On the Stellar Content of the Carina Dwarf Spheroidal Galaxy

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ABSTRACT. We present deep, accurate, and homogeneous multiband optical (U, B, V, I) photometry of the Carina dwarf spheroidal galaxy, based on more than 4000 individual CCD images from three different ground-based telescopes. Special attention was given to the photometric calibration, and the precision for the B, V, and I bands is generally better than 0.01 mag. We have performed detailed comparisons in the V, B − V, and V − I color–magnitude diagrams (CMDs) between Carina and three old, metal-poor Galactic globular clusters (GGCs, M53, M55, M79). We find that only the more metal-poor GCs (M55, [Fe/H] = −1.85; M53, [Fe/H] = −2.02 dex) provide a good match with the Carina giant branch. We have performed a similar comparison in the V, V − I CMD with three intermediate-age clusters (IACs) of the Small Magellanic Cloud (Kron 3, NGC 339, Lindsay 38). We find that the color extent of the subgiant branch (SGB) of the two more metal-rich IACs (Kron 3, [Fe/H] = −1.08; NGC 339, [Fe/H] = −1.36 dex) is smaller than the range among Carina’s intermediate-age stars. Moreover, the slope of the RGB of these two IACs is shallower than the slope of the Carina RGB. However, the ridge line of the more metal-poor IAC (Lindsay 38, [Fe/H] = −1.59 dex) agrees quite well with the Carina intermediate-age stars. These findings indicate that Carina’s old stellar population is metal-poor and appears to have a limited spread in metallicity (Δ[Fe/H] = 0.2–0.3 dex). The Carina’s intermediate-age stellar population can hardly be more metal-rich than Lindsay 38, and its spread in metallicity also appears modest. We also find that the synthetic CMD constructed assuming a metallicity spread of 0.5 dex for the intermediate-age stellar component predicts evolutionary features not supported by observations. In particular, red clump stars should attain colors that are redder than red giant stars, but this is not seen. These results are at odds with recent spectroscopic investigations suggesting that Carina stars cover a broad range in metallicity (Δ[Fe/H] ~ 1–2 dex). We also present a new method to estimate the metallicity of complex stellar systems using the difference in color between the red clump and the middle of the RR Lyrae instability strip. The observed colors of Carina’s evolved stars indicate a metallicity of [Fe/H] = −1.70 ± 0.19 dex, which agrees quite well with spectroscopic measurements.

Online material: color figures

1. INTRODUCTION

Dwarf galaxies play a fundamental role in several astrophysical problems. Current cosmological simulations predict dwarf satellite populations significantly larger than the number of dwarfs observed near giant spirals like the Milky Way and M31. This discrepancy is called the “missing satellite problem” and is a challenge to the currently most popular cosmological

1 Based on images collected with the MOSAIC II camera available at the CTIO 4 m Blanco telescope, La Serena; (2003B-0051, 2004B-0227, 2005B-0092, PI: A. R. Walker), and in part with the WFI available at the 2.2 m MPG/ESO telescope (A064.L-0327), and images obtained from the ESO/ST-ECF Science Archive Facility.

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model: the Λ Cold Dark Matter paradigm (Klypin et al. 1999; Moore et al. 2006; Madau et al. 2008). However, it has not yet been established whether this discrepancy is due to limitations in the theoretical modeling or to observational bias at the faint end of the dwarf galaxy luminosity function (Kilimanowsk et al. 2009; Koposov et al. 2009; Kravtsov 2010).

Moreover, detailed analyses of the distribution of dwarf galaxies in multidimensional parameter space indicate that they follow very tight relations. In particular, Prada & Burkert (2002) suggested that Local Group (LG) dwarf galaxies show strong correlations (fundamental line—FL) among mass-to-light (M/L) ratio, surface brightness, and metallicity. They explained the correlation between M/L ratio and metallicity using a simple chemical enrichment model in which the hot metal-enriched gas, at the end of the star-formation epoch, is lost via continuous galactic winds (Mac Low & Ferrara 1999). In a recent investigation, Woo & Chiuhe (2009) reached a similar conclusion, i.e., that LG dwarf galaxies follow a one-parameter relation driven by the total stellar mass. They also found that dwarf spheroidals (dSphs) appear to be, at fixed stellar mass, systematically more metal-rich than dwarf irregulars (dIs, see also Mateo (1998)). Furthermore, the FL of dIs in a five-dimensional parameter (total mass space, surface brightness, rotation velocity, metallicity, star-formation rate) is linear and tight, and extends the scaling relations of giant late-type galaxies into the low-mass regime. On the other hand, the FL of dSphs as defined in a four-dimensional parameter space (total mass, surface brightness, rotation velocity, metallicity) is also linear and very tight, but it does not lie on an extrapolation of the scaling relations of giant early-type galaxies. Iron and heavy-element abundances, the spread in these quantities, and the star-formation history (SFH) of LG dwarf galaxies, are crucial observational constraints on the physical mechanisms responsible for the scaling relations described above, and on their implications for different cosmological models (Orban et al. 2008). Spectroscopic investigations based on high-resolution spectra of bright red giants (RGs) in several LG dSphs indicate a large spread in iron abundance (Shetrone et al. 2001, 2003). This is also supported by metallicity estimates from the Ca II triplet method (Battaglia et al. 2008).

In this context, the Carina dSph is particularly relevant: (i) It is relatively close and its central density is modest (ρ = 0.17 M⊙ pc⁻³, Mateo 1998) so it is easily resolved with ground-based telescopes (Mould & Aaronson 1983). (ii) It is the LG dSph most clearly showing multiple, widely separated star-formation episodes (Mighell 1990, 1997; Smecker-Hane et al. 1994, 1996; Hurley-Keller et al. 1998; Hernandez et al. 2000; Harbeck et al. 2001; Dolphin 2002; Rizzi et al. 2003), with a tail that might extend to less than one Gyr ago (Monelli et al. 2003). (iii) It is also a benchmark to constrain the pulsation properties of old (RR Lyrae, Saha et al. 1986) and intermediate-age (dwarf Cepheids, Mateo et al. 1998; anomalous Cepheids, Dall’Ora et al. 2003) variable stars. (iv) High-resolution spectra are available for a sample of 10 bright RGs. The mean metallicity is [Fe/H] = −1.69 with σ = 0.51 dex (Koch et al. 2008). Independent measurements by Shetrone et al. (2003), using high-resolution spectra for five bright RGs, provided a mean metallicity of [Fe/H] = −1.64 and σ = 0.2 dex. (iv) Medium-resolution calcium triplet measurements are also available for a large sample (437) of RG stars (Koch et al. 2006); their metallicity distribution shows a peak at [Fe/H] = −1.72 ± 0.01 (metallicity scale by Carretta & Gratton 1997, hereafter CG97) and the metallicity ranges from ~ −2.5 to ~ −0.5 dex. Using the same spectra, but different selection criteria (364 candidate Carina stars, Helmi et al. 2006) found the same peak in the metallicity distribution ([Fe/H] = −1.7 ± 0.1 dex) and metallicities ranging from ~ −2.3 to ~ −1.3 dex (see their Fig. 2).

Deep, accurate photometric investigations indicate an old (13 Gyr) stellar population and several distinct intermediate-age populations (2–6 Gyr) together with a blue plume of younger stars. The occurrence of both old and intermediate-age populations is also indicated by two distinct samples of core helium-burning stars: an old, wide HB and a separate red clump (RC). The shape and thickness of the RGB (ΔB − V ≈ 0.02 for 20.5 ≲ V ≲ 20.75 mag) suggest that the old and intermediate-age stellar populations have a minimal spread in chemical composition. This seems inconsistent with the spectroscopic observations that indicate a metallicity distribution possibly reaching extreme values near −3.1 and +0.1 dex (scale Zinn & West 1984, hereafter ZW84), or near −2.8 and −0.2 dex (scale CG97).

Despite the criticisms raised by Koch et al. (2006), conclusions based on purely photometric indicators are hampered by only two major factors: (i) A decrease in photometric precision when moving from bright to faint RG stars might produce a spread in color mimicking a spread in metal content. In particular, Carina’s stellar density is very low, requiring that photometry be obtained with multichip CCD cameras or with many different pointings of a single CCD. A high degree of consistency in the photometric zero-points across the field is essential to avoid spurious broadening of the RG and main-sequence (MS) loci. (ii) Due to its low surface density, large extent, and low Galactic latitude (−22°), the Carina sample is contaminated by foreground field stars. Their colors, unfortunately, are similar to the Carina RGB, once again mimicking a broadening in color due to a spread in age/metallicity.

Our group is involved in a long-term investigation of the stellar populations in the Carina dSph. In particular, we have assembled our own and archival UBVI images covering the entire body of the galaxy. In this investigation we focus on comparing Carina with old and intermediate-age template clusters. We also present a new method for estimating the metal content of complex stellar systems from the difference in color between the middle of the RR Lyrae instability strip and the peak of RC stars.
2. OBSERVATIONS AND DATA REDUCTION

The data were collected in various observing runs between 1992 December and 2005 January. They include images from three telescopes: the CTIO 1.5 m telescope with a single Tektronix2K CCD, the CTIO 4 m Blanco telescope with the Mosaic II camera, and the ESO/MPG 2.2 m telescope with the Wide Field Imager camera (both proprietary and archival data). Details of the observations will be presented in a future paper. The data presented here represent 4152 individual CCD

Fig. 1.—Top, $U - V$, $B - I$ C-CD of Carina dSph. The curved box encloses candidate Carina stars (gray dots). The black dots represent probable field objects. Predicted distributions (Fioc & Rocca-Volmerange 2008) of elliptical (asterisks), spiral (pluses), SB (triangles), irregular and star burst (squares) galaxies as a function of the redshift are also showed. The vertical arrows mark the predicted (Castellani et al. 2002) peaks in $B - V$ color for the halo, the thick disk, and the thin disk. The black arrow shows the reddening vector. Bottom left, $V$, $B - V$ CMD of Carina dSph. Bottom middle, $V$, $B - V$ CMD of candidate field stars according to the C-CD selection. The error bars on the right represent the intrinsic photometric error in magnitude and in color. Rejection of thick-disk turnoff stars is obviously imperfect near $B - I \sim 0.5$, where the C-CD loses discriminating power. Bottom right, $V$, $B - V$ CMD of candidate Carina stars according to the C-CD selection. A hint of the Carina HB near $V \approx 20.75$ and of the SGB at $22.5 \lesssim V \lesssim 23.75$ confirm that discrimination is imperfect at these intermediate colors. The block of dots with $B - I < 0.5$, $V > 23.5$ is probably dominated by background galaxies rather than Carina turnoff stars. See the electronic edition of the PASP for a color version of this figure.
images with essentially complete coverage of the central regions of Carina ($\approx 40' \times 55'$, lacking only those regions obliterated by bright foreground stars), and some sampling of the galaxy’s halo out to an extreme radius of $\approx 108'$. They were obtained in four photometric bands ($B$ and $I$ with the 1.5 m telescope, and $UBVI$ with both the 4 m and 2.2 m telescopes).

The data were reduced using the DAOPHOT/ALLFRAME package (Stetson 1987, 1994). Individual point-spread functions (PSFs) were produced for each chip of every exposure, using semiautomated routines to select bright, isolated PSF stars. Subsets of the data from each observing run were first reduced separately. Finally, everything was merged together and a single run of ALLFRAME was adopted to reduce all the images of the center of Carina, with separate reductions for nonoverlapping outlying fields. Because of the multiple chips and pointings required to cover the galaxy, no star appears in every image; any given star may have up to 17 calibrated measurements in $U$, $156$ in $B$, $207$ in $V$, and $70$ in $I$. A total of 205,338 individual stars were catalogued and measured. Among these, 72,595 have photometric measurements in all four filters, and $129,230$ have at least $U$ and $V - I$. The remainder, either extremely faint or located near the periphery of our coverage, have astrometry and instrumental magnitudes only.

The Carina data were contained within $206$ individual data sets, where a data set is essentially the totality of data obtained with one C-CD from one night of observing. These, along with $1331$ data sets from other nights and other telescopes, were calibrated to the current version of Stetson’s (2000) photometric standard system, which is believed to be equivalent to that of Landolt (1992) to well under 0.01 mag in each of $B$, $V$, and $I$ (see also Stetson 2005). The $U$ photometric bandpass is more problematic, and in this article we will employ the $U$-band data only for qualitative and relative comparisons.

### 3. RESULTS AND DISCUSSIONS

For a robust discrimination of candidate Carina members from foreground field stars and background galaxies we adopted the $U - V$, $B - I$ color-color diagram (C-CD). The top panel of Figure 1 shows that this is effective for distinguishing candidate Carina and field stars. Carina RGs ($U - V \geq 0.6$, $B - I \geq 1.4$) attain, at fixed $B - I$, bluer $U - V$ colors than field stars. The difference is mainly caused by a difference in the mean metallicity between Carina and the more metal-rich Galactic disk stars, but the difference in surface gravity between galaxy giants and foreground dwarfs may also play a role. In contrast, hot horizontal-branch (HB) stars and relatively young MS stars in Carina ($B - I \lesssim 0.4$) are relatively free from field star contamination, since they are bluer than the thick disk and halo turnoffs; compact background galaxies represent the principal source of contamination among these bluer objects. Fortunately, this C-CD is also a good diagnostic to separate candidate Carina stars from blue background galaxies since the latter show, at fixed $B - I$, systematically bluer $U - V$ colors than stars of any luminosity class or metallicity (apart from white dwarfs, which are not an issue here).

Based on the above empirical evidence, we performed a series of tests to identify candidate Carina stars using various CMDs together with the C-CD. The solid-outlined box in the top panel of Figure 1 shows the final selection, while the bottom panels show the $V, B - V$ CMD of the total sample (left), the candidate Carina stars (middle), and the candidate nonmember objects (right). Note that after the selection there remain some field stars with colors similar to Carina’s RGB ($V \leq 21.5$, $B - V \sim 0.4 - 0.6$; middle panel). However, RG stars are distributed along a very narrow sequence over the entire magnitude range ($18 \leq V \leq 23$), and the number of field stars lying near that RGB in both color and magnitude is appreciably reduced. The same statement applies to the intermediate-age red clump

| TABLE 1 |
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| **INTRINSIC PARAMETERS OF OLD AND INTERMEDIATE-AGE CALIBRATING CLUSTERS** |

| Name         | $[\text{Fe/H}]^a$ | $[\text{Fe/H}]^b$ | $\mu$ | $E(B-V)$ |
|--------------|------------------|------------------|-------|--------|
| NGC 1904-M79 | $-1.64 \pm 0.10^c$ | $-1.58 \pm 0.02$ | $15.61 \pm 0.10^d$ | $0.01 \pm 0.02^d$ | $12.6 \pm 1.3^d$ |
| NGC 6809-M55 | $-1.85 \pm 0.10^c$ | $-1.93 \pm 0.02$ | $13.69 \pm 0.10^d$ | $0.09 \pm 0.02^d$ | $12.4 \pm 1.7^d$ |
| NGC 5024-M53 | $-2.02 \pm 0.15^c$ | $-2.06 \pm 0.09$ | $16.24 \pm 0.10^d$ | $0.01 \pm 0.02^d$ | $11.2 \pm 1.8^d$ |
| Kron 3        | $-1.08 \pm 0.12^c$ | $-0.97 \pm 0.14$ | $18.83^f$ | $0.006^f$ | $6.3^f$ |
| NGC 339       | $-1.36 \pm 0.16^c$ | $-1.25 \pm 0.18$ | $18.75^f$ | $0.04^f$ | $6.0^f$ |
| Lindsay 38    | $-1.59 \pm 0.10^c$ | $-1.52 \pm 0.12$ | $19.00^f$ | $0.04^f$ | $6.5^f$ |

$^a$ Iron abundance by Kraft & Ivans 2004.
$^b$ Iron abundance in the Z88 metallicity scale by Da Costa & Hatzidimitriou 1998 (Kron 3, NGC 339) and Kayser et al. 2007 (Lindsay 38).
$^c$ Iron abundance by C09.
$^d$ Distance modulus and reddening by Ferraro et al. 1999 (M79), Vargas et al. 2007 (M55) and Dékány & Kovács 2009 (M53). The uncertainty on distance and reddening are 5% and 20%.
$^e$ Distance modulus, reddening, and age by Glatt et al. 2009 using cluster isochrones by Dotter et al. 2007.
$^f$ Cluster ages: Salaris & Weiss 2002 (M79, M55), Sarajedini 2009 (M53).
These evolutionary phases are characterized by very narrow distributions in either magnitude or color or both. The improvement compared to data already available in the literature is due to smaller photometric uncertainties ($\sigma_{B-V} \leq 0.02$ for $V \leq 21$, see error bars in Fig. 1). Plain evolutionary arguments (Monelli et al. 2003; Zoccali et al. 2003) suggest that small dispersions in magnitude and color in these evolutionary phases imply a negligible spread in chemical composition. This finding supports the results based on $B, V, I$ photometry of Carina RG stars obtained by Rizzi et al. (2003). The presence of a few stars in the right panel with magnitudes and colors typical of red HB ($V \sim 20.75$, $B - V \sim 0.4$) and faint SGB stars ($V \sim 23$, $B - V \sim 0.5$) demonstrates that our C-CD selection is imperfect—especially at intermediate colors—and some real Carina members have probably been erroneously rejected. However, in these photometric selections it is more important to keep probable nonmembers out than to keep possible members in (Calamida et al. 2009).

To provide robust constraints on Carina’s stellar content, we compared it with stellar systems characterized by different ages and metal abundances. In particular, to constrain the old stellar population we selected three globular clusters (GCs) — M79 = NGC 1904, M55 = NGC 6809, and M53 = NGC 5024—with metal abundances ranging from $-1.64 \pm 0.15$ to $-2.02 \pm 0.15$, and low foreground reddenings ($E(B - V) \leq 0.09$, see Table 1). The optical $BVI$ photometry of these GCs is also on the Stetson (2005) system. The accuracy of the photometry is certainly better than our knowledge of the foreground reddening toward these clusters and Carina. The $V, B - V$ (left panels) and $V, B - I$ (middle panels) CMDs of the selected GCs are shown in Figure 2, together with their individual ridge points.
lines (red curves). We also selected three intermediate-age clusters (IACs) belonging to the Small Magellanic Cloud (SMC)—Kron 3, NGC 339, Lindsay 38—with similar ages and iron contents ranging from $-1.08 \pm 0.12$ to $-1.59 \pm 0.10$ dex (see Table 1 in Glatt et al. 2009). The photometry for these clusters is from Advanced Camera for Surveys on Hubble Space Telescope data transformed into the $V, I$ Johnson-Cousins bands using relations by Siranni et al. (2005). These clusters are not included in the homogenous photometry project (the original sources of the data are listed in Table 1), so we are unable to independently confirm the precision of the photometry or the accuracy of the calibrations. Data plotted in the right panels of Figure 2 display the $V, V - I$ CMDs for these clusters together with their ridge lines and the outlines of their RCs.

To compare the GCs with the old stellar populations in Carina, we arbitrarily shifted their ridge lines in magnitude and color to provide a good fit with the SGB ($23.25 \leq V \leq 23.75$, $0.45 \leq B - V \leq 0.60$) in Carina. Then we inferred the difference in distance and in reddening between Carina ($\mu = 20.15$, $E(B - V) = 0.03$; Dall’Ora et al. 2003; Pietrzynski et al. 2009) and the individual GCs. The distances and the cluster redenings we found following this approach agree, within the errors, with similar estimates available in the literature (see columns [4] and [5] in Table 1). The top and the middle left panels of Figure 3 show that the GCs M79 and M55 provide a poor match to Carina, since hot HB stars are systematically brighter than Carina HB stars. On the other hand, both the GB and the HB of the more metal-poor GC (M53) match Carina.

Fig. 3.—Left column, comparison in the $V, B - V$ CMD between candidate Carina stars (black dots) and the three old calibrating GCs, namely M79 (top), M55 (middle) and M53 (bottom). The distance modulus and the reddening adopted to overlap the SGB of old GCs with the SGB of Carina are labeled. Middle column, same as the left, but in the $V, B - I$ CMD. Right column, comparison in the $V, V - I$ CMD between Carina stars and the three intermediate-age SMC calibrating clusters, namely Kron 3 (top), NGC 339 (middle) and Lindsay 38 (bottom). The distance modulus and the reddening adopted to overlap the SGB of intermediate age SMC clusters with the SGB of Carina are labeled. See the electronic edition of the PASP for a color version of this figure.
These comparisons indicate that Carina’s old population is relatively metal-poor, and its spread in metallicity is modest: at most 0.2–0.3 dex. Carina’s intermediate-age population seems to have the same metallicity as Lindsay 38, or perhaps slightly lower. The spread in metal abundance in this stellar component also seems very limited, since the RGBs of the two more metal-rich IACs are considerably redder than the red envelope of Carina’s RGB. The lack of accurate photometry for metal-poor ([Fe/H] < −1.6 dex) IACs with well-populated RGBs prevents us from providing more firm constraints on Carina’s intermediate-age population. These findings do not depend on the adopted metallicity scale, and if we adopt instead iron abundances on the Carretta et al. (2009, hereafter C09) metallicity scale (see column [3] in Table 1), the metallicity range inferred for Carina is very similar.

For a new estimate of the metal abundance of Carina, we decided to use a new indicator. Evolutionary prescriptions for old and intermediate-age stellar structures indicate that the difference in color between the center of the RR Lyrae instability strip and the RC stars is strongly correlated with iron abundance. The correlation is caused by the mild dependence of the color of the instability strip on iron abundance and by the significant dependence of the color of RC stars when moving from metal-poor to metal-rich compositions (see Fig. 4). We estimated the predicted difference in color between RC stars (at the beginning of central helium burning) and the center of RR Lyrae strip (log $T_{\text{eff}} = 3.85$) from the large set of scaled-solar evolutionary models (Pietrinferni et al. 2004) available in the BaSTI database.\footnote{Evolutionary models can be downloaded from http://www.oa-teramo.inaf.it/BASTI.} We adopted evolutionary prescriptions that cover a wide range of iron abundances (−2.27 ≤ [Fe/H] ≤ +0.06 dex), and an age range of 1–6 Gyr for the intermediate-age population and 13 Gyr for the old population. Note that the instability strip is minimally affected by cluster age when moving from 7–8 to 12–13 Gyr. In this context two robust evolutionary predictions need to be underlined. (i) When moving from metal-poor to metal-rich

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**Fig. 3.** Top, cluster isochrones in the $V$, $B - V$ CMD at fixed age (6 Gyr) and for a broad range of chemical compositions (BaSTI database). The vertical dashed line shows the isochrone for an old (13 Gyr), metal-poor ([Fe/H] = −1.79 dex) stellar structure together with its ZAHB. The lozenges mark the RC color, while the square marks the middle of the RR Lyrae instability strip (log $T_{\text{eff}} = 3.85$). Bottom, cluster isochrones in the $V$, $B - V$ CMD at fixed age (13 Gyr) and for a broad range of chemical compositions (BaSTI database). The vertical dashed line shows the isochrone for an intermediate age (6 Gyr), metal-intermediate ([Fe/H] = −1.27 dex) stellar structure together with its He-burning phases. The symbols are the same as in the top panel. See the electronic edition of the *PASP* for a color version of this figure.
compositions, the intermediate-age RC becomes redder than the old RGB for \(\text{[Fe/H]} = -1.79\) dex (see the top panel of Fig. 4). Current evolutionary models predict that a change in metallicity from \(\text{[Fe/H]} = -1.96\) to \(\text{[Fe/H]} = -1.49\) produces a change in \(V\) magnitude of RC stars of 0.03 mag, but a change of 0.12 mag in the \(B - V\) color. (ii) The spread in magnitude of HB stars at the mean color of the RR Lyrae strip increases, as expected, with the spread in metallicity. Note that a change in metallicity from \(\text{[Fe/H]} = -1.96\) to \(\text{[Fe/H]} = -1.49\) implies a change in \(V\) magnitude of HB stars of 0.10 mag, but a change smaller than 0.01 mag in the \(B - V\) color of the instability strip (see the bottom panel of Fig. 4).

Finally, we performed a linear regression between metallicity and the \(RC - HB\) difference in three different colors:

![Figure 5](image.png)

**Fig. 5.—** Left column, zoom across the RC and old HB region of Carina in the \(V, B - V\) (top), \(V, B - I\) (middle), and in the \(V, B - I\) (bottom) CMD. The filled circle marks the position of the middle of the RR Lyrae instability strip and the \(X\) marks the position of the peak of RC stars. Right column, Predicted difference in \(B - V\) (top), in \(B - I\) (middle) and in \(V - I\) (bottom) colors between the middle of the RR Lyrae instability strip and the peak of RC stars as a function of iron abundance. Lines display predictions for different ages of intermediate-mass stars (see labeled values). The black asterisks mark the BaSTI grid points. The filled circles display Carina, while the error bars the uncertainties affecting the difference in color and the metallicity estimate. See the electronic edition of the *PASP* for a color version of this figure.
\[
\begin{align*}
[\text{Fe/H}] &= (-3.02 \pm 0.03) + (3.89 \pm 0.05) \Delta(B - V)_{HB}^{RC} \\
[\text{Fe/H}] &= (-3.47 \pm 0.04) + (2.37 \pm 0.04) \Delta(B - I)_{HB}^{RC} \\
[\text{Fe/H}] &= (-4.13 \pm 0.08) + (6.02 \pm 0.15) \Delta(V - I)_{HB}^{RC}
\end{align*}
\]

These relations (see also right panels in Fig. 5) indicate that the difference in the \(B - I\) color is significantly more sensitive to \([\text{Fe/H}]\) than the \(B - V\) color. The \(V - I\) is the least sensitive of all and shows a stronger nonlinear trend in the metal-poor ([\text{Fe/H}] \leq -1.5) regime. We estimated the difference in color between the RC and the middle of the RR Lyrae instability strip (see the left panels in Fig. 5). We found \(\Delta B - V_{HB}^{RC} = 0.37 \pm 0.05\), \(\Delta B - I_{HB}^{RC} = 0.75 \pm 0.05\) and \(\Delta V - I_{HB}^{RC} = 0.40 \pm 0.05\) mag, where the errors account for uncertainties in the photometry and in the estimate of the mean color of the RR Lyrae strip. We applied these relations and found the following mean metallicities: \([\text{Fe/H}] = -1.60 \pm 0.24(\Delta B - V_{HB}^{RC})\), \([\text{Fe/H}] = -1.70 \pm 0.19(\Delta B - I_{HB}^{RC})\) and \([\text{Fe/H}] = -1.76 \pm 0.44(\Delta V - I_{HB}^{RC})\).

We adopted the estimate based on \(B - I\), since it is the most precise.

As a further test to constrain the spread in metallicity of the Carina subpopulations, we computed a series of synthetic CMDs changing the spread both in age and in metal content. The set of evolutionary models used for these numerical simulations are the same used to derive the new metallicity indicator (Pietrinferni et al. 2004). The code adopted to compute the synthetic CMDs has already been discussed by Pietrinferni et al. (2004) and by Cordier et al. (2007). We only briefly mention the initial parameters adopted to compute the synthetic CMDs. The initial mass function was modeled using a power law with a Salpeter exponent (\(\alpha = -2.35\)), and we assumed a fraction of unresolved binaries of the order of 10% with a minimum mass ratio for the binary systems equal to 0.7. The synthetic CMDs were constructed assuming two star-formation events, with a mean age of 2.5–4 Gyr for the intermediate-mass and of 11–13 Gyr for the low-mass subpopulation (Monelli et al. 2003). We also assumed that the two star-formation episodes include the same fraction of stars. Moreover, we assumed mean metallicities of \([\text{Fe/H}] = -1.5\) and of \(-2.0\) dex for the intermediate-age and the old burst, respectively. In accordance with these findings, we assumed the same spread in metallicity \(\pm 0.1\) dex—for the intermediate and the old star-formation episode. Finally, to mimic actual observations, synthetic photometric errors were added using a Gaussian in the \(B\) and \(V\) bands with a dispersion equal to 0.02 mag. The assumptions adopted to simulate the Carina observations are crude, but a detailed analysis is beyond the aims of this investigation. We plan to study the Carina star-formation history in a forthcoming paper (Monelli et al. 2010, in preparation). Data plotted in the top panel of Figure 6 show that the aforementioned assumptions provide evolutionary features that are in reasonable agreement with the observations (see Fig. 2). In particular, both RC and HB stars are clearly separated in magnitude and in color from each other and from RG stars. Moreover, we selected two bins along the RGB for \(20.75 \leq m_v \leq 21.25\) and \(21.50 \leq m_v \leq 22.00\) and we found that the spread in \(B - V\) color is \(\sim 0.06\) mag. This

![Figure 6](image_url)

**Fig. 6.** Top, synthetic \(V, B - V\) CMD of Carina. The CMD was constructed by assuming two star-formation episodes, with ages of 1113 Gyr for the old and of 2.54 Gyr for the intermediate-age stellar component (Monelli et al. 2003). The two star-formation episodes include the same fraction of stars and have a mean metallicity of \([\text{Fe/H}] = -1.5\) and of \(-2.0\) dex, respectively. The spread in metallicity is \(\pm 0.1\) dex for both the intermediate and the old subpopulation. Intrinsic photometric error was added using a Gaussian with a mean equal to 0.02 mag. Middle, same as the top, but the synthetic CMD was constructed assuming a spread in metallicity of \(\pm 0.2\) dex for the old and the intermediate-age subpopulation. Bottom, same as the middle, but the synthetic CMD was constructed assuming a spread in metallicity of \(\pm 0.5\) dex for the intermediate-age subpopulation.
value is quite similar, within the errors, to the spread in $B - V$ color of the observed CMD at the same magnitude intervals, i.e., 0.06 mag. To constrain the impact of a spread in metal content, we used the same evolutionary ingredients adopted to construct the synthetic CMD, but we assumed for each of the two stellar components a spread in metallicity of 0.2 dex. The spread in $B - V$ color at the same magnitude intervals is slightly larger than observed, namely 0.08 mag.

Finally, we adopted for the intermediate-age stellar component alone a spread in metallicity of 0.5 dex. Data plotted in the bottom panel of Figure 6 clearly show that such a spread in metallicity causes the RC stars to attain colors that are redder than the RG stars. The spread in $B - V$ color at the same magnitude intervals is a factor of 2 larger than observed, i.e., 0.12 mag. Moreover, the synthetic CMD suggests the occurrence of subgiant and giant branch stars with colors that are redder than the subgiant of the old subpopulation. The observed CMD does not show these features.

The comparison with empirical calibrators further supports the contention that Carina hosts predominantly metal-poor stellar populations, in agreement with the spectroscopic investigations. However, the limited range in color covered by the RC stars appears incompatible with the spectroscopic results: the spread in iron abundance of the intermediate-age population is either small, or is counterbalanced by some other—as yet unrecognized—variable. The same conclusion applies for the old population, based on the limited magnitude spread among the old HB stars. These conclusions are also supported by synthetic CMDs constructed assuming a different spread in metallicity between the intermediate and the old subpopulations. The simulations indicate a spread in metallicity of the two subpopulations smaller than 0.2 dex.

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REFERENCES

Battaglia, G., Irwin, M., Tolstoy, E., Hill, V., Helmi, A., Letarte, B., & Jablonka, P. 2008, MNRAS, 383, 183
Calamida, A., et al. 2009, ApJ, 706, 1277
Carretta, E., & Gratton, R. G. 1997 A&AS, 121, 95 (CG97)
Carretta, E., Bragaglia, A., Gratton, R., D’Orazi, V., & Lucatello, S. 2009, A&A, 508, 695 (C09)
Castellani, V., Cignoni, M., Degl’Innocenti, S., Petroni, S., & PradaMoroni, P. G. 2002, MNRAS, 334, 69
Cordier, D., Pietrinferni, A., Cassisi, S., & Salaris, M. 2007, AJ, 133, 468
Da Costa, G. S., & Hatzidimitriou, D. 1998, AJ, 115, 1934
Dall’Ora, M., et al. 2003, AJ, 126, 197
Dékány, I., & Kovács, G. 2009, A&A, 507, 803
Dolphin, A. E. 2002, MNRAS, 332, 91
Dotter, A., Chaboyer, B., Ferguson, J. W., Lee, H.-c., Worthey, G., Jevremović, D., & Baron, E. 2007, ApJ, 666, 403
Ferraro, F. R., Messineo, M., Fusi Pecci, F., de Palo, M. A., Straniero, O., Chieffi, A., & Limongi, M. 1999, AJ, 118, 1738
Fioc, M., & Rocca-Volmerange, B. 1997, A&A, 326, 950
Glatt, K., et al. 2009, AJ, 138, 1403
Harbeck, D., et al. 2001, AJ, 122, 3092
Helmi, A., et al. 2006, ApJ, 651, L121
Hernandez, X., Gilmore, G., & Valls-Gabaud, D. 2000, MNRAS, 317, 831
Hurley-Keller, D., Mateo, M., & Nemec, J. 1998, AJ, 115, 1840
Kayser, A., Grebel, E. K., Harbeck, D. R., Cole, A. A., Koch, A., Glatt, K., Gallagher, J. S., & da Costa, G. S. 2007, in IAU Symp. Proc. 241, Stellar Populations as Building Blocks of Galaxies, ed. A. Vazdekis, & R. F. Peletier (Cambridge: Cambridge Univ. Press), 351
Klimentskoi, J., Lokas, E. L., Kazantzidis, S., Mayer, L., Mamon, G. A., & Prada, F. 2009, MNRAS, 400, 2162
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Koch, A., Grebel, E. K., Wyse, R. F. G., Kley, J. T., Wilkinson, M. L., Harbeck, D. R., Gilmore, G. F., & Evans, N. W. 2006, AJ, 131, 895
Koch, A., Grebel, E. K., Gilmore, G. F., Wyse, R. F. G., Kley, J. T., Harbeck, D. R., Wilkinson, M. L., & Wyn Evans, N. 2008, AJ, 135, 1580
Koposov, S. E., Yoo, J., Rix, H.-W., Weinberg, D. H., Macciò, A. V., & Escudé, J. M. 2009, ApJ, 696, 2179
Kormendy, J. 1985, ApJ, 295, 73
Kormendy, J., Fisher, D. B., Cornell, M. E., & Bender, R. 2009, ApJS, 182, 216
Kraft, R. P., & Ivans, I. I. 2004, Origin and Evolution of the Elements, ed. A., McWilliam, & M., Rauch (Pasadena: Carnegie Obs.), 33
Kravtsov, A. 2010, Adv. Astron., 2010, 1
Landolt, A. U. 1992, AJ, 104, 340
MacLow, M., & Ferrara, A. 1999, ApJ, 513, 142
McCall, M. L. 2004, AJ, 128, 2144
Madau, P., Diemand, J., & Kuhlen, M. 2008, ApJ, 679, 1260
Mateo, M. L. 1998, ARA&A, 36, 435
Mateo, M., Hurley-Keller, D., & Nemec, J. 1998, AJ, 115, 1856
Mighell, K. J. 1990, A&AS, 82, 1
———. 1997, AJ, 114, 1458
Monelli, M., et al. 2003, AJ, 126, 218
Moore, B., Diemand, J., Madau, P., Zemp, M., & Stadel, J. 2006, MNRAS, 368, 563
Mould, J., & Aaronson, M. 1983, ApJ, 273, 530
Orban, C., Gnedin, O. Y., Weisz, D. R., Skillman, E. D., Dolphin, A. E., & Holtzman, J. A. 2008, ApJ, 686, 1030
Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, ApJ, 612, 168
Note added in proof.—Note that Kormendy et al. (2009; see also Kormendy 1985) have argued that dSph galaxies define fundamental-plane relations distinct from those of elliptical galaxies, and more similar to those of late-type galaxies. They suggest that the dSph galaxies like Carina were irregular galaxies that have either lost their gas content, or consumed it through star formation. This assertion is consistent with the range of intermediate-age subpopulations found in Carina.