VARIABLE STARS IN THE NEWLY DISCOVERED MILKY WAY DWARF SPHEROIDAL SATELLITE CANES VENATICI I

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ABSTRACT

We have identified 23 RR Lyrae stars and three possible anomalous Cepheids (ACs) among 84 candidate variables in the recently discovered Canes Venatici I (CVn I) dwarf spheroidal galaxy. The mean period of 18 RRab type stars, \( \langle P \rangle = 0.60 \pm 0.01 \) days, and the location of these stars in the period-amplitude diagram suggest that CVn I is likely an Oosterhoff-intermediate system. The average apparent magnitude of the RR Lyrae stars, \( V = 22.17 \pm 0.02 \) mag, gives a distance of 210 kpc, for an adopted reddening \( E(B-V) = 0.03 \) mag. We present a \( B, V \) color-magnitude diagram (CMD) of CVn I that reaches \( V \sim 25 \) mag, and shows that the galaxy has a mainly old stellar population with a metal abundance near \( [Fe/H] = -2.0 \) dex. The width of the red giant branch and the location of the candidate ACs on the CMD may indicate that the galaxy hosts a complex stellar population with stars from \( \sim 13 \) Gyr to as young as \( \sim 0.6 \) Gyr.

Subject headings: galaxies: distances and redshifts — galaxies: dwarf — galaxies: individual (Canes Venatici I) — stars: horizontal-branch — stars: variables: other — techniques: photometric

Online material: color figure, machine-readable table

1. INTRODUCTION

The Canes Venatici I dwarf spheroidal (dSph) galaxy (R.A. = 13° 28′ 03.5″, decl. = 38° 33′ 32.1″; J2000.0), discovered by Zucker et al. (2006), is one of the new satellite companions to the Milky Way (MW) discovered by the Sloan Digital Sky Survey (SDSS) (Belokurov et al. 2007). Zucker et al. (2006) found CVn I to have an absolute magnitude \( M_V = -7.9 \pm 0.5 \) mag and a central surface brightness of \( 28 \) mag arcsec\(^{-2}\), slightly fainter than the well-known dSph galaxies Draco and UMi, but brighter than other recently discovered dSph galaxies. The SDSS \( i, g - i \) CMD showed CVn I to have a morphology suggesting a dominant old stellar population. However, de Jong et al. (2007), applying an automated numerical CMD analysis technique to the SDSS data, also suggested the possible presence of a younger stellar component about 2.5–4 Gyr old. The CVn I CMD exhibits a well-populated horizontal branch (HB), which extends across the region of the RR Lyrae (RRL) instability strip, raising the possibility that CVn I contains a significant RRL population. RRL stars, indicative of an old stellar population, have been found in all the dSph systems identified prior to the recent SDSS discoveries, as well as in the newly discovered Boötes dwarf (Siegel 2006; Dall’Ora et al. 2006). Although MW globular clusters (GCs) with significant numbers of RRL stars exhibit the well-established Oosterhoff dichotomy (Oosterhoff 1939), many (but not all) of the dSph galaxies have Oosterhoff-intermediate properties (see Catelan 2004, 2005). Notably, the Boötes dSph is in fact an Oosterhoff type II (OoII) system (Siegel 2006; Dall’Ora et al. 2006).

In this Letter we present the first results of a search for variable stars in CVn I, and use the RRL stars that were discovered to establish its Oosterhoff classification. We also present a \( B, V \) CMD of CVn I extending to \( V \sim 25 \) mag, about 3 mag fainter than the CMD of Zucker et al. (2006).

2. OBSERVATIONS AND DATA REDUCTION

\( B, V \), and Cousins \( I \) time-series photometry of CVn I was obtained in 2006 May and 2007 April and May at the 2.3 m Wisconsin Infrared Observatory telescope (WIRO), using the prime focus CCD camera (Pierce & Nations 2002). Additional \( B, V, I \) photometry was obtained at the 4.2 m William Herschel Telescope (WHT) in 2007 April using the Prime Focus Imaging Camera. The WIRO and WHT observations cover fields of view (FOVs) measuring approximately \( 17.8′ \times 17.8′ \) and \( 16.2′ \times 16.2′ \) in size. We obtained 36 \( V, 22 \ B \), and 12 \( J \) frames in total. The images were bias subtracted and flat-field corrected using IRAF. The DAOPHOT II/ALLSTAR packages (Stetson 1987, 1994) were used to obtain instrumental magnitudes for each star. These were transformed to the standard system using observations of Landolt standard fields PG 1323, PG 1633, and SA 104 (Landolt 1992) at WIRO, and PG 0918 and PG 1633 at the WHT. Typical errors at the level of the CVn I HB \( (V \sim 22.2 \) mag) for the combined photometry of nonvariable
Table 1

Identification and Properties of the Confirmed Variable Stars

| Name | ID  | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | Type | $P$ (days) | Epoch(max) | $A_V$ | $A_B$ |
|------|-----|-------------------|-------------------|------|------------|------------|-------|-------|
| V1   | 1054 | 13 27 29.1        | 33 38 03.0        | RRab | 0.59       | 4204.834   | 22.12 | 22.53 |
| V2   | 1067 | 13 27 50.3        | 33 38 02.2        | RRab | 0.57       | 4229.708   | 22.18 | 22.57 |
| V3   | 1179 | 13 28 38.7        | 33 37 28.8        | RRab | 0.61       | 4230.280   | 22.21 | 22.61 |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

3. VARIABLE STARS

We used the V-band time series, which had more phase points than the other bands, to identify variable stars using Stetson’s (1994) ALLFRAME/TRIAL package. A total of 84 candidate variables were identified. Period searches were carried out using Supersmoothen (Reimann 1994). The resultant light curves were fit to template light curves (Layden 1998) in order to classify the type of variable star. We obtained reliable periods and light curves for 23 RRL stars: 18 fundamental-mode (RRab) variables and five first-overtone (RRc) stars. Three brighter variables about 1.5–2 mag above the galaxy’s HB were also identified. They are possibly anomalous Cepheids (ACs), but have incomplete phase coverage. According to the position on the galaxy’s CMD, the vast majority of the remaining 58 candidate variables are likely RRL stars. Properties of the confirmed variable stars are provided in Table 1 and example light curves are shown in Figure 1. The average periods for the RRL stars are $<P_{\text{RRab}}>$ $= 0.60 \pm 0.01$ days ($\sigma = 0.02$ days) and $<P_{\text{RRc}}>$ $= 0.38 \pm 0.01$ days ($\sigma = 0.03$ days). The period-amplitude relation for the V band is shown in Figure 2. The majority of the CVn I RRab stars fall in the region between the Oosterhoff type I (OoI) and OoII loci and, along with the average period $<P_{\text{RRab}}>$, support the classification of CVn I as an Oosterhoff-intermediate object. CVn I would be in this sense like the majority of dSph systems previously searched for RRL stars (Catelan 2004), but unlike the recently discovered Boötes system.

4. STRUCTURE, CMD, AND DISTANCE

Figure 3 shows a map of the CVn I stars in the FOV of the WHT observations, with the confirmed variable stars marked by different symbols. A smoothing filter was applied to the data to enhance the stellar densities over the background. Although CVn I (half-light radius $r = 8.5' \pm 0.5'$; Zucker et al. 2006) extends beyond the WHT FOV, the bulk of the CVn I stars appear to be inside the elongated structure outlined by the ellipse of Figure 3, whose semimajor axis measures $\sim 6.7'$. The RRL stars appear instead to be more evenly distributed over the field. The candidate ACs all lie outside the ellipse. Two of them are in the upper left portion of the map, in opposite direction with respect to the region occupied by the blue/young population detected in CVn I by Martin et al. (2008); the third one lies slightly outside the map in the east direction. Figure 4a shows the $V, B - V$ CMDs of the CVn I dSph obtained from stars in the whole $16.2' \times 16.2'$ field covered by the WHT observations, and in three separate regions corresponding to the ellipse region (Fig. 4b), the region between ellipse and circle (Fig. 4c), and example light curves are shown in Figure 1. The average periods for the RRL stars are $<P_{\text{RRab}}>$ $= 0.60 \pm 0.01$ days ($\sigma = 0.02$ days) and $<P_{\text{RRc}}>$ $= 0.38 \pm 0.01$ days ($\sigma = 0.03$ days). The period-amplitude relation for the V band is shown in Figure 2. The majority of the CVn I RRab stars fall in the region between the Oosterhoff type I (OoI) and OoII loci and, along with the average period $<P_{\text{RRab}}>$, support the classification of CVn I as an Oosterhoff-intermediate object. CVn I would be in this sense like the majority of dSph systems previously searched for RRL stars (Catelan 2004), but unlike the recently discovered Boötes system.

![Fig. 1.—$V$ and $B$ light curves of variable stars in CVn I. Top: RRab star with $P = 0.63$ days. Middle: RRc star with $P = 0.40$ days. Bottom: Candidate AC with a possible period of 1 day.](image1.png)

![Fig. 2.—Period-amplitude diagram in the $V$ band for the CVn I RR Lyrae stars. RRab stars are indicated by plus signs and RRc stars by triangles. The solid and dashed lines are the positions of OoI and OoII Galactic GCs from Clement & Rowe (2000). [See the electronic edition of the Journal for a color version of this figure.](image2.png)
Fig. 3.—Smoothed map of the CVn I stars in the field of view of the WHT observations, in differential R.A. and decl. (in arcminutes) from the galaxy center, which was set at R.A. = 33° 28′ 02″; decl. = 33° 33′ 40″ (2000.0). North is up and east to the left. The bulk of the CVn I stars are within the ellipse which has semimajor axis $r = 6.7'$ and ellipticity $e = 0.55$. The circle has a radius of $r = 7'$. Confirmed RR Lyrae stars are displayed by open circles, candidate ACs by crosses. One of the ACs lies about half an arcminute outside the map, in the east direction.

and the region outside the circle (Fig. 4d) in Figure 3. The three regions cover areas in the ratio 1 : 1 : 1.5. Only stars with $\sigma_x$, $\sigma_y \leq 0.10$ mag, $\chi \leq 2$, and shape-defining parameter [SHARP] $\leq 0.5$ are plotted in the figure. Confirmed variable stars are plotted in different colors. The photometric data generating the CMDs, and the time-series data for the confirmed variables, are available in electronic form on request. The solid and dashed lines in Figure 4 are, respectively, the mean ridge lines of the Galactic GCs M68 (NGC 4590, from Walker [1994]) and M3 (NGC 5272, from Buonanno et al. [1994]), shifted in magnitude and color to match the CVn I HB.

The galaxy has well-populated horizontal and red giant branches, confirming that the dominant population in CVn I is old. The HB stretches across the RRL instability strip, which is entirely filled by the large number of confirmed and candidate RRL stars, and extends significantly to the blue. The red giant branch (RGB) is a prominent feature of the CMD, and exhibits some scatter. Its width suggests the existence of a composite population in CVn I, with stars having some spread in metallicity and/or age. The CMD becomes very crowded below $V = 24$ mag, but nevertheless shows hints of a young main sequence at $B - V < 0.2$ mag, thus providing support for de Jong et al.’s (2007) earlier suggestion. From the average luminosity of the HB ($V_{\text{lim}} \sim 22.2$ mag), the turnover of the old stellar population is estimated to lie a few tenths below the limiting magnitude reached by our photometry, as also shown by the comparison with M68 and M3. Contamination by field stars and background galaxies is present in Figure 4a. Source Extractor (SExtractor; Bertin & Arnouts 1996) was run on the WHT data, and the morphological parameters of the detected sources were used to discriminate between stars and background galaxies. We found that brighter than $V = 24$ mag, more than 95% of the sources are bona fide stars. Among them, contaminating stars from the MW disk dominate for $B - V > 1.2$ mag, while stars from the Galactic halo may contaminate the CVn I CMD at bluer colors. We do not have a control field devoid of CVn I stars to discuss the field contamination by MW stars properly. However, synthetic CMDs of the MW field at the position of CVn I show that a large fraction of the bright stars at $V \sim 20$ mag and $B - V \sim 0.4$–0.5 mag in the galaxy CMD may be accounted for by MW halo stars (M. Cignoni 2007, private communication). Contamination by field stars is minimized in Figure 4b, where we have considered only stars within the ellipse to take into account the elongated structure of CVn I. The main features of the galaxy CMD, including the blue plume of a young stellar component, show up much more clearly in Figure 4b. The blue plume becomes increasingly prominent moving outward (see Figs. 4c and 4d). Adopting for the reddening of M68 $E(B - V) = 0.07 \pm 0.01$ mag (Walker 1994), and for M3 $E(B - V) = 0.01 \pm 0.01$ mag (Harris 1996), the color shifts required to match the CVn I HB to those of M68 and M3 thus imply a reddening $E(B - V) = 0.03 \pm 0.02$ mag for CVn I. This is slightly larger than the $0.014 \pm 0.026$ mag value derived for the galaxy from the Schlegel et al. (1998) maps. The RGB of M68 provides an excellent fit to CVn I, implying that the galaxy has a dominant old ($t \sim 13$ Gyr) stellar population with metallicity close to that of M68: $[\text{Fe/H}] = -2.1$ or $-2.0$ dex on the Zinn & West (1984) and Carretta & Gratton (1997) scales, respectively. On the other hand, the M3 RGB is by far too red to match that of CVn I, which excludes any metallicity spread as large as 0.5 dex or larger in CVn I, since the metallicity of M3 is $[\text{Fe/H}] = -1.6$ or $-1.3$ dex on the Zinn & West and Carretta & Gratton scales, respectively. Recent spectroscopic analysis of stars in CVn I (Ibata et al. 2006; Martin et al. 2007) distinguished two separate components in CVn I with $-2.5$ dex $< [\text{Fe/H}] <$
−2.0 dex and −2.0 dex < [Fe/H] < −1.5 dex, respectively, on the Carretta & Gratton scale. These results were contested by Simon & Geha (2007), who found no evidence for a second metallicity component in CVn I. Using the Rutledge et al. (1997) technique, which provides metallicities that are consistent with the Carretta & Gratton scale, Simon & Geha obtained [Fe/H] = −2.09 ± 0.02 dex, with dispersion σ_{Fe/H} = 0.23 dex, in good agreement with the metallicity we infer from the comparison with M68. Our CMD and the comparison with M68 and M3 does not provide evidence in favor of two separate components with differences in metallicity as large as claimed by Ibata et al. and Martin et al. in CVn I. In order to investigate this point further, and to possibly disentangle the age and the metallicity effects, we have fitted isochrones from the PISA database (Cariulo et al. 2004) to the CMD of CVn I in Figure 4a, varying the metallicity from Z = 0.0002 to Z = 0.0004 (this upper limit being set by the ACs) and the age from 13 to 0.6 Gyr. Results of the best fit are shown in Figure 5, where we also plot the variable stars in different symbols. The best-fit procedure does not favor significant metallicity spreads among the CVn I stars. The galaxy CMD and its variable stars are best reproduced by the superposition of at least two and possibly up to four subsequent generations of stars with roughly the same metal abundance, Z = 0.0002 ([Fe/H] = −2.0 dex). They include a 13 Gyr component (red isochrone) accounting for the redder RGB, the HB, and the large number of RRL stars; a 0.6 Gyr component (black isochrone) producing the bluest part of the blue plume and the ACs; and possibly two intermediate age components: a 5 Gyr population (blue isochrone) producing the bluer RGB and the fainter portion of the red clump, and 1.5 Gyr stars (green isochrone) providing part of the blue plume and the brighter portion of the red clump. A deeper CMD is needed to fully confirm this interpretation.

The intensity-weighted mean magnitude of the CVn I RRL stars is \( V = 22.17 \pm 0.02 \) mag (with a dispersion of 0.07 mag among the 23 stars). We adopt an absolute magnitude of \( M_V = 0.46 \pm 0.03 \) mag for RRL stars with metallicity \([\text{Fe/H}] = −2.1\) dex (Cacciari & Clementini 2003) and for the reddening the value of \( E(B-V) = 0.03 \pm 0.02 \) mag inferred from the comparison with M68 and M3. We thus find a distance modulus of \( \mu = 21.62 \pm 0.06 \) mag which corresponds to a distance of \( d = 210^{+25}_{-16} \) kpc. This agrees with the distance of \( 210^{+25}_{-16} \) kpc found in Zucker et al. (2006).

5. CONCLUSIONS

We have identified and obtained periods and light curves for 18 RRab stars and five RRc stars in the CVn I dSph galaxy.

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Fig. 5.—Best fit of the CVn I CMD in Fig. 4a, using isochrones from the PISA data set with Z = 0.0002 ([Fe/H] = −2.0 dex), and four age components: 13 Gyr (red line), 5 Gyr (blue line), 1.5 Gyr (green line), and 0.6 Gyr (black line). The CVn I confirmed variable stars are plotted with the same symbols as in Fig. 4. Candidate variables are marked by cyan circles. Typical error bars of the photometry are provided on the left-hand side.

We also identified three potential ACs and 58 additional candidate variable stars that are very likely RR Lyrae stars. The average period of the CVn I RRab stars for which we have complete and reliable light curves and their location on the period-amplitude diagram suggest that CVn I is an Oosterhoff-type object, following the trend of the other "classic" dSphs (Catelan 2004). This similarity is strengthened in that CVn I seems to contain a complex stellar population with components of different age in the range from 0.6 to 13 Gyr.

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