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The Carina dSph galaxy: where is the edge?

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Abstract. Recent cosmological N-body simulations suggest that current empirical estimates of tidal radii in dSphs might be underestimated by at least one order of magnitude. To constrain the plausibility of this theoretical framework, we undertook a multiband (U,B,V,I) survey of the Carina dSph. Deep B,V data of several fields located at radial distances from the Carina center ranging from 0.5 to 4.5 degrees show a sizable sample of faint blue objects with the same magnitudes and colors of old, Turn-Off stars detected across the center.
We found that the (U-V,B-I) color-color plane is a robust diagnostic to split stars from background galaxies. Unfortunately, current U,I-band data are too shallow to firmly constrain the real extent of Carina.

Key words. Stars: Population II – Stars: evolution – Cosmology: observations

1. Introduction

The Carina dSph plays a fundamental role among the dwarf galaxies in the Local Group, because it is relatively close to the Galaxy and shows multiple star-formation episodes (Smecker-Hane et al. 1994). Detailed Color-Magnitude Diagrams (CMDs) show an old ($t \approx 11$ Gyr) stellar component, including subgiant and Horizontal Branch (HB) stars, an intermediate-age ($t \approx 5$ Gyr) component including Turn-Off and Red Clump stars, and a younger ($t \leq 1$ Gyr) component of blue

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Main Sequence (MS) stars (Smecker-Hane et al 1996; Dall'Ora et al. 2003; Monelli et al. 2003).

Photometric surveys based on robust stellar tracers (RR Lyrae, Red Giants) indicate the existence of extra-tidal stars (Kuhn at al. 1996; Majewski et al. 2000a,b). However, this empirical evidence is hampered by small-number statistics. This is the reason why we decided to use MS stars bluer than $B-V$=0.4 to trace the radial extent of this galaxy. Recent predictions based on detailed N-body simulations suggest that empirical tidal radii of dSphs might be significantly larger than currently estimated. In particular, Hayashi et al. (2003) found that the Carina tidal radius might be at least one order of magnitude larger than estimated by Majewski et al. (2000a). This prediction is further supported by independent calculations by Mayer et al. (2001) who found that the current luminosity cut-off of Carina is too small when compared with the predicted massive dark halo of this dSph.

To assess the existence of extra-tidal stars around Carina, we undertook a detailed study of the outer regions of this galaxy collecting deep, wide field, and multiwavelength data. In the following we discuss some preliminary results based on a subset of these data.

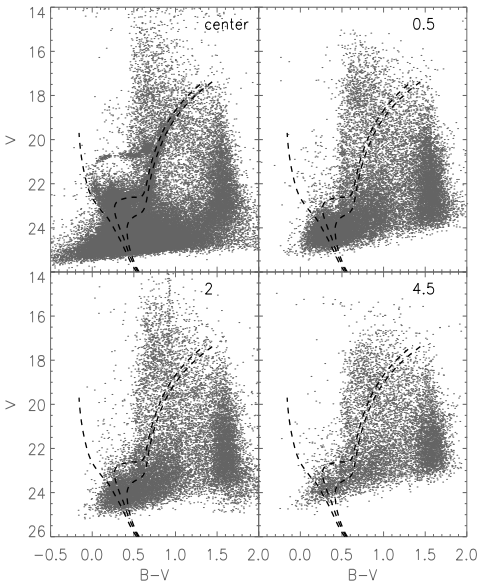

Fig. 1. Top Left - CMD (V,$B-V$) of the Carina central region (36×36 arcmin) which includes ≈ 90,000 objects. The comparison with stellar isochrones (DM=20.24, E(B-V)=0.03) suggests that the three main star formation episodes occurred at t ≈11, 5, and 1 Gyr ago. **Others** - The same isochrones have been overplotted on the CMDs of three external regions located at different distances ranging from 0.5 to 4.5 degrees from the center. Note that the spur of faint blue objects located at $23 \leq V \leq 24.5$, $B-V \leq 0.4$ is located in the same CMD region of the Carina old MS stars. The different CMDs include on average ≈ 20,000 objects.

2. Observations and preliminary results

We observed the central region and eight different fields along the major and minor axes, with distances ranging from 0.5 up to 4.5 degrees from the Carina center. These regions have been observed in B and V bands with the MOSAICII camera (f.o.v. 36′×36′) available at the 4m CTIO Blanco telescope.

Time series data of the Carina center were collected in December 1999 and January 2000. The external fields was observed in different runs between October 2002 and January 2005. Standard IRAF routines (Valdes 1997) were adopted for basic reduction, and the photometric analysis was performed using DAOPHOT/ALLFRAME (Stetson, 1987; Stetson 1994). The details of the reduction and calibration strategy will be discussed in a forthcoming paper (Monelli et al. 2005, in prep.).

Fig. 1 shows the Carina V,B-V CMDs of the central (top left panel) and of outer (other) regions. The CMDs of the external fields disclose a sizable sample of faint blue objects ($23 \leq V \leq 24.5$, $B-V \leq 0.4$). The comparison between observations and isochrones (Monelli et al. 2004), at fixed chemical composition (DM=0.24, Z=0.0004), indicates that these objects are located in the same CMD region of old TO stars we have already detected in the Carina center. Note that this spur of faint blue objects is present in all the fields we observed, up to a distance of 4.5° from the center.

In order to explain the nature of these objects we are left with three working hypotheses:

i) Extra-tidal stars - They could be either extra-tidal stars as originally suggested by Kuhn at al. (1996) and by Majewski et al. (2000a) or belong to an extended halo surrounding Carina as suggested by recent N-body simulation (Hayashi et al. 2003; Mayer et al. 2001; Kazantzidis et al. 2004)

ii) Galactic field stars - We performed several numerical simulations of Galactic models (Castellani et al. 2002) by adopting a broad range of input parameters, namely, the Initial Mass Function, the Star Formation Rate, and the thin/thick disk scale heights. Interestingly enough, we found that the contamination of field stars in the CMD region located between $23 \leq V \leq 24.5$ and $0.0 \leq B-V \leq 0.4$ is limited to small samples of thin and thick disk white dwarfs. Fortunately, field halo stars in the same magnitude range are systematically redder than the faint blue objects we have detected.

iii) Background galaxies - To constrain on a quantitative basis the contamination by background galaxies, we devised a new diagnostic based on the ($U-V$,$B-I$) color-color plane. The left panels of Fig. 2 shows the comparison between different stellar templates, namely a sample of field stars, two globular clusters (Reticulum [Large Magellanic Cloud], NGC2808 [Galaxy]) for which accurate multi-band data are available, and predicted colors for background galaxies provided by Fioc & Rocca-Volmerange (1997). Data plotted in this figure display that TO stars ($U-B \approx 0.5$, $B-I \approx 1$) are systematically redder than background galaxies at redshift smaller than 2 (Fontana et al. 2000). Therefore, we collected U,I-band data with the MOSAICII camera available at the 4m CTIO telescope of the central field and of a field located 1 degree southern from the Carina center.

Data plotted in the right panel of Fig. 2 show the color-color plane of the Carina central region. We selected ≈6000 objects in the region where background galaxies are expected. Fig. 3 shows the Carina V,B-V CMD before (left) and after (right) subtracting background galaxies. This diagnostic appears to work quite well, since down to $V \sim 23.5$ the ≈70% of blue objects appear to be real stars. Moreover, the TO region seems better defined, and the color spread of MS stars is smaller. The width in color of MS in dSphs has been considered as a robust evidence of a spread both in age and/or in chemical composition. Data plotted in Fig. 3 indicate that this region is also contaminated by background galaxies. The removal of these objects will allow us to better constrain the TO of the different populations, and in turn to provide robust estimates of the different star formation episodes.

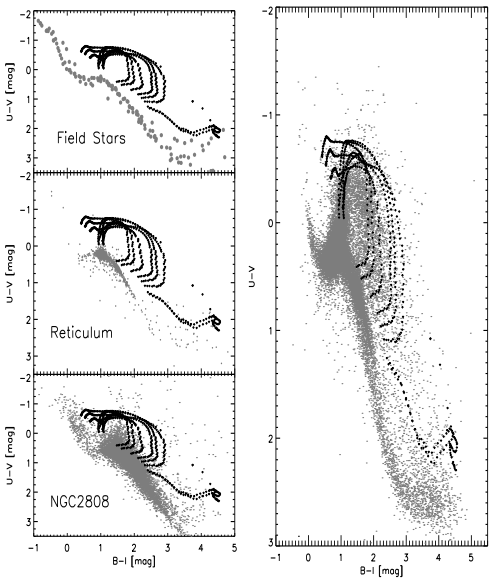

Fig. 2. Left - Color-color plane, U-V,B-I, showing the comparison between three stellar samples with metal abundance ranging from solar (top, [Fe/H]=0) down to [Fe/H]=-1.7 (bottom, NGC2808), and evolutionary sequences for galaxies with redshift ≤2. **Right** - Same as the right, but for the Carina central regions.

The limiting magnitude of U and I-band data is too shallow to firmly establish the nature of the objects around the TO luminosity of old MS stars ($V \sim 24.5$, $U \sim 25$). Unfortunately, this problem is even more severe for the field located at 1 degree from the Carina center (bad weather conditions). However, the circumstantial evidence that the

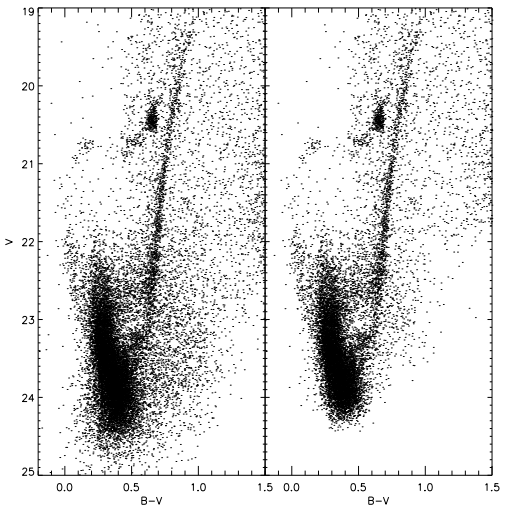

Fig. 3. The left and the right panel show the CMD of the Carina central regions before and after the cleaning from galaxy contamination. Approximately ≈ 6000 galaxy candidates have been selected from the color-color plane and subtracted. The left panel shows the objects (≈40000) which have been detected in all the four bands. The TO region of the old stellar component appears better defined in the right panel and the spread in color of MS stars is smaller.

blue objects we detected are located in a region of the color-color plane typical of MS stars indicates that they might be truly Carina stars.

3. Final remarks

The preliminary results presented in this investigation are part of a long-term photometric and spectroscopic project aimed at investigating the stellar content of the Carina dSphs (Monelli et al. 2005, in prep.). We have already collected photometric data over a large area around Carina and both low and intermediate-resolution spectra across the center. However, accurate estimates of a basic parameter such as the tidal radius still hinge on the robust multi-band identification of the Carina faint stellar components. In particular, it appears crucial to establish whether both old and intermediate-age, extra-tidal stars are present in Carina, and in turn whether they are distributed in an extended spherical halo or along tidal stream(s). These occurrences will supply robust empirical constraints on the physical assumptions currently adopted in numerical simulations of galaxy formation and evolution.

No doubt that a comprehensive photometric and spectroscopic investigation of the Carina stellar structure will be an important step forward in our knowledge of these elusive stellar systems and how they interact with the Galaxy.

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