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## THE EXTENSIVE AGE GRADIENT OF THE CARINA DWARF GALAXY

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### ABSTRACT

The evolution of small systems such as dwarf spheroidal galaxies (dSphs) is likely to have been a balance between external environmental effects and internal processes within their own relatively shallow potential wells. Assessing how strong such environmental interactions may have been is therefore an important element in understanding the baryonic evolution of dSphs and their derived dark matter distribution. Here we present results from a wide-area CTIO/MOSAIC II photometric survey of the Carina dSph, reaching down to about two magnitudes below the oldest main-sequence turnoff (MSTO). This data set enables us to trace the structure of Carina in detail out to very large distances from its center, and as a function of stellar age. We observe the presence of an extended structure made up primarily of ancient MSTO stars, at distances between 25' and 60' from Carina's center, confirming results in the literature that Carina extends well beyond its nominal tidal radius. The large number statistics of our survey reveals features such as isophote twists and tails that were undetected in other previous, shallower surveys. This is the first time that such unambiguous signs of tidal disruption have been found in a Milky Way "classical" dwarf other than Sagittarius. We also demonstrate the presence of a negative age gradient in Carina directly from its MSTOs, and trace it out to very large distances from the galaxy center. The signs of interaction with the Milky Way make it unclear whether the age gradient was already in place before Carina underwent tidal disruption.

*Key words:* galaxies: dwarf – galaxies: evolution – galaxies: individual (Carina) – galaxies: stellar content – galaxies: structure – Local Group

*Online-only material:* color figures

### 1. INTRODUCTION

The dwarf spheroidal galaxies (dSphs) surrounding the Milky Way (MW) are the galaxies studied in better detail than any other (see Tolstoy et al. 2009 for a recent review), yet many fundamental questions about their nature remain unanswered. Are they the most dark-matter-dominated galaxies we know of, as their large apparent dynamical mass-to-light ratios would suggest, or is tidal disruption a contributing factor? What drives the observed variety of star formation (SF) and chemical enrichment histories? Were dSphs born as we see them today or are they the descendants of larger and intrinsically different systems?

The evolution of small systems such as dwarf galaxies is likely to be particularly susceptible to the environment that they have experienced as well as being influenced by their own low potential well. However, the relative importance of both these factors has yet to be established.

Among the MW satellites, an example of a dSph whose evolution may have been strongly affected by the environment is given by Carina. This galaxy is the one "classical" dSph where most hints of tidal disruption have been found, such as the presence of probable members well beyond the nominal tidal radius, a rising velocity dispersion profile, and a velocity shear reminiscent of tidally disrupted dwarf galaxies (see Muñoz et al. 2006 and references therein). However, no report of such kinematical features is given in Koch et al. (2006) and Walker et al. (2009), so that the hypothesis of tidal disruption awaits confirmation.

Carina is a particularly interesting object among the Local Group dwarf galaxies also because it is the only clear example of a galaxy with well-separated SF episodes, visible as distinct

main-sequence turnoffs (MSTOs) in the color–magnitude diagram (CMD; e.g., Smecker-Hane et al. 1996; Monelli et al. 2003; Bono et al. 2010). The effects of its unique star formation history (SFH) can be traced in its chemical evolution as well (Koch et al. 2008; Venn et al. 2012; Lemasle et al. 2012). It is unclear at present whether the influence of the MW may have induced the main SF episodes (e.g., see simulations by Pasetto et al. 2011) as episodic SFHs can be qualitatively explained also by models of low-mass dSphs treated in isolation (e.g., Revaz et al. 2009).

Another feature that can provide information on the evolution of a small galaxy is the spatial distribution and kinematics of its stellar population mix. Negative age and metallicity gradients are found in several of the Local Group dSphs, both around the MW (Harbeck et al. 2001; Tolstoy et al. 2004; Battaglia et al. 2006, 2011; de Boer et al. 2012a, 2012b) and in isolation (e.g., Bernard et al. 2008); the latter finding suggests that internal effects are the main drivers in setting up the observed gradients. In Carina, indications of an age gradient have been found from the spatial distribution of red clump (RC) stars as compared to horizontal branch (HB) stars (Harbeck et al. 2001). Although this is similar to the behavior of other MW dSphs with multiple stellar components, for Carina there have been no findings of different kinematics among stars belonging to different age/metallicity ranges (e.g., Walker & Peñarrubia 2011), unlike that observed in Fornax, Sculptor, and Sextans (Tolstoy et al. 2004; Battaglia et al. 2006, 2011; Walker & Peñarrubia 2011). Interestingly, it has been shown that strong interaction with the MW is a viable mechanism for erasing differences in the kinematics of multiple stellar components (Sales et al. 2010).

Several of the observed properties of Carina could therefore be explained in a framework of strong interaction with the MW.

It is then particularly interesting to fully characterize the stellar population of this object and to put on a secure ground the possible existence of tidal features.

Here we present results from a deep, wide-area photometric survey of Carina, which yields major improvements with respect to previous studies of the morphology and spatial distribution of Carina’s stellar population mix.

## 2. OBSERVATIONS

Deep optical photometry covering the Carina dSph was obtained using the CTIO 4m MOSAIC II camera over six nights in 2007 December, as part of observing proposal 2007B-0232 (PI: M. Mateo). Observations in the  $B$  and  $V$  bands were obtained in eight pointings around the center of Carina, covering a total area of  $\approx 2$  deg<sup>2</sup>. The observing strategy was to obtain multiple long ( $\approx 600$  s) exposures for each pointing, which have been stacked together to obtain deep photometry. In addition, short (30 s) exposures were also obtained to sample bright stars that are saturated in the deep images. To ensure accurate photometric calibration of the data set, observations of Landolt standard fields (Landolt 1992) were made, covering a range of airmass and color.

The first stage image processing steps included standard bias and overscan correction, trimming to the reliable active detector area, and flat fielding by the creation of master flats from a dithered set of  $B$ -band and  $V$ -band twilight sky exposures. The flat-fielding step also corrects for internal gain variations between the detectors.

Prior to deep stacking of the individual exposures, detector-level catalogs were generated for each science image to refine the astrometric calibration and also to assess the data quality. For astrometric calibration, a Zenithal polynomial projection (Greisen & Calabretta 2002) was used to define the World Coordinate System. A third-order polynomial includes all the significant telescope radial field distortions leaving just a six-parameter linear model per detector to completely define the astrometric transformations. The Two Micron All Sky Survey point-source catalog (Skrutskie et al. 2006) was used for the astrometric reference system.

The common background regions in the overlap area from each image in the stack were used to compensate for sky variations during the exposure sequence and the final stack included seeing weighting, confidence (i.e., variance) map weighting, and clipping of cosmic rays.

Catalogs for each deep stacked image were then generated using standard aperture photometry techniques (e.g., Irwin et al. 2004) and cross-matching with published photometry of Carina (Stetson 2000) was used to directly photometrically calibrate the central fields. Outlying fields were calibrated with respect to the central region using the overlaps between adjacent pointings.

## 3. RESULTS

### 3.1. Age Gradient

While the exact age of Carina’s SF episodes varies among the various works in the literature, there is consensus about Carina experiencing at least three main SF episodes: an “ancient” one, around 11–13 Gyr ago; a main episode at intermediate ages (around 2.5–4 Gyr ago according to Bono et al. 2010, but  $\sim 7$  Gyr ago according to Hurley-Keller et al. 1998), after a long quiescent period; and a relatively recent episode,  $\gtrsim 1$  Gyr ago (e.g., Monelli et al. 2003). The way these “ancient,” “intermediate-age,” and “young” stellar components are spatially distributed

has not yet been studied in detail. Notably, notwithstanding its complex SFH, Carina has a very narrow red giant branch (RGB). This makes photometry of RGB stars unsuitable for exploring the existence of age gradients in this galaxy, even though such spatially extended data sets exist ( $\sim 10$  deg<sup>2</sup>; Muñoz et al. 2006). Indications for a negative age gradient in Carina were found by Harbeck et al. (2001) over a relatively small radial range ( $30'$ ), using photometry down to  $\sim 1$  mag below the HB. The shallow photometry allowed only the use of indirect age indicators for tracing the gradient, i.e., the RC for the young/intermediate-age stars and the HB for the ancient stars.

Figure 1 shows the CMD resulting from our photometric survey, split over a selection of elliptical radii  $R$ . This spatially extended photometric data set reaches down to  $\sim 2$  mag below the oldest MSTO, allowing us to trace possible age gradients *directly* from the presence or the absence of the MSTOs belonging to the various SF episodes *and* over a large area.

In the innermost region ( $R < 10'$ ), all the main features of the Carina stellar population are present: the thin RGB, the RC, the red and blue HB, the ancient MSTO and subgiant branch (SGB), the intermediate-age MSTO and SGB, and younger MS stars at  $B - V \sim 0$  and  $21 \lesssim V \lesssim 23$  (for a detailed discussion on the various features of the CMD, see, e.g., Hurley-Keller et al. 1998). At larger radii ( $10' < R < 25'$ ), the young stars are barely visible, while the features containing intermediate-age and ancient stars are still well populated. In the outer parts ( $R > 25'$ ), the MSTO of the intermediate-age population disappears, while the ancient stars are still visible, as witnessed by the presence of the old MSTO and SGB.

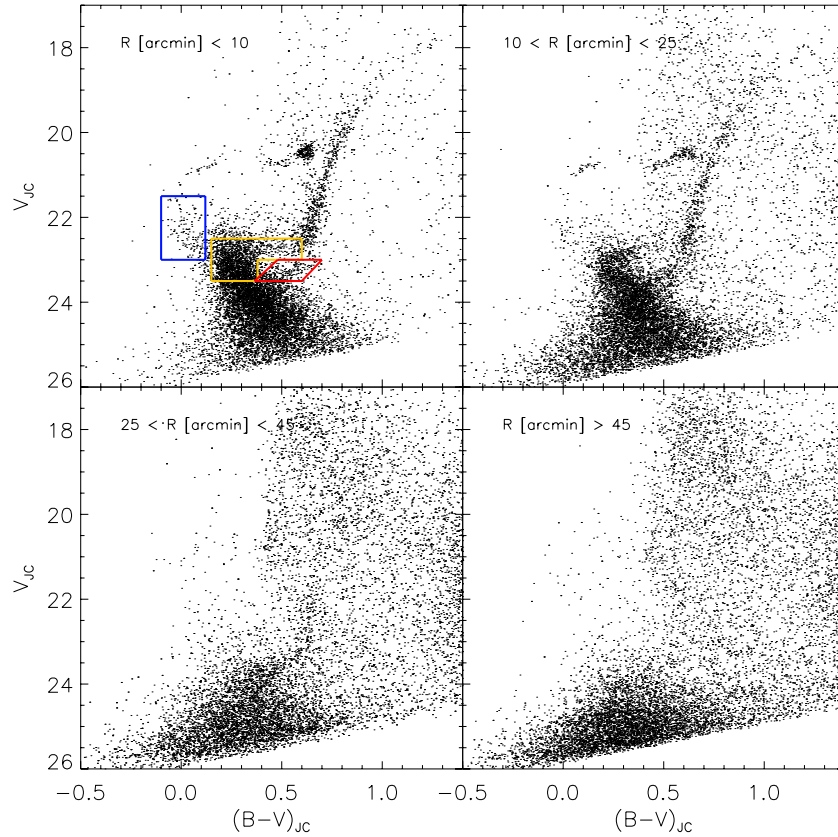
The above direct detection of an age gradient in Carina, as traced from MSTO stars, confirms the early findings of Harbeck et al. (2001) and extends them over a much larger radial range.

We note that the presence of a sizeable population of ancient MSTO stars in the last two panels of Figure 1 ( $R > 25'$ ) shows that Carina extends well beyond its nominal King tidal radius ( $r_t = 28.8$ ; Irwin & Hatzidimitriou 1995, hereafter IH95). This confirms the conclusions by Muñoz et al. (2006) based on the spatial distribution and kinematics of a sample of RGB stars.

Both the presence of the age gradient and the large extent of Carina are also illustrated in Figure 2, where we compare the luminosity function (LF) in bins of  $R$  of stars in the region of the MS, MSTO, and SGB to a control field. Owing to the large extent of Carina, it is difficult to accurately identify a region containing only contaminants (i.e., MW stars and unresolved galaxies) to use as a control field. We chose to use a sub-region of the outermost pointing on the northeast (see Figure 3) because it has the lowest density of objects among the various pointings; the significantly different shape of the control field LF from the two outer elliptical zones confirms that it mostly contains contaminants and demonstrates the presence of appreciable numbers of Carina members out to  $1^\circ$  radius. Furthermore, the similarity of the LFs of the two outer zones and the absence of obvious intermediate-age and young stars beyond  $\sim 25'$  strongly suggest this extended structure is made up primarily of ancient stars.

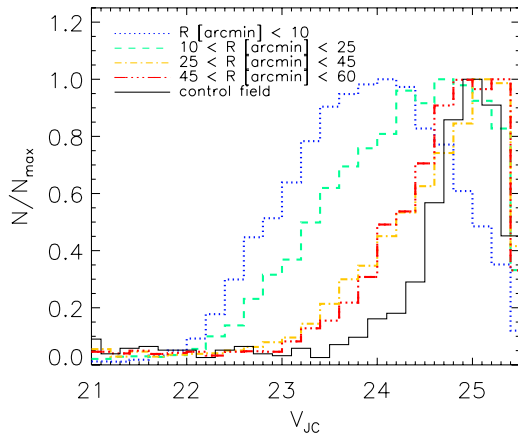
### 3.2. Extended Spatial Structure

Figure 3(a) illustrates the spatial distribution of the overall Carina stellar population after applying magnitude cuts of  $B < 25.1$ ,  $V < 25.5$ —corresponding to  $\sim 50\%$  completeness levels—to counter the variable depth of the pointings due to differences in total exposure time. To minimize the presence of contaminants, we isolate the main features of Carina’s overall



**Figure 1.** Color–magnitude diagram of stellar objects along the line of sight to the Carina dSph, over different ranges of projected elliptical radius (see labels). The elliptical annuli have P.A. and  $e$  values from IH95. All the panels contain the same number of stars (15,000) to enable a comparison of the relative strength of the features in the CMD. The boxes in the top-left panel show the cuts in magnitude and color applied to select young (blue), intermediate-age (yellow), and old (red) stars for Figure 3.

(A color version of this figure is available in the online journal.)



**Figure 2.** Luminosity function of Carina’s stars, normalized to the peak value and plotted in bins of elliptical radii (see legend). The stars are selected to have  $21 < V < 25.5$  and  $B - V < 0.6$ . The control field corresponds to the region with rectangular coordinates  $60' < \xi < 80'$  and  $20' < \eta < 40'$  (see Figure 3).

(A color version of this figure is available in the online journal.)

stellar population on the CMD by selection in magnitude and color. Figures 3(b)–(d) show how the spatial distribution varies with age.

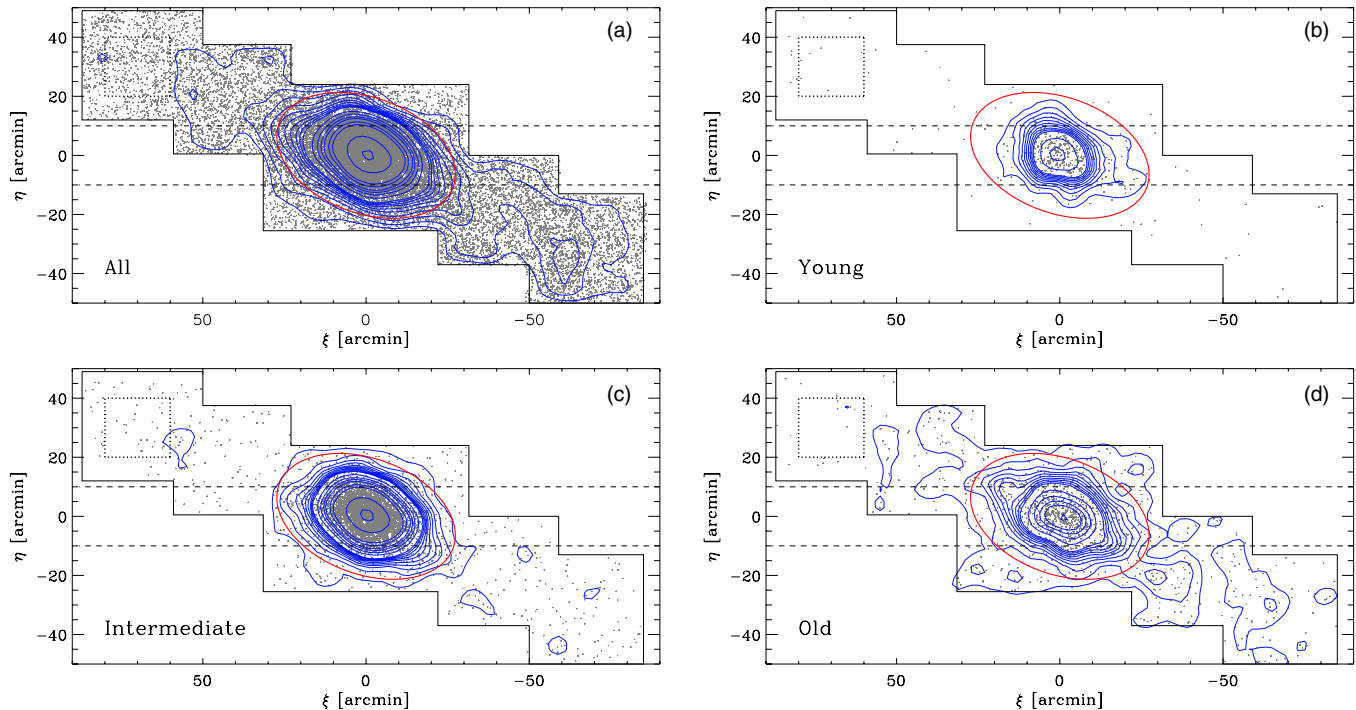
The isodensity contours in each panel were derived from maps of stellar counts (Hess diagrams) on a  $2' \times 2'$  pixel grid, from which we subtracted the density of contaminants,  $\Sigma_{\text{cont}}$ . This was calculated as the median of the pixel values in the

control field (shown in Figure 3 and discussed in Section 3.1). The isodensity contours are then plotted in units of noise ( $\sigma$ ), which we determine as the rms of the pixel values in the contaminant-subtracted control field. Should the derived  $\Sigma_{\text{cont}}$  be overestimated because of a leakage of Carina’s stars, the main effect will cause Carina to appear smaller than it is and to underestimate the significance of the contours; hence the extent of Carina found here should be considered as a “lower limit” and the significance of the outer contours as conservative.

Figure 3(a) shows that the main body of Carina appears of regular morphology, although with slightly boxy isodensity contours, out to  $R \sim 18\text{--}20' \sim 0.6\text{--}0.7 r_t$ . Beyond this radius, the contours become elongated and distorted, with very extended tails emerging from both sides of the main body and a well-defined overdensity of stars at  $(\xi, \eta) \sim (-60', -30')$ . The much larger number statistics of this study with respect to studies in the literature makes it possible to observe isophote elongation and twists; these had not been detected in previous, shallower photometric surveys of Carina, even though optimized to minimize the contamination from MW stars (e.g., Muñoz et al. 2006).

Fitting of ellipses as a function of  $R$  to the map of stellar counts confirms the change in shape and orientation of the contours, yielding a position angle (P.A.) and ellipticity  $e$  that are constant around a P.A. =  $53^\circ.5 \pm 1^\circ.0$  and  $e = 0.29 \pm 0.01$  at  $R < 18'$ , and then increase, yielding a P.A. =  $62^\circ.5 \pm 0^\circ.5$  and  $e = 0.35 \pm 0.02$  at  $R > 18'$ ; the latter values tend to the literature values of P.A. =  $65^\circ \pm 5^\circ$  and  $e = 0.33 \pm 0.05$  (Irwin & Hatzidimitriou 1995).





**Figure 3.** Spatial distribution of stars in Carina for the overall stellar population, young stars, intermediate-age population, and old stars (see labels and Figure 1). The overlaid isodensity contours were derived from the contaminant-density-subtracted Hess diagram obtained on a  $2' \times 2'$  pixel grid and show levels of  $1\sigma, 2\sigma, 3\sigma, 4\sigma, 5\sigma, 6\sigma, 7\sigma, 8\sigma, 9\sigma, 10\sigma, 15\sigma, 20\sigma, \dots$  (where  $\sigma$  is the noise, see the text for details). The values of  $\sigma$  are 2, 0.51, 0.24, and 0.24 stars pixel $^{-1}$  for panels (a)–(d), respectively, while the values of the subtracted  $\Sigma_{\text{cont}}$  are 3.08, 0.007, 0.01, and 0.01 stars pixel $^{-1}$ ; the region used for determining  $\sigma$  and  $\Sigma_{\text{cont}}$  is enclosed by the dotted lines. The ellipse indicates the nominal tidal radius (parameters from IH95; center coordinates from Mateo 1998). The horizontal dashed lines are meant to guide the eye when comparing the direction of the isophote elongation for the various populations.

(A color version of this figure is available in the online journal.)

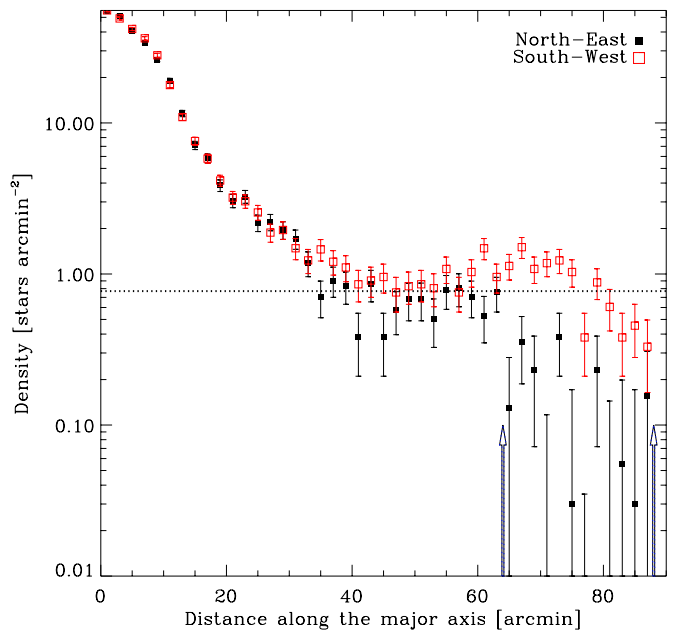
We also note the presence of a break in the surface number count profile of Carina’s stars lying along the projected major axis of the system (Figure 4). The break occurs in both N–E and S–W halves of the galaxy at around  $20'$  from the center, where the isodensity contours start becoming elongated, and at a similar radial distance to that found by, e.g., Majewski et al. (2000), Walcher et al. (2003), and Muñoz et al. (2006) in shallower samples.

The youngest Carina stars do not extend as far out as the intermediate-age and ancient ones, but signs of isophote elongation are arguably also visible in the spatial distribution of these stars (Figure 3(b)). This would set the last pericentric passage less than 1–2 Gyr ago. The intermediate-age and ancient population both show distorted outer isophotes (Figures 3(c) and (d)). Notably, as visible in the figure and confirmed by ellipse fitting of the Hess diagrams, the shape parameters of the contours are subtly different for these two stellar populations of different ages and this may have an impact on models trying to reconstruct the orbital history of Carina.

#### 4. DISCUSSION AND CONCLUSIONS

We have used CTIO/MOSAIC II photometry to study the morphology and spatial distribution of Carina’s stellar population mix.

The combination of wide area and photometric depth, reaching down to  $\sim 2$  mag below the oldest MSTO, allows for a direct detection of an extensive age gradient in Carina, traced from the presence/absence of the MSTOs belonging to the various SF episodes.



**Figure 4.** Surface number count profile of Carina, derived from the stars in Figure 3(a) that lie on a  $20'$  wide slice running along a P.A. =  $65^\circ$ . Filled and open squares refer to the northeast and southwest part of the galaxy, respectively. The contaminant density subtracted from the profile is indicated by the dotted line; the arrows show the radial range occupied by the region for calculating  $\Sigma_{\text{cont}}$ . We note the change of slope at  $R \sim 20'$  present in both halves of the galaxy, and the overdensity at  $R \sim 70'$  in the S–W half, corresponding to the overdensity visible in Figure 3(a) at  $(\xi, \eta) \sim (-60', -30')$ .

(A color version of this figure is available in the online journal.)

We find a clear presence of ancient MSTO stars at  $R > 25'$ , which demonstrates that Carina extends well beyond its literature nominal tidal radius, confirming results from previous works. The increased number statistics from this study reveals the existence of faint features such as isophote elongation and twists, which could not be detected in previous shallower photometric surveys. Such features are even visible when separating the stars in age. We confirm the presence of a clear break in the surface brightness profile at radii  $>20'$  and observe an overdensity of stars in the S–W half of Carina, at  $\sim 70'$  from the center.

Features such as breaks in the surface brightness profile, together with variations in the elongation and direction of the isophotes, have been detected in other objects that are good candidates for ongoing tidal disruption such as NGC 205 and M32 (Choi et al. 2002), and are predicted by  $N$ -body simulations of tidally disrupted dwarf galaxies (e.g., Choi et al. 2002; Muñoz et al. 2008; Peñarrubia et al. 2009). These morphological traits strongly suggest that Carina is being tidally disrupted.

At a distance of  $\sim 100$  kpc, the low Galactocentric line-of-sight velocity of Carina ( $\sim 7$  km s $^{-1}$ ) places it either close to apocenter or pericenter. Given the signs of tidal disturbance and the current best estimate of the proper motion (Piatek et al. 2003), Carina is most likely close to the apocenter with an orbital period of between 1 and 2 Gyr and hence the last pericentric passage likely occurred  $<1$  Gyr ago. The presence of signs of tidal disruption at the apocenter is consistent with the timescales from the simulations of Peñarrubia et al. (2009), where tidal tails can remain clearly visible at projected radii larger than the break radius until up to  $\sim 15$  dynamical crossing times, i.e., between 1 and 2 Gyr in this case.

The existence of signs of tidal disruption complicates the interpretation of the observed age gradient, as it is not obvious whether it was (in part) already in place before Carina was tidally disturbed. Related questions are whether Carina showed distinct kinematic signatures for the different populations prior to tidal interactions and how these may have been affected by close pericentric passages.

This also impacts on the derived dark matter content and distribution. Treated as an isolated equilibrium system, Carina has a large dynamical mass-to-light ratio (e.g.,  $M/L_V \sim 100(M/L)_{V,\odot}$ ; Walker et al. 2007), as do most other “classical” dSphs. An attempt to model Carina as a tidally perturbed system was made by Muñoz et al. (2008), who found that the surface brightness and internal kinematic properties of Carina are compatible with a mass-follows-light model still containing large amounts of dark matter ( $M/L \sim 40$ ). The two-dimensional distribution resulting from such model is remarkably regular, in contrast with what is observed here over the same spatial region. However, it should be considered that the best model of Muñoz et al. (2006) was aiming at reproducing the spatial distribution from the data available at the time, too shallow to reveal the signs of tidal distortion seen in our survey.

Knowledge of the distorted structure of the galaxy from this deep survey, combined with the extensive spectroscopic data sets present in the literature (e.g., Koch et al. 2006; Muñoz et al. 2006; Walker et al. 2009), should provide important constraints for assessing the impact of tidal disruption on the derived mass-to-light ratio—and dark matter content.

Tidal disruption of dwarf galaxies has been detected in some M31 satellites (e.g., Choi et al. 2002; Geha et al. 2006; McConnachie & Irwin 2006). However, around the MW, apart

from the clear case of Sagittarius, the quest has proven difficult due to the combination of the large extent on the sky of MW dSphs and their low surface brightness. The question therefore remains if tidal disruption is common among the MW dSphs and ultra-faint dwarfs, or whether Carina belongs to a “minority” of tidally disrupted objects such as the Sagittarius dwarf (Ibata et al. 1994). Hints of tidal disruption have been found in some of these other systems, e.g., Ursa Minor (e.g., Martínez-Delgado et al. 2001; Palma et al. 2003), Leo I (Mateo et al. 2008), and Ursa Major II (Muñoz et al. 2010). In contrast, Draco, the only other dSph surveyed with photometric data as deep and wide area as those used here, shows a “flawless,” regular morphology (Ségall et al. 2007) and an enormous  $M/L \sim 300$  (Kleyna et al. 2002).

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*Facility:* Blanco (Mosaic II)

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