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The Carina Project: bright variables *

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Abstract. We present recent results on variable stars in the Carina Dwarf Galaxy based on B,V time series data collected over three consecutive nights with the Wide Field Imager available at the 2.2m ESO/MPI telescope.
At present we have already detected and measured a sample of 92 variable stars. Among them 75 are RR Lyrae stars (54 fundamental, 15 first overtone, and 6 suspected double-mode pulsators), while 15 are Anomalous Cepheids. By adopting recent theoretical predictions we discuss evolutionary and pulsation properties of these objects. Finally, we estimate the Carina distance according to three different methods that use RR Lyrae stars as distance indicators.

Key words. Galaxies: dwarf – Galaxies: individual (Carina) – Local Group – Stars: distances - Stars: horizontal branch – Stars: oscillations

1. Introduction

Dwarf spheroidal galaxies (dSph) form the most common type of galaxies in the Local Group and, presumably, in the present Universe (Marzke, & Da Costa 1997). In a hierarchical formation scenario, they are the "fundamental units" to build up larger galaxies, therefore they appear to be as cornerstones in the understanding of the formation and the evolution of galaxies. Interestingly, the study of the stellar con-

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tent of dSphs indicate that they generally show complex star formation histories, with different stellar populations that cover a wide age range and in some cases also in chemical abundances. Variable stars are useful tools to trace stellar populations in these galaxies, since they are easily recognizable from their light curve. Moreover, they can also be used to test evolutionary and pulsation theories.

Among dSphs, Carina is one of the most interesting objects, since its color-magnitude diagram (CMD) reveals a very complex star formation history. Comparisons of the multiple Main Sequence Turn-Offs with theoretical isochrones suggest the presence of three significant stellar populations, with age of 3, 7 and 15 Gyr (Smecker-Hane et al. 1996; Hurley-Keller, Mateo, & Nemec 1998; Monelli et al. 2003). Moreover, the CMD shows two morphologically distinct central helium burning sequences, i.e. a Horizontal Branch typical of an old population, and a Red Clump, located close to the Red Giant Branch, distinctive of a young population (Smecker-Hane et al. 1994). In their seminal work, Saha, Monet, & Seitzer (1986, hereafter SMS) reported the discovery of 172 candidate variable stars in the central region of Carina. Among them, 58 were confirmed as RR Lyrae stars, that are "bona fide" tracers of old stellar populations, while 8 object, with light curves similar to those of RR Lyrae stars, were significantly brighter. These latter variables were subsequently identified as Anomalous Cepheids (AC; Da Costa 1988; Nemec, Nemec, & Lutz 1994), i.e. central helium-burning stars with stellar masses larger than $1.3 M_{\odot}$. Note that the origin of these stars is still debated, since it is not clear if they are young single objects or the merging of old binary systems.

2. Observations and data reductions

We collected 54 B, V images, of ~ 500 sec each, with the Wide Field Imager (WFI), a mosaic CCD camera (8 chips x 2k x 4k, 0.238 arcsec/pixel) available at the 2.2m ESO/MPI telescope. The data were collected over three consecutive nights. Data were pre-reduced with the *mscred* IRAF package. Data were reduced using aperture photometry with DAOPHOTII (Stetson 1987), with a radius 4 pixels (~ 0.95 arcsec). We adopted this strategy because the Carina central field is not crowded, and the exposure time allowed us to reach on individual frames a high signal-to-noise ratio at the HB luminosity ($B \approx 21$, see Dall'Ora et al. 2003, and Monelli et al. 2003). Search for variability was performed with the variability index developed by Welch & Stetson (1993), which correlates luminosity variations in two or more photometric bands. This index is marginally affected by spurious detections. Period search was performed by means of Fourier analysis. As a whole, we identified 92 variables, 75 of which are RR Lyrae stars (26 new detections), 15 are "bona fide" ACs (7 new identifications), 1 is a bright variable located on the RGB, and 1 is a probably field RR Lyrae star. The quality of the light curves is typically quite good, however, for some variables located close to bright stars they are noisy. The PSF photometry can certainly improve the quality and Figure 1 shows a convincing example. In the near future we plan to perform PSF photometry not only on the 2.2m images but also on the B,V images collected with the MOSAIC camera available at the CTIO 4m Blanco telescope.

3. Pulsation properties

Fig. 2 shows the distribution of RR Lyrae and Anomalous Cepheids in the CMD, while Fig. 3 shows the same sample of variable stars in the $M_V - \log P$ plane (top panel), together with the Bailey diagram for RR Lyrae stars, i.e. period vs luminosity amplitude.

The split between RR Lyrae stars (circles) and bright variables (triangles) is quite evident, with the formers located, as expected, on the Horizontal Branch. Data plotted

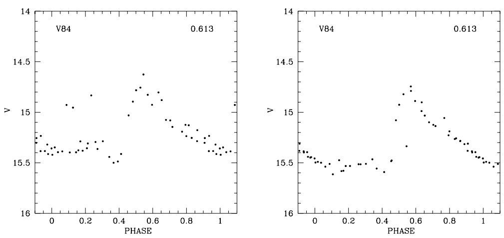

Fig. 1. Instrumental v magnitude light curve for the variable star V84 with aperture photometry (left) and PSF photometry (right). This star is located near a very bright star and the aperture photometry is affected by seeing fluctuations.

in Figures 2 and 3 display that Carina RR Lyrae stars present the same pulsation properties of RR Lyrae stars in Galactic Globular Clusters (GGCs, see e.g. Corwin, > & Carney 2001). In particular, they present a roughly constant V magnitude and $B-V$ colors ranging from 0.15 to 0.4 mag. Their distribution in the Bailey's diagram show the two well-defined groups, namely fundamental (*RRab*, longer periods) and first-overtone pulsators (*RRc*). Fundamental RR Lyrae stars follow a roughly linear relation between period and amplitude, while first overtones present a "bell-shape" distribution, predicted by current theoretical models (Bono et al. 1997b). Interestingly enough, the period distribution of Carina RR Lyrae stars shows an intermediate behavior between Oosterhoff type I clusters, with a mean fundamental period of $< Pab >= 0.55$ days, and Oosterhoff type II clusters, with a mean fundamental period of $< Pab >= 0.64$. At the same time, the fraction $RRc/(RRab + RRc) \approx 0.3$, is quite similar to OoII clusters (≈ 0.4) than to OoI clusters (≈ 0.2). Similar evidence have also been found by other Local Group dSphs (Mateo 1998; van den Bergh 2000). The comparison between predicted (Di Criscienzo et al. 2003, hereafter DMC) and observed amplitudes as well as mean colors shows that the bulk of RR Lyrae stars has stellar masses in the range $M = 0.65 - 0.80 M_{\odot}$. For the bright variables, the same comparison suggests that they are objects with stellar masses 1.5-2.5 times larger than RR Lyrae stars. This finding confirms the fact that they are metal-poor, intermediate-mass stars, during their central He-burning phase (Bono et al. 1997a; Dall'Ora et al. 2003).

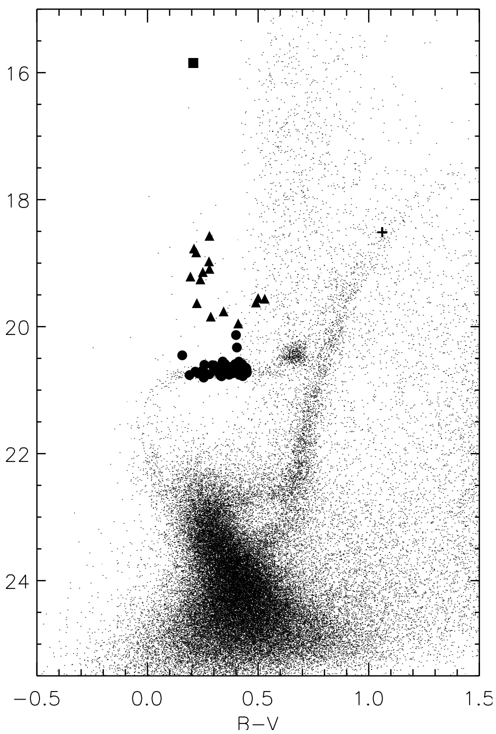

Fig. 2. Color-Magnitude Diagram of the Carina dSph. Filled circles display RR Lyrae stars, while filled triangles ACs. The cross shows a red variable located along the RGB and the filled square a candidate field RR Lyrae star.

4. Distance modulus

RR Lyrae stars are well-known Population II distance indicators since they approximately attain the same V magnitude. Their V magnitudes depend on the metallicity, but the empirical relation is still debated. However, the RR Lyrae luminosity can also be estimated according to their pulsation properties. The main advantage of such

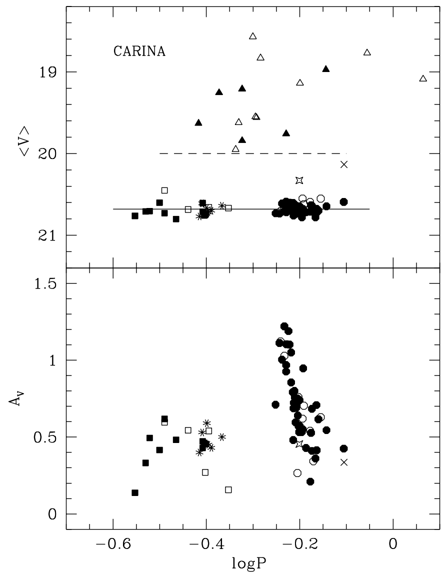

Fig. 3. Top: distribution of RR Lyrae and ACs in the M_V $\log P$ plane. Circles mark fundamental RR Lyrae stars, while squares and asterisks mark first overtone an double mode pulsators, respectively. Triangles display ACs. Open symbols refer to objects with poor sampled light curves. The cross and the lozenge mark two "bona fide" massive RR Lyrae stars (Dall'Ora et al. 2003). Bottom: Bailey's diagram of the Carina RR Lyrae stars.

an approach is that pulsation predictions rely on observables (periods and amplitudes) that are marginally affected by observational uncertainties, and in particular on distance and reddening. Then, we first compared the observed distribution of *RRc* stars with the expected position of the hot limit of the pulsation region for such variables (First Overtone Blue Edge, FOBE, Caputo 1997, Caputo et al. 2000), of a given mass and metallicity, in the $M_V - \log P$ plane. By adopting for Carina a metallicity of $[Fe/H] = -1.7$ (Monelli et al. 2003), and estimating from evolutionary HB models a mass for *RRc* variables of $M = 0.7M_\odot$ (Bono et al. 2003), the apparent distance modulus we obtain is $DM_V = 20.19 \pm 0.04$ mag (see Fig. 4). An indepen-

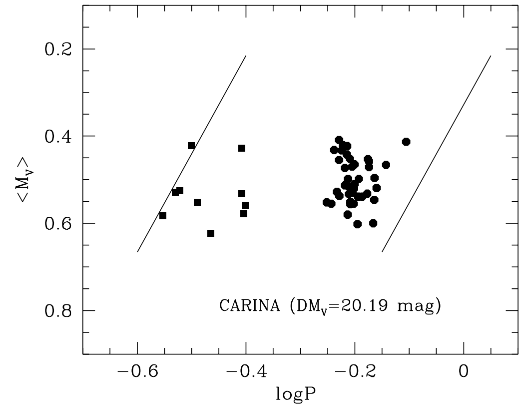

Fig. 4. Comparison of the observed distribution of *RRc* stars with the predicted position of the First Overtone Blue Edge. This supplies an estimate of the absolute magnitude of *RRc* variables.

dent estimate of the Carina distance can be obtained using the Period-Luminosity-Amplitude relation of *RRab* stars (DMC):

$$\log P_F = 0.080 - 0.396 < M_V > - \\ -0.593 \log M/M_\odot - 0.167 A_V \quad (1)$$

By adopting this method we found $DM_V = 20.09 \pm 0.10$ mag. Finally, we also estimated the distance modulus with a Period-Luminosity-Color relation (DMC)

$$\log P_F = 0.38 - 0.74 \log M/M_\odot - \\ -0.36 < M_V > - \\ -0.07 \log Z[< B > - < V >]_0 \quad (2)$$

Note that *RRc* variables have been "fundamentalized" i.e. $\log P_F = \log P_{FO} + 0.127$. The mean value of these three independent estimates gives 20.19 ± 0.12. By assuming a reddening of $E(B-V) = 0.03 \pm 0.02$ mag (Monelli et al. 2003), we derive a true distance modulus of $\mu_0 = 20.10 \pm 0.12$. Current estimate is in good agreement with recent evaluations available in literature. The latter range from $\mu_0 = 19.87 \pm 0.11$ (Mighell 1997) to $\mu_0 = 20.19 \pm 0.13$ (Dolphin 2000).

5. Conclusions

The WFI@2.2ESO/MPI provided the unique opportunity to investigate Carina bright variables. We confirm 57 variables out of the 140 suspected variables detected by SMS in the same field. We also detected 35 new variables. As a whole, we found 75 RR Lyrae stars, of which 54 are *RRab* variables, 15 are *RRc* and 6 are suspected double-mode pulsators (*RRd*). We also found 15 Anomalous Cepheids. The comparison of their pulsation properties with theoretical models strongly suggest that they are intermediate-mass He-burning stars. The period distribution of *RRab* variables and the ratio of *RRc* and total number of RR Lyrae stars, seem to suggest that Carina dSph attains intermediate pulsation properties between Oosterhoff type I and II clusters. We give three independent estimates of the Carina distance according to the pulsation properties of RR Lyrae stars. Current estimate agree quite-well with similar determination available in the literature.

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