. $= +23\degree 54'15''$, $J2000.0$, $l = 241\degree 9$, $b = 83\degree 6$; B07), located at a heliocentric distance of $44 \pm 4$ kpc with a position angle of $120\degree$ and an absolute magnitude of $M_V = −3.6 \pm 0.6$ mag, is among the faintest of the SDSS new discoveries. It has half-light...
General objective: studying variable stars in the Coma dSph galaxy

1. Introduction
   - The Coma dSph is a satellite galaxy of the Milky Way.
   - It is known for hosting a high percentage of RR Lyrae variables.

2. Observations and Data Reduction
   - B, V, I photometry was collected.
   - The dataset includes time-series observations for several stars.

3. Identification of the Variable Stars
   - Variable stars were identified using the V and I time-series data.
   - The variability was analyzed, and reliable periods were obtained.

4. Analysis
   - The photometric data was cross-correlated to identify variable stars.
   - The variability was confirmed using the Fourier transforms.

5. Results
   - The dataset contains information on hundreds of variable stars.
   - The results are summarized in Table 1.

6. Conclusions
   - The Coma dSph is a rich environment for variable star research.

Figure 1. V (left panels) and I (right panels) light curves of variable stars discovered in the Coma dSph. From top to bottom: fundamental-mode RR Lyrae star, first-overtone RR Lyrae pulsator, and short period variable.

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radii: \( r_h (\text{Plummer}) = 5.0 \text{ arcmin} \), and \( r_h (\text{exponential}) = 5.9 \text{ arcmin} \), and an irregular and extended shape (B07). The \( i, g−i \) CMD obtained by B07 goes down to \( i \sim 25 \text{ mag} \), is consistent with a single, old stellar population of metallicity \([\text{Fe}/\text{H}] \sim −2\), and shows a poorly populated HB. Metallicities of radial velocity members of the Coma dSph were obtained by Simon & Geha (2007) and confirm the low metal abundance of the galaxy. These metallicities were reevaluated by Kirby et al. (2008), who derived for the galaxy an average metallicity \([\text{Fe}/\text{H}] = −2.53 \pm 0.05 \text{ dex} \) with dispersion \( \sigma_{\text{[Fe/H]}} = 0.45 \text{ dex} \). In this Letter, we present the first study of the variable stars in the Coma dSph, which led us to identify two RR Lyrae stars and one short period variable in the galaxy. We provide multiband light curves and properties of the variables, and use the magnitude of the HB stars to measure the distance to Coma. We also present B, B−V and V, V−I CMDs to \( V \sim 23.0\text{–}23.2 \text{ mag} \), which show the galaxy main-sequence turnoff at \( V \sim 21.7 \text{ mag} \), and reveal the presence of several candidate blue straggler stars (BSSs).

2. Observations and Data Reduction
   - Time-series B, V, I photometry of the Coma dSph galaxy was collected on 2007 March 12–16 and 2007 April 13–17, with BFOSC at the 1.52 m telescope of the Bologna Observatory in Loiano.\(^9\) (V and I data), on April 30 and May 9–10, using WIRO-Prime, the prime focus CCD camera (Pierce & Nations 2002) of the 2.3 m Wyoming Infrared Observatory telescope (WIRO; B and V data), and B, V, I observations were gathered on April 21–22, using Wide Field Camera (WFC), the prime focus mosaic CCD camera of the 2.5 m Isaac Newton Telescope (INT). The field of view (FOV) covered by the three instruments is \( 13 \times 12.6 \text{ arcmin}^2 \) for BFOSC@LOIANO, \( 17.8 \times 17.8 \text{ arcmin}^2 \) for WIRO, and \( 33 \times 33 \text{ arcmin}^2 \) for WFC@INT. We needed two partially overlapping fields to cover the galaxy with BFOSC, while just one WIRO pointing was sufficient, and from the WFC@INT field we could also infer some additional information about the contamination by field stars and background galaxies. We obtained 14 B images, 83 V frames, and 64 I frames of the Coma dSph. Images were prereduced following standard procedures (bias subtraction and flat-field correction) with IRAF. The I-band images were corrected for fringing by adopting, for each instrument, a well-suited fringing map. We then performed PSF photometry using the DAOPHOT IV/ALLSTAR/ALLFRAME packages (Stetson 1987, 1994). Typical internal errors of the single-frame photometry for stars at the HB magnitude level are of about 0.005 mag in all the three bands. The absolute photometric calibration was derived using observations of standard stars in the Landolt fields SA 101, SA 107, SA 110, and PG1323 (Landolt 1992), as extended by P. B. Stetson,\(^10\) which were obtained at the INT during the night of 2007 April 22. Errors of the absolute photometric calibration are \( \sigma_B = 0.01, \sigma_V = 0.01, \) and \( \sigma_I = 0.02 \text{ mag} \), respectively.

3. Identification of the Variable Stars
   - Variable stars were identified using the V and I 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 I photometries were cross-correlated, and all stars with \( S/N > 4 \) in both photometric bands were visually inspected, for a total of about 500 candidates. We also checked whether some of the stars in the BSSs region might be pulsating variables of SX Phoenicis (SX Phe) type. Study of the light curves and period derivation were carried out using Graphical Analyzer of Time Series (GraTiS; Clementini et al. 2000). We confirmed the variability and obtained reliable periods and light curves for two RR Lyrae stars: one fundamental-mode (RRab) variable with period \( P = 0.66971 \) days (V1), one first-overtone (RRc) pulsator with period \( P = 0.31964 \) days (V2), and for one short period variable with period \( P = 0.12468 \) days (V3). Identification and properties of the confirmed variable stars are summarized in Table 1; their light curves are shown in Figure 1.

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\(^9\) http://www.bo.astro.it/loiano/index.htm.

\(^10\) See http://cadcwww.dao.nrc.ca/standards.
by fitting the galaxy CMD with the ridgelines of the Galactic fully consistent with the average luminosity of the HB we infer, dSph. However, while the average magnitude of the RRc star is definitely assess the actual nature of the star.

The two RR Lyrae stars both fall near the HB of the Coma dSph. However, while the average magnitude of the RRc star is fully consistent with the average luminosity of the HB we infer, by fitting the galaxy CMD with the ridgelines of the Galactic GC M3 (from Cacciari et al. 2005), are also shown for comparison.

one-third the value supported by the period search analysis is adopted. The shape of the light curve and the similarity of the $A_V$, $A_I$ amplitudes may suggest a classification as a W UMa binary system. However, the present data do not allow us to definitely assess the actual nature of the star.

The two RR Lyrae stars both fall near the HB of the Coma dSph. However, while the average magnitude of the RRc star is fully consistent with the average luminosity of the HB we infer, by fitting the galaxy CMD with the ridgelines of the Galactic GC M3 (see Section 4), that the RRab star is about 0.2 mag brighter. The overluminosity of the RRab star could be due to geometrical projection effects, since the galaxy appears to be elongated due to the tidal interaction with the MW (see Dall’Ora et al. 2008 and Section 4). Contamination by an unresolved companion may also be possible, but this is constrained by the large amplitude of the RRab star, and by its color, which is consistent with the expected color of an RRab star. A further possibility is that evolution off the zero-age HB contributes to the enhancement of the brightness of the RRab star (see the end of Section 4).

The rather long period of the RRab star suggests that Coma is, like CN II (Greco et al. 2008), more similar to Oosterhoff type-II systems in the MW, and differs from CN I, the brightest of the SDSS dSph’s, which has Oosterhoff-intermediate type (Kuehn et al. 2008). Figure 2 shows the position of the Coma RR Lyrae stars in the V-band period–amplitude diagram of the Bootes I and CN II RR Lyrae stars. The Coma RRab star (filled circle) falls closer to the loci of Oo II systems (from Clement & Rowe 2000, dot-dashed line) and evolved fundamental-mode RR Lyrae stars in the Galactic GC M3 (from Cacciari et al. 2005, dashed curve). The RRc star falls at the short extreme of the bell-shaped distribution defined by Oo II RRc stars. Both these results suggest an Oo II classification for the Coma dSph, although with some caution given the very small number of variable stars. We have used the parameters of the Fourier decomposition of the V-band light curves, along withJurcsik & Kovács (1996) and Morgan et al. (2007) formulas, to estimate individual metallicities for the Coma RR Lyrae stars, on the Zinn & West (1984) metallicity scale. Results are summarized in the last column of Table 1, they confirm the low metallicity derived for the Coma dSph by the spectroscopic studies.

4. CMD, STRUCTURE, AND DISTANCE

The upper panels of Figure 3 show the V, B−V and V, V−I CMDs of the Coma dSph. We have plotted all stellar-like objects (selected using the CHI and SHARP parameters provided by the reduction packages), over the whole 0.5 deg$^2$ covered by the INT observations. This selection is rather secure for magnitudes above $V \sim 20.5$–21.0 mag, while it becomes increasingly uncertain at fainter magnitudes. The variable stars (filled triangles) are plotted according to their intensity-averaged magnitudes and colors (see Table 1). The CMDs reach $V \sim 23.2$ mag, and appear to be heavily contaminated at every magnitude level by field objects belonging to the MW halo and disk, and by galaxies which escaped selection. We have used the mean ridgelines of the Galactic GC M68 (NGC 4590; solid blue lines in Figure 3), drawn from Walker’s (1994) B, V, I photometry for the cluster, shifted by $\Delta V = +2.95$ mag in magnitude, and $\Delta(B - V) = +0.025$ mag, $\Delta(V - I) = +0.030$ mag in color, to match the HB and RGB of the Coma dSph. Then we selected as most likely belonging to the galaxy the sources lying within $\pm 0.06$ mag in $B-V$, and $\pm 0.05$ mag in $V-I$, from the ridgelines of M 68 (red dots in the upper panels of Figure 3). The slightly larger range adopted for the $B-V$ color takes into account the larger uncertainty caused by the small number of B frames. To allow for the larger photometric errors below $V = 21.5$ mag, we also considered as belonging to the galaxy stars with colors in the range from $\pm 0.05/0.06$ to $\pm 0.1$ mag from the ridgelines of M 68 (cyan dots). M 68 is well suited for identifying members of the Coma dSph since, like Coma, is very metal-poor ([Fe/H]$_{M68} = -2.1$ dex; Walker 1994) and has a well defined and tight RGB, as well as an extended HB well populated inside and to the blue of the RR Lyrae instability strip (Walker 1994). Adopting for M 68 the reddening value of $E(B-V) = 0.07 \pm 0.01$ mag (Walker 1994) the color shifts needed to match the HB and RGB of Coma imply a reddening of $E(B-V) = 0.045 \pm 0.015$ mag for the galaxy, which can be compared with the value of $0.019 \pm 0.026$ mag derived from the Schlegel et al. (1998) maps. We also show in Figure 3 results of the fit based on a less metal-poor GC:

### Table 1

| Name | $\alpha$ (2000) | $\delta$ (2000) | Type | $P$ (days) | Epoch (max) ($-2450000$) | $V$ (mag) | $I$ (mag) | $A_V$ (mag) | $A_I$ (mag) | [Fe/H]$_{ZW}$^a |
|------|-----------------|-----------------|------|------------|-------------------------|--------|--------|-------------|-------------|----------------|
| V1   | 12 27 33.50     | 23 54 55.7      | RRab | 0.66971    | 4171.583                | 18.44  | 17.74  | 0.78        | 0.53        | $-2.068$     |
| V2   | 12 26 50.89     | 23 56 00.6      | RRc  | 0.31964    | 4172.128                | 18.69  | 18.20  | 0.37        | 0.24        | $-2.074$     |
| V3   | 12 26 58.68     | 23 57 04.5      | Short period | 0.12468    | 4171.950                | 21.57  | 21.13  | 0.29        | 0.28        | ...          |

Note. a Metallicities derived from the Fourier parameters of the light curves.

![Figure 2](image-url) Period–amplitude diagram in the V band. Dashed and dot-dashed lines are the positions of the Oo I and Oo II Galactic GCs, from Clement & Rowe (2000). Period–amplitude distributions of the bona fide regular (solid curve) and well-evolved (dashed curve) fundamental-mode RR Lyrae stars in M3, from Cacciari et al. (2005), are also shown for comparison.
Figure 3. Upper panels: $V$, $B-V$ (left) and $V$, $V-I$ (right) CMDs of sources in the INT FOV. Solid (blue) and dashed (black) lines are the ridgelines of the Galactic GCs M 68 and M 3, respectively. Red and cyan dots are stars respectively within $\pm 0.06$ mag in $B-V$ and $\pm 0.05$ mag in $V-I$, and from $\pm 0.05/0.06$ to $\pm 0.1$ mag from the ridgelines of M 68. Blue dots are nonvariable stars on the HB, green dots are stars in the BSSs region. Variable stars are marked by filled triangles, cyan: RRc star, magenta: RRab star, blue: short period variable. Open circles mark 24 member stars of the Coma dSph from Kirby et al. (2008). Black dots are galaxies of cluster MaxBCG J186.85861+2380004. Lower panels: maps of objects most likely belonging to the Coma dSph, color-coded and with same symbols as in the top panels of the figure. HB stars are outlined by squares. The large circles show the galaxy half-light radius $r_h$ (exponential) = 5.9 arcmin (B07). The dashed circles show the position of the galaxy cluster.

M 3 (Ferraro et al. 1997; Johnson & Bolte 1998). The RGB of M 3 is too red and, to match that of Coma, would require for the galaxy a negative reddening $E(B-V) \sim -0.06$ mag. With the help of the M 68 ridgelines, it is possible to determine the average luminosity of the Coma dSph HB roughly at the center of the RR Lyrae instability strip: $(V_{HB}) = 18.64 \pm 0.04$ mag, and to locate the galaxy main-sequence turnoff at $V \sim 21.7$ mag. The CMDs also show several stars in the BSS region (green dots in Figure 3), which are likely BSSs of the Coma dSph. Our identification of the Coma member stars is confirmed in an excellent way by the comparison with the Kirby et al. (2008) spectroscopic study of 24 stars with membership to the Coma dSph confirmed by radial velocity measurements (open circles in Figure 3). The agreement between the two studies is impressive, and proves the reliability of our procedure to select member stars, and our identification of the Coma HB. The lower panels of Figure 3 show the position of the stars we consider to belong to the Coma galaxy in the FOV of the $B$-band (left panel) and $I$-band (right panel) INT observations. Symbols and color-coding are the same as in the top panels of the figure. Symbol sizes are proportional to the object’s magnitudes. The HB stars are outlined by squares. It is noteworthy that, with the exception only of the RRc variable, all the HB stars fall outside the galaxy half-light radius, but generally close to stars whose membership to Coma is confirmed by the spectroscopic studies.

A further feature is visible in the CMDs of the Coma dSph (see the upper panels of Figure 3), formed by sources having roughly $20.6 < V < 21.9$ mag, $1.3 < V - I < 1.5$ mag, and $B - V \sim 1.5$ mag. Among them those marked by black dots are mainly concentrated in the left-hand portion of the maps.
outlined by dashed circles (see the lower panels of Figure 3). In the literature, at this position, we find the cluster of galaxies MaxBCG J186.85861+2380004 (Koester et al. 2007), which has a photometric redshift $z = 0.243050$. The feature we see in the CMDs is, probably, the “red sequence” of this cluster, as confirmed by the $V-I$, $B-V$ colors we derive for early-type galaxies at $z \sim 0.25$ using the GISSEL03 spectral code (Bruzual & Charlot 2003).

The average magnitude of the Coma dSph HB, set by the matching with the ridgelines of M 68, is $(V_{UB}) = 18.64 \pm 0.04$ mag (where the error includes both uncertainties in the photometry and in the matching procedure). Assuming $M_V = 0.59 \pm 0.03$ mag for the absolute magnitude of HB stars at $[\text{Fe}/\text{H}] = -1.5$ dex (Cacciari & Clementini 2003), the distance modulus of Coma is $18.13 \pm 0.08$ mag ($d = 42.51$ kpc). Errors include uncertainties in the photometry, reddening, metallicity, and RR Lyrae absolute magnitude. On the same assumptions, the average apparent magnitude of the RRab star is $18.44 \pm 0.03$ mag leads, instead, to the distance modulus of 17.93 $\pm$ 0.08 mag ($d = 39.12$ kpc). While the first estimate is in good agreement with the distance of 44 $\pm$ 4 kpc found by B07, the value inferred from the RRab stars is, respectively, 3 and 5 kpc shorter than the galaxy distance derived in the present study and in B07. An additional distance estimate for the two RR Lyrae stars was obtained using the empirical Wesenheit relation in the $B$, $V$ bands as defined by Kovács & Walker (2001) and calibrated by Kovács (2003), this calibration is consistent with a distance modulus for the Large Magellanic Cloud of 18.55 mag. The resulting moduli: $\mu_0$(RRab) = 18.06 $\pm$ 0.10 and $\mu_0$(RRc) = 18.09 $\pm$ 0.10 mag, are in good agreement with each other and are consistent with the distance inferred from the average magnitude of the galaxy HB. The overabundance of the RRab reflects into the Wesenheit index, however it is balanced by the star longer period, thus the resulting distance modulus is in good agreement with that derived for the RRc variable. These results suggest that the RRab star is brighter because it has evolved off the zero-age HB, rather than because it is significantly closer to us.

5. SUMMARY AND CONCLUSIONS

We have identified and obtained $V$, $I$ light curves for 2 two RR Lyrae (one RRc and one RRab) and one short period variable, in the Coma dSph galaxy. The behavior of the RR Lyrae stars suggests an Oosterhoff II classification for the galaxy. From the average luminosity of the HB stars, the distance modulus of the Coma dSph is $\mu_0 = 18.13 \pm 0.08$ mag ($d = 42.51$ kpc). The galaxy appears to be elongated with irregular and extended shape, likely caused by the tidal interaction with the MW. The RRab star lies outside the galaxy half-light radius and is about 0.2 mag brighter than the average magnitude of the galaxy’s HB. Its bright mean magnitude leads to a distance of $d = 39.12$ kpc, which, if interpreted in terms of projection effects, could provide a rough estimate for the galaxy elongation. However, the Wesenheit results suggest that the star overabundance is indeed due, at least in part, to evolution off the zero-age HB. Finally, from the analysis of the CMDs we identify in the lower northeast field of the Coma galaxy, the background cluster of galaxies MaxBCG J186.85861+2380004 (Koester et al. 2007).

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