A DEEP LARGE BINOCULAR TELESCOPE VIEW OF THE CANES VENATICI I DWARF GALAXY

Nicolas F. Martin,1 Matthew G. Coleman,2 Jelte T. A. de Jong,2 Hans-Walter Rix,2 Eric F. Bell,2 David J. Sand,3,4 John M. Hill,3 David Thompson,5 Vadim Burwitz,6 Emanuele Giallongo,7 Roberto Ragazzoni,8 Emiliano Diolaiti,9 Federico Gasparo,10 Andrea Grazian,7 Fernando Pedichini,7 and Jill Bechtold3

Received 2007 September 20; accepted 2007 November 7; published 2007 November 30

ABSTRACT

We present the first deep color-magnitude diagram of the Canes Venatici I (CVn I) dwarf galaxy from observations with the wide-field Large Binocular Camera on the Large Binocular Telescope. Reaching down to the main-sequence turnoff of the oldest stars, it reveals a dichotomy in the stellar populations of CVn I: it harbors an old (≥10 Gyr), metal-poor ([Fe/H] ~ −2.0), and spatially extended population along with a much younger (∼1.4–2.0 Gyr), 0.5 dex more metal-rich, and spatially more concentrated population. These young stars are also offset by 64±40 pc to the east of the galaxy center. The data suggest that this young population, which represents ~3%–5% of the stellar mass of the galaxy within its half-light radius, should be identified with the kinematically cold stellar component found in a recent spectroscopic survey. CVn I therefore follows the behavior of the other remote MW dwarf spheroidals, which all contain intermediate-age and/or young populations: a complex star formation history is possible in extremely low mass galaxies.

Subject headings: galaxies: individual (Canes Venatici I) — galaxies: stellar content — Local Group

Online material: color figures

1. INTRODUCTION

Although the Canes Venatici I (CVn I) dwarf galaxy (α0 = 13h28m03.5s, δ0 = 33°33′21.0″) is not much less luminous than previously known satellites of the Milky Way (MW; Mv = −7.9 ± 0.5), its large distance (224 ± 21 kpc) kept it hidden until it was recently discovered by Zucker et al. (2006) in the Sloan Digital Sky Survey (SDSS). Unlike most other Galactic satellites at more than 200 kpc from the MW, CVn I seems dominated by old stellar populations. However, applying an automated color-magnitude diagram (CMD) fitting technique to SDSS data, de Jong et al. (2007) show tentative evidence for the presence of a much younger population of only ~3 Gyr.

A spectroscopic survey of CVn I stars (Ibata et al. 2006; Martin et al. 2007) also revealed the presence of two kinematically distinct populations. The most metal-rich half of the sample (−1.9 ≤ [Fe/H] ≤ −1.5) shows a kinematically extremely cold component, with a radial velocity dispersion <1.9 km s−1, whereas the most metal-poor half of the sample (−2.5 ≤ [Fe/H] ≤ −1.9) is much hotter (σ ≥ 10 km s−1). The hot component is also measured to be twice as spatially extended as the cold one. However, these findings have been challenged by Simon & Geha (2007), who do not find such a dichotomy of kinematic properties in their larger spectroscopic sample.

In order to better understand the stellar populations that are present in CVn I and understand their role in shaping the structure of the dwarf galaxy, we have used the blue Large Binocular Camera (LBC; Ragazzoni et al. 2006; E. Giallongo et al. 2008, in preparation) on the Large Binocular Telescope (LBT; Hill et al. 2006) to obtain photometric observations that are deep enough to reach the main-sequence turnoff (MSTO) of the oldest stars. We briefly present the data in § 2 before analyzing and discussing them in §§ 3 and 4.

2. DATA

The observations comprise 6 × 5 minute and 4 × 5 minute exposures in the B and V band, respectively, and were performed as part of the LBC-Blue Science Demonstration Time program during the night of 2007 June 11, with a seeing of 1.1′′–1.4′′. Data reduction was handled with the same pipeline as used for the reduction of the Hercules dwarf galaxy LBT observations (Coleman et al. 2007).

A comparison of the LBT photometry (BLT and VBLT) with the SDSS stars having g < 22.5, transformed into Landolt B and V (Jester et al. 2005), reveals the presence of a slight color term that we correct by its best linear fit:

\[ V = V_{\text{BLT}} + 0.051(B - V)_{\text{BLT}} - 0.121. \]

An iterative 3σ clipped Gaussian fit of the residuals around this linear correction yields a dispersion of 0.08 mag. The color term in B is found to be close to zero (although with a larger scatter), and no correction is applied. While this is not optimal, it will not impact our conclusions that are dependent on imaging depth rather than photometric precision.

The 50% completeness limits are Blt = 25.90 ± 0.07 and
V_50 = 25.87 ± 0.11, and the 5σ flux limits are reached for B = 25.2 and V = 25.1. Finally, we only keep stars with δm < 0.15 in both magnitudes and with a DAOPHOT sharpness parameter in the B band of ±0.25.

3. ANALYSIS

3.1. Revised Distance from the Horizontal Branch

The CMD of the region within the half-light radius (r_{hl} = 8.4′, ellipticity = 0.38, and P.A. = 73°; Zucker et al. 2006) of CVn I is shown in Figure 1a and provides a quite dramatic improvement over the shallow SDSS CMD that barely reaches the horizontal branch (HB) at V ≈ 22.5 (Zucker et al. 2006). Figure 1b shows the underlying CMD contamination in a region of equal coverage at the southern edge of the field. Given the good LBT photometry (the errors at these magnitudes are dominated by the dispersion in the color correction from §2), these stars can be used directly to constrain the distance of the dwarf galaxy more precisely than from the tip of its sparsely populated red giant branch (RGB). The median magnitude of these HB stars is m_v(HB) = 22.22 ± 0.09. To determine their absolute magnitude, we follow Cacciari & Clementini (2003):

\[ M_v(HB) = (0.23 ± 0.04)([\text{Fe/H}] + 1.5) + (0.59 ± 0.03). \]

As the spectroscopic sample from Ibata et al. (2006) and Martin et al. (2007) also covers the region within the half-light radius, we use their median spectroscopic [Fe/H] = −2.0 ± 0.2 to determine M_v(HB) = 0.48 ± 0.06. Assuming A_v = 0.05 (Schlegel et al. 1998; Zucker et al. 2006) finally leads to (m − M)_V = 21.69 ± 0.10 or D = 218 ± 10 kpc, a value that is in agreement with, but more accurate than, previous determinations from Zucker et al. (2006) and de Jong et al. (2007).

3.2. Stellar Populations

The LBT data are deep enough to show the subgiant branch of the galaxy and reach the MSTO of old populations. To remove the contamination from background compact galaxies masquerading as stars, we subtract the scaled Hess diagram of regions to the north and south of the galaxy center, where none of the CMD features of CVn I are found ([δ − δ_0] > 9; see Fig. 2). The resulting diagram is shown (identically) in Figures 1c–1e and reveals the turnoff of an old stellar population at V ≈ 25.0 and 0.0 ≲ B − V ≲ 0.5. Both the CMD and Hess diagram also reveal a blue plume (BP) of stars at B − V ≈ 0.1 and 23.5 ≲ V ≲ 25.0, betraying the presence of a possible young stellar population.

The isochrones of Girardi et al. (2002) with an age of 14.1 Gyr (Fig. 1b) are in good agreement with the color and magnitude of the “old red population” of CVn I, as they overlap nicely with the turnoff and the subgiant branch and give the proper location of the HB for metallicities in the range −2.3 ≲ [Fe/H] ≲ −1.7. The relatively red color of the RGB, however, seems to indicate a metallicity above −2.0. Isochrones of 10.0 Gyr also give a reasonable agreement, although in this case, the MSTO barely copes with the data, suggesting that the old population of CVn I has an age ≳10 Gyr.

The origin of the BP is harder to ascertain given the well-known confusion between young stars and blue stragglers produced by binaries in dwarf galaxies. However, determining the blue straggler frequency as defined in Momany et al. (2007) yields log F_B^RS = 0.5 ± 0.2, a value that is ≃1.5σ away from the relation these authors find in galaxies believed to contain no young stars. Moreover, the spatial offset of the BP stars from the center of CVn I (see below) would require the binary population at the origin of the putative blue stragglers to have different properties from the bulk of the CVn I stars. Finally, the presence of a carbon star (Zucker et al. 2006) as well as Cepheid variables (Kuehn et al. 2007) in CVn I would be a natural outcome of the presence of a young/intermediate age population. All these points favor the presence of a young population in CVn I, with an age between ~1.4 and ~2.0 Gyr from the isochrone fitting of Figure 1d. These isochrones also need to be more metal-rich than the old population ([Fe/H] ~ −1.3; although a slightly more metal-rich population is still in agreement with the data). In addition, they can explain the fuzz of stars in the Hess diagram at V ≈ 23.0 and B − V ≈ 0.3.

To determine the relative luminosity contribution of both components in CVn I, we extrapolate the completeness-corrected luminosity measured in the two selection boxes of
Figure 1e. Using the 2 Gyr, [Fe/H] = −1.5 luminosity function from Dotter et al. (2007) with a Salpeter initial mass function (IMF; Salpeter 1955), we extrapolate a total luminosity of $L_{V,\text{old}} \sim 3.5 \times 10^4 L_\odot$ within $r_{\text{half}}$. The 12 Gyr, [Fe/H] = −2.0 luminosity function is assumed for the old population and yields total luminosity $L_{V,\text{old}} \sim 3.5 \times 10^4 L_\odot$, once again within the half-light radius. The young stars therefore represent $\sim$10% of the luminosity of the galaxy, which translates to $\sim$3%–5% of the stellar mass of the galaxy within $r_{\text{half}}$ (although there are sizable uncertainties on this number given the assumptions made, especially on the IMF).

3.3. Spatial Distribution of Stellar Populations

To build the maps of these two populations, we use the “matched-filter” method that is the optimal search strategy (in the least-squares sense) to recover a signal, assuming that one has a perfect model of the signal and of its contamination (see, e.g., Rockosi et al. 2002 for more details). In this case, the signal CMD is the one of Figure 1a after removing obvious nonmembers with $B - V > 1.5$, and the contamination CMD is obtained from regions of the LBT field with $|\delta - \delta_\odot| > 9^\prime$ (Fig. 2, hatched region in top left panel).

The resulting contour maps of detections higher than the mean background level are shown in Figure 2 for all the stars in the sample (top left panel) and the right and left selection boxes of Figure 1e (top right and bottom left, respectively). The various maps are overlaid in the bottom right panel for a direct comparison. The galaxy exhibits rather distorted contours, although the degrading star/galaxy separation at fainter magnitudes can also be (at least partly) responsible for this effect. Shallower regions produced by the gaps between the CCDs of the camera at $(\alpha - \alpha_\odot) \cos \delta_\odot = \pm 4^\prime$ also seem responsible for the boxy shape of the inner regions of the dwarf.

A more surprising feature is the double core at the center of CVn I, along with the slight offset of its densest region that lies to the east. Given that the old stars are distributed over the whole galaxy and are centered on $(\alpha_\odot, \delta_\odot)$, this double-core

\footnote{For the sparser blue population that is more strongly affected by background galaxies, we also apply a stricter cut of $\pm 0.15$ on the DAOPHOT sharpness parameter.
has to be produced by the much more spatially confined young
population offset by 1.0 \pm 0.3 \text{ arcmin or } 64 \pm 20 \text{ pc to the east (the uncertainties have been determined by a bootstrap resampling of the position of the BP stars within } r_{\text{disp}}).

The spectroscopic survey of Ibata et al. (2006) and Martin et al. (2007) has also revealed the presence of two distinct components in this galaxy from the spectroscopy alone. The methodologically independent discovery of two distinct stellar components in CVn I from the LBC photometry and the much smaller extent of the young population surprisingly recalls their findings.

A direct comparison of their spectroscopic sample with the LBC contour maps of the old and young populations is presented in Figure 3. Stars belonging to the kinematically cold, more metal-rich population are represented by filled (open) star symbols when they are within 1 \sigma (2 \sigma) of the Ibata et al. (2006) radial velocity peak of this component (see the top middle panel of their Fig. 2). Other stars in the sample belong to the kinematically hot component and are plotted as filled circles. These stars extend over the contours of the old population (top panel) and do not exhibit any clustering, whereas the cold component stars are mainly clustered over or close to the contours of the young population (bottom panel). Although the numbers considered here are small and a random clustering of these stars does not have a negligible probability, the fact that they closely follow the distribution of the independently selected young stars suggests that the cold component of Ibata et al. (2006) is indeed real and that it corresponds to the young population seen in the LBT data. The hot component would then be produced by the old population of the galaxy. The metallicities between the spectroscopic and photometric data are also in agreement since the hot component is metal-poor with [Fe/H] \sim -2.0 (compared to -2.3 \leq [Fe/H] \leq -1.7 from the LBT photometry) and the cold one more metal-rich by \sim 0.5 dex in both cases.

The only significant discrepancy between the two surveys is the relative proportion of the two components since the young stars should represent less than 10% of the CVn I stars within its half-light radius. However, assuming the kinematic properties of the two populations from Ibata et al. (2006), only \sim 9 open or filled star symbols of Figure 3 are expected to be genuine members of the cold components with the other being contaminants from the hot component. This translates to \sim 14% of the spectroscopic sample. Given the small number of stars we are dealing with, the difference in the proportion of young stars in the photometry and cold stars in the spectroscopic sample is reasonable.

4. CONCLUSION

From deep B- and V-band photometry of the Canes Venatici I galaxy reaching to the old main-sequence turnoff, we found evidence for

1. a (known) dominant old population that represents \sim 95\% of the mass of the galaxy, with an age \geq 10 \text{ Gyr and [Fe/H]} \sim -2.0;
2. a new, much younger population revealed by a blue plume that corresponds to \sim 1.4-2.0 \text{ Gyr stars that are also slightly more metal-rich ([Fe/H]} \sim -1.5).

We show that the old population is extended and mainly shapes the structure of CVn I. In contrast, the young population is very compact as well as offset from the dwarf center by 1.0 \pm 0.3 \text{ arcmin or } 64 \pm 20 \text{ pc. This suggests that it is not yet dynamically relaxed, although this is not surprising given that the typical relaxation time for a dwarf galaxy is higher than a Hubble time (e.g., Gilmore et al. 2007). Such a clump could therefore be used to constrain the shape of the CVn I potential, as has been done in UMi (Kleyna et al. 2003).

These two distinct populations are in good agreement with previous more tentative determinations from an automated study of the SDSS CMD of CVn I by de Jong et al. (2007). They are also in line with the spectroscopic results from Ibata et al. (2006), who have shown that the dwarf harbors two kinematically very different populations with different metallicities. From their spatial distribution, we link their extremely cold component to the young compact population that we found in the LBT data.

Even though it is a faint and low-mass galaxy (10^2-10^5 \text{ M}_\odot; Martin et al. 2007; Simon & Geha 2007), CVn I, which is located at a distance of 218 \pm 10 \text{ kpc}, behaves as its brighter counterparts located at more than 200 kpc. Indeed, it exhibits unmixed, distinct components and a complex star formation history.

The authors gratefully thank the LBT Science Demonstration Time team for making these observations possible.

REFERENCES

Cacciari, C., & Clementini, G. 2003, in Stellar Candles for the Extragalactic Distance Scale, ed. D. Alloin & W. Gieren (Berlin: Springer), 105
Coleman, M. G., et al. 2007, ApJ, 668, L43
de Jong, J. T. A., Rix, H., Martin, N. F., Zucker, D. B., Dolphin, A. E., Bell, E. F., Belokurov, V., & Evans, N. W. 2007, ApJ, submitted (arXiv: 0708.3758)
Dotter, A., Chaboyer, B., Jevremović, D., Baron, E., Ferguson, J. W., Sarajedini, A., & Anderson, J. 2007, AJ, 134, 376
Gilmore, G., Wilkinson, M. I., Wyse, R. F. G., Kleyna, J. T., Koch, A., Evans, N. W., & Grebel, E. K. 2007, ApJ, 663, 948
Girardi, L., Bertelli, G., Bressan, A., Chiosi, C., Groenewegen, M. A. T., Marigo, P., Salasnich, B., & Weiss, A. 2002, A&A, 391, 195
Hill, J. M., Green, R. F., & Slagle, J. H. 2006, Proc. SPIE, 6267, 62670Y
Ibata, R., Chapman, S., Irwin, M., Lewis, G., & Martin, N. 2006, MNRAS, 373, L70
Jester, S., et al. 2005, AJ, 130, 873
Kleyna, J. T., Wilkinson, M. I., Gilmore, G., & Evans, N. W. 2003, ApJ, 588, L21
Kuehn, C., et al. 2007, ApJ, submitted (arXiv: 0709.3281)
Martin, N. F., Ibata, R. A., Chapman, S. C., Irwin, M., & Lewis, G. F. 2007, MNRAS, 380, 281
Momany, Y., Held, E. V., Saviane, I., Zaggia, S., Rizzi, L., & Gullieuszik, M. 2007, A&A, 468, 973
Ragazzoni, R., et al. 2006, Proc. SPIE, 6267, 626710
Rokciski, C. M., et al. 2002, AJ, 124, 349
Salpeter, E. E. 1955, ApJ, 121, 161
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Simon, J. D., & Geha, M. 2007, ApJ, 670, 313
Zucker, D. B., et al. 2006, ApJ, 643, L103