THE CARINA PROJECT. VI. THE HELIUM-BURNING VARIABLE STARS

G. Coppola1, P. B. Stetson2, M. Marconi1, G. Bono3,4, V. Ripper1, M. Fabrizio5, M. Dall’Ora1, I. Musella1, R. Buonanno1,6, I. Ferraro4, G. Fiorentino7, G. Iannicola8, M. Monelli8,9, M. Nonino10, L. Pulone4, F. Thévenin11, and A. R. Walker12

1 INAF-Osservatorio Astronomico di Capodimonte, Via Moiariello 16, I-80135 Napoli, Italy; coppola@na.astro.it
2 Dominion Astrophysical Observatory, NRC-Herzberg, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada
3 Dipartimento di Fisica-Università di Roma Tor Vergata, Via della Ricerca Scientifica 1, I-00133 Roma, Italy
4 INAF-Osservatorio Astronomico di Roma, Via Frascati 33, I-00040 Monte Porzio Catone, Italy
5 INAF-Osservatorio Astronomico di Collurania, via M. Maggini, I-64100 Teramo, Italy
6 Agenzia Spaziale Italiana Spazio Data Center (ASDC), c/o ESRIN, via S. Gargnano 1, I-00044 Frascati, Italy
7 INAF-Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy
8 Instituto de Astrofísica de Canarias, Calle Via Lactea s/n, E-38205 La Laguna, Tenerife, Spain
9 Departamento de Astrofísica, Universidad de La Laguna, E-38200 Tenerife, Spain
10 INAF-Osservatorio Astronomico di Trieste, via G. Tiepolo 11, I-40131 Trieste, Italy
11 Université de Nice-Sophia Antipolis, Lab. Lagrange, UMR 7293, Observatoire de la Côte d’Azur, BP 4229, F-06304 Nice, France
12 Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, Casilla 603, La Serena, Chile

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ABSTRACT

We present new optical (BVI) time-series data for the evolved variable stars in the Carina dwarf spheroidal galaxy. The quality of the data and the observing strategy allowed us to identify 14 new variable stars. Eight out of the 14 are RR Lyrae (RRL) stars, 4 are Anomalous Cepheids (ACs), and 2 are geometrical variables. Comparison of the period distribution for the entire sample of RRLs with similar distributions in nearby dwarf spheroidal galaxies and in the Large Magellanic Cloud indicates that the old stellar populations in these systems share similar properties. This finding is also supported by the RRL distribution in the Bailey diagram. On the other hand, the period distribution and the Bailey diagram of ACs display significant differences among the above stellar systems. This evidence suggests that the properties of intermediate-age stellar populations might be affected both by environmental effects and structural parameters. We use the $B$V Period–Wesenheit (PW) relation of RRLs together with evolutionary prescriptions and find a true distance modulus of 20.09 ± 0.07 (intrinsic) ± 0.1 (statistical) mag that agrees quite well with similar estimates available in the literature. We identified four peculiar variables. Taking into account their position in the Bailey diagram and in the $B$V PW relation, two of them (V14 and V149) appear to be candidate ACs, while two (V158 and V182) might be peculiar RRLs. In particular, the variable V158 has a period and a $V$-band amplitude very similar to the low-mass RRL—RRLR-02792—recently identified by Pietrzyński et al. in the Galactic bulge.

Key words: galaxies: individual (Carina) – Local Group – stars: variables: RR Lyrae

Online-only material: color figures

1. INTRODUCTION

Nearby dwarf spheroidal galaxies (dSphs) play a fundamental role in modern astrophysics. Wide-field imagers available at the 4–8 m class telescopes provide a complete census of their stellar content down to the main sequence of the old stellar population (Bono et al. 2010; Stetson et al. 2011; Monelli et al. 2012). Multi-slit and multi-fiber spectrographs available at the same facilities have provided the opportunity to investigate their kinematic structure (Battaglia et al. 2008; Fabrizio et al. 2011) and their metallicity distribution (Clementini et al. 2005; Fabrizio et al. 2012; Lemasle et al. 2012; Venn et al. 2012). dSphs are also important laboratories for near-field cosmology. Recent investigations indicate that the galaxies obey a well-defined relation between mass and metallicity, where more massive galaxies are more metal-rich than less massive ones. This evidence has typically been explained as a consequence of galactic outflows, wherein more massive systems are able to retain metal-rich gas, while galactic outflows expel it in low-mass stellar systems. However, we are facing evidence that nearby dSphs are, at a fixed mass, more metal-poor than expected by the canonical mass–metallicity relation (Chilingarian et al. 2011).

Moreover, it has recently been shown that the metallicity in stellar systems with a total mass smaller than $10^{10}$ $M_\odot$ is anti-correlated with the star formation rate (SFR; Mannucci et al. 2010). This empirical evidence is typically explained as a local infall of metal-poor gas that simultaneously increases the SFR and decreases the mean metallicity of these systems. Recent investigations have indicated quite complex star formation activity in nearby dSphs. For example, it has been suggested that Leo I experienced almost continuous star formation during the last 10 Gyr (Fiorentino et al. 2012), while Carina experienced multiple and distinct star formation events (Bono et al. 2010). Moreover, several dSphs in the Local Group (LG) show broad metallicity distributions (Hill 2010) suggesting that they have been able to retain the supernova yields of previous stellar generations.

Variable stars in nearby dwarfs are important benchmarks for determining not only their distance and their geometry (Minniti et al. 2003; Ripepi et al. 2012; Inno et al. 2013), but also their stellar populations (Pritzl et al. 2005; Pietrzyński et al. 2006, 2010; Kinemuchi et al. 2008; Kuehn et al. 2008; Szewczyk
et al. 2008, 2009; Moretti et al. 2009; Musella et al. 2009, 2012; Matsunaga et al. 2011; Dall'Ora et al. 2012).

Nearby dwarfs also offer the unique opportunity to study the dependence of stellar pulsation properties on the environment and, in particular, on the chemical enrichment history (Caputo et al. 2005; Lanfranchi et al. 2006). In this context, the Carina dSph plays a key role, since it hosts a significant number of evolved and unevolved (Mateo et al. 1998) variable stars tracing the different episodes of star formation (see, e.g., Dall'Ora et al. 2005; Lanfranchi et al. 2006). In this context, the Carina dSph plays a key role, since it hosts a significant number of evolved and unevolved (Mateo et al. 1998) variable stars tracing the different episodes of star formation (see, e.g., Dall'Ora et al. 2005; Lanfranchi et al. 2006).

In this paper, we present an updated investigation of the Carina variables with similar variable stars in nearby dwarfs. In this paper, we present an updated investigation of the Carina variables with similar variable stars in nearby dwarfs.

Table 1 lists the number of different exposures obtained of Carina within 327 distinct datasets, where a dataset consists of either (1) all images obtained by a given CCD on a given photometric night, or (2) all images obtained by a given CCD on one or more non-photometric nights during a given observing run.

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2. OBSERVATIONS AND DATA REDUCTION

Our imaging data for the main body of Carina\textsuperscript{13} are divided into 23 observing runs, as detailed in Table 1. To be more precise, there were in fact 21 different observing runs, but in two cases (here named wfi17/W00Jan and B03Jan/double) we obtained incomplete sets of observations from the same observing run via two different sources. In each case, after elimination of duplicate observations, the non-redundant sets of images were kept as two separate “observing runs” lest any inconsistencies in the preprocessing of the different sets of images lead to subtle changes in the absolute flux calibrations of the data. The observations of Carina were contained within 327 distinct datasets, where a dataset consists of either (1) all images obtained by a given CCD on a given photometric night, or (2) all images obtained by a given CCD on one or more non-photometric nights during a given observing run.

\begin{table}[h]
\centering
\caption{Log of Observations}
\begin{tabular}{lllllllllll}
\hline
Run ID & Dates & Telescope & Camera & U & B & V & R & I & Multiplex \\
\hline
1 & c92: & 1992 Dec 19–22 & CTIO 1.5 m & Tek2K-1 & \ldots & 30 & \ldots & \ldots & 42 \\
2 & w13: & 1999 Mar 17 & MPI/ESO 2.2 m & WFI & \ldots & 1 & \ldots & \ldots & \times 8 \\
3 & fors9912: & 1999 Dec 2 & ESO VLT 8.0 m & FORS1 & \ldots & 1 & \ldots & \ldots & 1 \\
4 & w15: & 1999 Dec 15–19 & MPI/ESO 2.2 m & WFI & \ldots & 52 & \ldots & 16 & \times 8 \\
5 & B00Jan: & 1999 Dec 30–2000 Jan 10 & CTIO 4.0 m & Mosaic2 & \ldots & 48 & \ldots & \ldots & \times 8 \\
6 & w17: & 1999 Dec 31–2000 Jan 7 & MPI/ESO 2.2 m & WFI & \ldots & 45 & 48 & \ldots & \times 8 \\
7 & W00Jan: & 2000 Jan 6–8 & MPI/ESO 2.2 m & WFI & \ldots & 26 & 28 & \ldots & \times 8 \\
8 & w122: & 2000 Feb 26 & MPI/ESO 2.2 m & WFI & \ldots & 12 & 13 & \ldots & \times 8 \\
9 & w121: & 2000 Mar 5 & MPI/ESO 2.2 m & WFI & \ldots & 2 & 2 & \ldots & \times 8 \\
10 & w14: & 2000 Oct 291 & MPI/ESO 2.2 m & WFI & 5 & 8 & 8 & \ldots & \times 8 \\
11 & cg: & 2001 Jan 17–18 & CTIO 4.0 m & Mosaic2 & \ldots & 6 & \ldots & 12 & \times 8 \\
12 & B02oct: & 2002 Oct 31 & CTIO 4.0 m & Mosaic2 & \ldots & 5 & \ldots & \ldots & \times 8 \\
13 & B02nov: & 2002 Nov 29 & CTIO 4.0 m & Mosaic2 & \ldots & 5 & \ldots & \ldots & \times 8 \\
14 & B03Jan: & 2003 Jan 2 & CTIO 4.0 m & Mosaic2 & \ldots & 4 & \ldots & \ldots & \times 8 \\
15 & double: & 2003 Jan 2 & CTIO 4.0 m & Mosaic2 & \ldots & 1 & \ldots & \ldots & \times 8 \\
16 & w19: & 2003 Mar 1–7 & MPI/ESO 2.2 m & WFI & 19 & 15 & \ldots & \ldots & \times 8 \\
17 & B03octa: & 2003 Oct 7 & CTIO 4.0 m & Mosaic2 & \ldots & 5 & 7 & \ldots & \times 7 \\
18 & B03nov: & 2003 Nov 28 & CTIO 4.0 m & Mosaic2 & \ldots & 8 & 10 & \ldots & \times 7 \\
19 & B04jan: & 2004 Jan 22–23 & CTIO 4.0 m & Mosaic2 & \ldots & 13 & 15 & \ldots & \times 7 \\
20 & B04jan29: & 2004 Jan 29 & CTIO 4.0 m & Mosaic2 & \ldots & 1 & \ldots & \ldots & \times 7 \\
21 & B04dec11: & 2004 Dec 12 & CTIO 4.0 m & Mosaic2 & 4 & 5 & \ldots & 7 & \times 8 \\
22 & B04dec19: & 2004 Dec 20 & CTIO 4.0 m & Mosaic2 & 6 & \ldots & \ldots & 12 & \times 8 \\
23 & w29: & 2008 Sep 28–Oct 7 & MPI/ESO 2.2 m & WFI & 14 & 14 & 14 & 14 & \times 8 \\
\hline
\end{tabular}
\end{table}

Notes. (1) Observers: T. Sneider-Hane, P. B. Stetson; (2) Program ID: unknown, unknown unknown; (3) Program ID: 64.N-0421(A); (4) Program ID: 000.H-0597; (5) Observers: A. Walker, C. Smith; (6) Program IDs: 064.N-0512, 0164.N-0210, 064.L-0327; (7) Program ID: a064.L-0327, proprietary data not found in the archive; (8) Program ID: 164.O-0561(E), observer M. Schirmer; (9) Program ID: 064.N-0564, observer V. Tena; (10) Program ID: 164.O-0089(A), observer V. Rippe; (11) Observers: C. Gallart, J. P. Garcia; (12) Proposal ID: 2002B-0077, observer A. Walker; (13) Proposal ID: 2002B-0077, observer A. Walker; (14) Observer: A. Walker; (15) Observer: A. Walker, single exposure missing from Run 14; (16) Program ID: 70.B-0635(A); (17) Observer: A. Walker, chip #3 non-functional; (18) Observer: A. Walker, chip #3 non-functional; (19) Proposal ID: 2004b-051, observer A. Walker, chip #3 non-functional; (20) Observers: C. Aguierra, C. Smith, A. Walker, chip #3 non-functional; (21) Observer: A. Walker; (22) Observers: A. Walker, M. Monelli; (23) Program ID: 081.A-9026(A).

\textsuperscript{13} We also have observations of flanking fields to the south and northeast of the galaxy, but we do not discuss them here.
determined from all available observations of primary and secondary standards, but the photometric zero point of each individual CCD image was determined by reference to secondary standards contained within the image itself.

Because of the non-overlapping nature of the fields of the different CCDs in each mosaic camera, no individual star appears in more than a small fraction of the total number of images. The maximum number of flux measurements for any given star was 17 in U, 167 in B, 222 in V, and 85 in I. The 14 exposures in the R filter (comprising 112 individual CCD images) were all obtained on non-photometric occasions; as a result, Stetson was unable to define local secondary standards in the R photometric bandpass, and we were not able to calibrate these R-band observations to the Landolt photometric system. Nevertheless, these 112 R-band images were included in the ALLFRAME reductions of Carina in order to make use of the information they contribute to the completeness of the star list and the precision of the astrometry.

3. VARIABLE STARS

We applied a slightly more robust variant of the Welch & Stetson (1993) variability search technique to the new multi-band optical photometry of the main body of Carina. On the basis of these data, we identified 108 evolved variable stars; among them, 14 are new identifications. A simple string-length basis of these data, we identified 108 evolved variable stars; among them, 14 are new identifications. A simple string-length algorithm was applied to the time-series data to search for periodicity. Fourier series were then fitted by nonlinear least-squares to refine the periods and determine mean magnitudes and amplitudes.

For eight of the already known variables (six ACs: V27, V115, V149, V178, V187, and V203; two RR Lyraes: V22 and V176) we have updated the pulsation periods. Indeed, the previous search for variable stars had been performed on BV time-series data covering only three consecutive nights (Dall’Ora et al. 2003), and a few period determinations were affected by alias problems. Table 2 lists (from left to right) the identification, the classification, the epoch of maximum light, the period (days), the magnitude-averaged \((V), (B)\), the intensity-averaged \((\langle V \rangle), (\langle B \rangle)\), and the \(V\) and \(B\) amplitude (\(A_V, A_B\)) for the entire sample of variable stars identified in the current photometric survey.

Eight out of the 14 new variables are RR Lyrae stars (RRLs), 4 are candidate Anomalous Cepheids (ACs), and 2 are geometrical variables (eclipsing binary and W UMa). The pulsation properties of the new variables are listed in Table 3. A more detailed discussion of the pulsation characteristics of the entire sample will be addressed in a future paper (G. Coppola et al. 2013, in preparation).

Figure 1 shows the \(V, (B-V)\) CMD of Carina in the region across the helium-burning phases for both the old (horizontal branch, HB) and the intermediate-age (red clump, RC) stellar populations. The 69 RRLs associated with the old stellar populations have been plotted as circles: red and green circles mark RRLs pulsating in the fundamental (RRL\(_f\), 57) and in the first-overtone (RRL\(_o\), 12) modes, respectively, while orange triangles mark the six candidate mixed-mode variables, i.e., variables oscillating simultaneously in two or more pulsation modes (RRL\(_{od}\)). The five RRLs showing modulation in both amplitude and phase (i.e., the so-called Blazhko RRLs) are plotted as gray circles. The newly detected fundamental RRLs have been plotted as crosses. The 16 variables brighter than the RRLs have been classified according to Dall’Ora et al. (2003) as fundamental-mode ACs: cyan squares represent previously
known variables while the cyan crosses indicate, once again, our new AC candidates. Four variables located between the RRLs and the ACs have been plotted as blue circles, since the nature of these objects, based only on their location in the CMD, is not yet clear.

To further constrain the evolutionary status of the Carina variables, solid curves in the left panel of Figure 1 represent the theoretical central helium-burning sequence for both old and intermediate-age stellar structures with the labeled solar-scaled chemical compositions and stellar masses ranging from 0.5 to 2.8 \( M_\odot \). The black and red curves in the right-hand panel of Figure 1 represent theoretical evolutionary tracks for stars near the transition mass between central helium burning in degenerate (red) and non-degenerate (black) cores; for clarity, these are shown only for the lower of the two metallicity values. The adopted true distance modulus and reddening (Dall’Ora et al. 2003) are also labeled. The metal abundances we have adopted for this illustration follow current spectroscopic measurements based on high resolution spectra (Fabrizio et al. 2012; Venn et al. 2012; Lemasle et al. 2012).

The data plotted in this figure display several interesting features.

1. The observed RRLs agree quite well with the predicted zero-age horizontal branches (ZAHBs). The same conclusion applies to the distribution of RRLs within the predicted instability strip. Indeed, only a few RR\(_c\) variables appear to be slightly bluer than the predicted first-overturn blue edge for \( Z = 0.0004 \) ([Fe/H] = −1.7 dex).

2. The ACs are only partially explained by current low-mass evolutionary prescriptions, since a fraction of them (\( V < 19.2 \) mag, \( B - V < 0.3 \) mag) are systematically hotter and brighter than predicted by partially electron-degenerate helium-burning models (\( M/M_\odot < 2.2 \); red curves in the right-hand panel of Figure 1). The data plotted here support the suggestion that the brighter ACs are candidate short-period classical Cepheids. The difference between ACs and classical Cepheids is that the latter stars are slightly more massive (\( M/M_\odot > 2.2 \) for the metal abundances considered here) and are characterized by quiescent helium burning in non-degenerate cores.

3. The intermediate-mass stars (AC and RC) show a spread in metallicity of the order of 0.25 dex as currently suggested by the spectroscopic measurements (Fabrizio et al. 2012 and references therein).

Figure 2 shows the same data, but here the comparison is with alpha-enhanced ([\( \alpha/Fe \)] = 0.4) theoretical helium-burning structures. The data plotted in this figure indicate that a decrease in iron abundance to [Fe/H] = −2.14 dex combined with the \( \alpha \) enhancement (resulting in an overall metallicity of [M/H] = −1.79 dex, virtually the same as a solar-scaled abundance pattern with [Fe/H] = −1.79 dex) has a minimal impact, at least on the RRLs. On the other hand, the blue circles in Figures 1 and 2 appear brighter than typical RRLs, but fainter than ACs for the assumed metallicity. Therefore, the classification of these objects is more uncertain and further information is required to constrain their evolutionary and pulsational status.

### 4. PULSATION PROPERTIES

#### 4.1. Period Distribution

The period distribution of the Carina RRLs is shown in Figure 3(a). The period distribution shows two well-defined peaks for RR\(_{ab}\) (log \( P \sim −0.19 \)) and RR\(_c\) (log \( P \sim −0.4 \)) variables, plus a third minor peak at (log \( P \sim −0.5 \)).
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Figure 1. Left: V, B − V CMD showing theoretical predictions for central helium-burning structures, based on scaled-solar evolutionary models constructed assuming a primordial helium of Y = 0.25 and different iron abundances (see legend) from the BaSTI database (Pietrinferni et al. 2004). The brown and purple solid lines represent the central helium-burning sequence for stars with stellar masses ranging from ∼0.5 to 2.8 M⊙. The blue and red solid lines in the left panel delimit the theoretical instability strip for RRLs provided by Di Criscienzo et al. (2004). The red and green circles represent fundamental and first-overtone RRLs. The orange triangles and gray circles stand for double-mode pulsators and candidate Blazhko RRLs. The cyan symbols represent ACs. The blue circles stand for peculiar variables whose position in the CMD is intermediate between RRLs and ACs. The crosses indicate newly discovered variables. Right: same as the left, but here the solid curves represent the evolutionary changes in the stellar properties near the transition mass between central helium burning in an electron-degenerate core (red lines) and quiescent central helium burning (black lines), and are presented only for the more metal-poor abundance patterns. The mass values are also labeled. (A color version of this figure is available in the online journal.)

Figure 2. Same as Figure 1, but for α-enhanced helium-burning evolutionary models. (A color version of this figure is available in the online journal.)

The mean period of fundamental RRLs is a crucial observable in the definition of the so-called Oosterhoff dichotomy (Oosterhoff 1939), typical of Galactic globular clusters (GGCs). The GGCs hosting RRLs can be split, according to the mean period of RRL stars, into two different groups: the Oosterhoff type I [OoI] with ⟨Pab⟩ ∼ 0.55 days and the Oosterhoff type II [OoII] with ⟨Pab⟩ ∼ 0.65 days. In order to provide a more complete picture of the Carina variable star content, the periods of both first-overtone and double-mode pulsators were fundamentalized according to the relation log P_{F} = log P_{FO} + 0.127. The mean period of the entire sample of RRLs is then ⟨P_{RRL}⟩ = 0.60 ± 0.01 days. This suggests that Carina can be classified as an OoII system, in agreement with previous results (Dall’Ora et al. 2003). However, the Oosterhoff dichotomy also shows up in the RRL population ratio, i.e., the ratio between the number of RRc and the total number of RRLs. The OoI clusters have a ratio ∼0.17, while for OoII clusters this ratio is ∼0.44 (Clement et al. 2001). On the basis of the new RRL sample, we found Nc/N_{tot} ∼ 0.17, thus suggesting that this system is, according to the RRL population ratio, more similar to an OoI cluster. This discrepancy suggests that Carina is, in fact, Oosterhoff-intermediate, like Draco (Kinemuchi et al. 2008), Ursa Minor (Nemec et al. 1988), Large Magellanic Cloud (LMC) globular clusters (Bono et al. 1994), and the outer-halo globular cluster Palomar 3 (Kinemuchi et al. 2008).

To better understand the period distribution of Carina variables, we compare their properties with those of other LG dSphs. We start with the pulsating variables in the Leo I dSph
Figure 3. Left: period distribution of the RRL samples (RR\textsubscript{ab} + RR\textsubscript{c} + RR\textsubscript{d}) of, from top to bottom, Carina (82), Leo I (95; Fiorentino et al. 2012), Fornax (514; Bersier & Wood 2002), Sculptor (221; Kaluzny et al. 1995), Cetus (155; Bernard et al. 2009), Tucana (298; Bernard et al. 2009), and the LMC (95; OGLE-III sample by Soszyński et al. 2008, 2009). Right: same as the left, but for ACs. (A color version of this figure is available in the online journal.)

\begin{itemize}
\item Carina
\item Leo I
\item Fornax
\item Sculptor
\item Cetus
\item Tucana
\item LMC
\end{itemize}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Left: period distribution of the RRL samples (RR\textsubscript{ab} + RR\textsubscript{c} + RR\textsubscript{d}) of, from top to bottom, Carina (82), Leo I (95; Fiorentino et al. 2012), Fornax (514; Bersier & Wood 2002), Sculptor (221; Kaluzny et al. 1995), Cetus (155; Bernard et al. 2009), Tucana (298; Bernard et al. 2009), and the LMC (95; OGLE-III sample by Soszyński et al. 2008, 2009). Right: same as the left, but for ACs. (A color version of this figure is available in the online journal.)}
\end{figure}

\begin{itemize}
\item Carina \([\text{[Fe/H]} = -1.43, \sigma = 0.33 \text{ dex}; \text{Kirby et al. 2011}])
\item Leo I \([\text{[Fe/H]} = -1.68, \sigma = 0.48 \text{ dex}; \text{Kirby et al. 2009, 2011}])
\item Fornax \([\text{[Fe/H]} = -1.99, \sigma = 0.36 \text{ dex}; \text{Kirby et al. 2011; Figure 3(c)}])
\item Cetus \([\text{[Fe/H]} = -1.68, \sigma = 0.48 \text{ dex}; \text{Kirby et al. 2009, 2011}])
\item Tucana \([\text{[Fe/H]} = -1.68, \sigma = 0.48 \text{ dex}; \text{Kirby et al. 2009, 2011}])
\item LMC \([\text{[Fe/H]} = -1.43, \sigma = 0.33 \text{ dex}; \text{Kirby et al. 2011}])
\end{itemize}

The period distribution of the 221 RRLs in the Sculptor dSph \([\text{[Fe/H]} = -1.68, \sigma = 0.48 \text{ dex}; \text{Kirby et al. 2009, 2011}]) by Kaluzny et al. (1995) peaks around a mean period \((P_{\text{RR}}) \approx 0.53 \pm 0.01 \text{ days (Figure 3(d))}, suggesting an Oo system, but once again this is in contrast with the value of \(N_c/N_{\text{tot}} \approx 0.40 \text{ making it more similar to an OoII system.} \]

Together with the above satellite dwarf galaxies, we decided to include in our analysis two isolated dwarfs, namely Cetus and Tucana (Bernard et al. 2009). The former galaxy hosts 155 RRLs and the period distribution shows a well-defined main peak with a mean period \((P_{\text{RR}}) \approx 0.56 \text{ days (Figure 3(e))}, suggesting an
OoII system. In spite of the large sample of RRLs, Cetus only hosts eight first overtones. This means that the RRL population ratio is quite small, \( N_c/N_{\text{tot}} = 0.06 \), therefore suggesting an OoI system. The period distribution of RRL (298) in Tucana is quite different when compared with Cetus. The mean period is \( \langle P_{RR} \rangle = 0.56 \pm 0.01 \) days (Figure 3(i)) and suggests an OoI system. Moreover, Tucana hosts a sizable sample of first overtones (82) that is almost 30% of the entire sample, and indeed the RRL population ratio attains a value significantly larger, \( N_c/N_{\text{tot}} = 0.23 \). This means that Tucana could be a “pure” OoI system. This and the evidence that this system hosts a high fraction of mixed-mode variables (60) makes Tucana a very interesting laboratory to investigate the occurrence of this still poorly understood pulsation phenomenon (Bernard et al. 2009). The current results for Cetus and Tucana appear even more appealing if we take into account the fact that they have a similar mean metallicity \([\text{Fe}/\text{H}] \sim -1.8\) dex and a similar internal abundance dispersion \((\sim 0.2\ \text{dex}; \text{Bernard et al.} \ 2009)\). 

Finally, according both to the value of \( \langle P_{RR} \rangle \sim 0.55 \) days and to the fraction of RR\(_{c}\), \( N_c/N_{\text{tot}} \sim 0.22 \), the LMC \([\text{Fe}/\text{H}] = -1.48, \sigma = 0.29\ \text{dex}; \text{Gratton et al.} \ 2004\) resembles an OoI system (Soszynski et al. 2009; see Figure 3(g)).

The above empirical evidence brings forward a few interesting findings: the RRLs in nearby dSphs show similar period distributions, with pulsation properties ranging from OoI to OoII globulars, but the exact classification does depend on the diagnostic adopted to parameterize the pulsation properties. None of these dSphs can be described as a clean example of either OoI or OoII according to all available classification criteria, except for Tucana, suggesting that the HB and the RGB luminosity functions of this last system deserve a more detailed analysis. The RRLs in the LMC also show similar properties, but this might be a consequence of the broad range in metal abundance (Gratton et al. 2004) and/or age shown by the old stellar component. The differences among the other dwarf galaxies and canonical GGCs, considered together, are not yet clearly understood.

A third peak at \( \log P \sim -0.55 \) is present in all the above histograms, possibly strengthening the inference that this feature is more likely an indicator of a spread in metal abundance rather than a population of second-overtone RRLs, as originally suggested by Dall’Ora et al. (2003). We note here that current nonlinear pulsation models do not predict second-overtone pulsators (see Bono et al. 1997b) among RRLs.

Figure 3(h) shows the period distribution of the ACs in Carina. The period distribution of these variables ranges from \( \log P \sim -0.4 \) to \( \sim +0.2 \), with a well-defined peak at \( \sim 0.0 \) and a secondary group located in the short period range \((\sim 0.2)\). To begin to interpret the pulsation properties of ACs in Carina, we compared their period distributions with similar samples of ACs in Leo I, Fornax, and the LMC. The period distribution of the ACs in Leo I (Fiorentino et al. 2012; see Figure 3(i)) peaks at periods that are systematically longer than in Carina, and indeed the mean period is systematically longer \((1.2 \pm 0.1 \ \text{versus} \ 0.8 \pm 0.1 \ \text{days})\). Moreover, the ACs in Leo I also show a tail in the long-period range \((\log P \sim 0.2–0.6)\) that is not present in Carina.

The period distribution of ACs in Fornax (Figure 3(j)) is even more puzzling, since it shows two well-defined peaks. However, in contrast with the Carina and Leo I samples, the main peak of the Fornax ACs is in the short-period range \((\log P \sim -0.25)\). This is a peculiar feature, since the number of ACs in this period range is small in the other dSphs (see also the case of LMC in Figure 3(n)).

The number of ACs currently known in Sculptor, Cetus, and Tucana does not allow us to reach any firm conclusion concerning their pulsation properties.

The period distribution of the ACs in the LMC ranges from \( \sim -0.4 \) to \( \sim 0.4 \) (see Figure 3(n)) with a well-defined mode at \( \log P \sim -0.1 \). The period histogram is characterized by a broad distribution extending across both the short and the long period range.

The above findings indicate that the ACs in nearby dSphs display significant differences among these stellar systems. The same conclusion applies to ACs in the LMC, thus suggesting that the intermediate-age star formation and enrichment history of these systems followed different paths (Fiorentino & Monelli 2012). In this context, it is worth recalling that ACs in Leo I display a period distribution more skewed toward longer periods than ACs in the LMC. This evidence might be the consequence of a very recent star formation episode, a systematic difference in metal abundance, or both.

4.2. The Period–Amplitude Diagram

To further investigate the pulsation properties of helium-burning variable stars in Carina, we also adopted the Bailey diagram, i.e., the luminosity amplitude versus the logarithmic period. From top to bottom, the first two left panels of Figure 4 show, once again, that the RRLs in Carina and in Leo I (P. B. Stetson et al. 2013, in preparation) have similar properties. Indeed, the RR\(_{ab}\) variables display V-band amplitudes that are between the normal trend of OoI and OoII globular clusters (black solid lines). However, the RR\(_c\) in Carina cover a slightly broader range in periods when compared with the RR\(_c\) in Leo I. It is worth mentioning that both the Blazhko and double-mode RRLs cover very limited ranges of period. The former group clusters around \( \log P \sim -0.25 \) to \( \sim -0.20 \), while the latter is concentrated around \( \log P \sim -0.40 \). The comparison with Leo I is hampered by the fact that only two Blazhko RRLs are currently known in this system.

Moving to the lower panels, the RR\(_{ab}\) in Sculptor, Cetus, and Tucana cover a broad range of both periods and amplitudes, but they seem to be in better agreement with the properties of OoI globulars. The RR\(_c\) in Carina, Sculptor, Cetus, and Tucana show similar behavior, displaying the so-called bell-shaped distribution, which is more typical of OoII globular clusters (Bono et al. 1997c). However, the spread in amplitudes and periods of RR\(_c\) in Carina and in Cetus is significantly smaller than in Sculptor and in Tucana. This empirical evidence further suggests that the spread in metallicity of the old stellar population in Carina and in Cetus is smaller than in Sculptor and in Tucana. This empirical evidence further suggests that the spread in metallicity of the old stellar population in Carina and in Cetus is smaller than in Sculptor and in Tucana. The bar oc-
Bailey diagram ($V$-band amplitude vs. logarithmic period) for RRLs (left) and ACs (right) in Carina, Leo I, Sculptor, Cetus, and Tucana. The solid lines display the positions of OoI and OoII galactic globular clusters according to Clement & Rowe (2000). The symbols are the same as in Figure 1. The cyan cross in the left top panel marks the position of the peculiar RRLYR-02792 recently discovered by Pietrzyński et al. (2012).

Figure 4. (A color version of this figure is available in the online journal.)

V-band amplitudes (0.1–0.2 mag), but their position in the Period–Wesenheit (PW) diagram does not appear to be peculiar (see below).

It is worth noting that according to the Bailey diagram, the four peculiar variables ($V_{14}$, $V_{149}$, $V_{158}$, and $V_{182}$, indicated by blue circles) appear to be candidate ACs, and indeed they attain amplitudes similar to the other ACs in the same period range. However, two ($V_{158}$ and $V_{182}$) out of the four might be candidate RRL stars. The reason is twofold: (1) they are located in the same region of the Bailey diagram as the other RRLs, while the variables $V_{14}$ and $V_{149}$ exhibit amplitudes that are too large for their periods; (2) they are both fainter and redder than the other ACs (cf. Figure 2).

The hypothesis that $V_{158}$ and $V_{182}$ are candidate RRL stars was first suggested by Monelli et al. (2003). In particular, these authors suggested that $V_{158}$ and $V_{182}$ might be the aftermath of intermediate-mass stars that during their evolution experienced violent mass-loss events. The existence of this class of objects has been soundly demonstrated by Pietrzyński et al. (2012). They identified an RRL-like variable in an eclipsing binary system (RRLYR-02792) located in the Galactic bulge and provided a firm estimate of its dynamical mass. They found that its mass is $0.26M_\odot$, thus confirming its peculiar nature. This object mimics a typical RRL, but its evolutionary status is significantly different. The main energy source of this low-mass variable seems to be hydrogen-shell burning, since current theoretical and empirical constraints indicate that central helium burning—typical of RRLs—can take place only in structures more massive than $\approx 0.5M_\odot$ (Castellani et al. 2007). The peculiar evolutionary history of RRLYR-02792 is also supported by the fact it is characterized by a large negative period derivative ($-8.4 \pm 2.6 \times 10^{-6}$ days yr$^{-1}$), thus further supporting the difference with canonical RRLs for which the same derivative is typically two orders of magnitude smaller (Kunder et al. 2011). Interestingly enough, the prototype of this new class of variable stars in the Bailey diagram is located (cyan cross) very close to $V_{158}$, i.e., one of the two peculiar candidate RRLs. Unfortunately, the current data do not allow us to estimate the period derivatives of $V_{158}$ and $V_{182}$.

To further investigate the nature of the two peculiar RRL candidates, we considered whether they might be either evolved RRLs or candidate type II Cepheids (P2C). To our knowledge, P2C variables have been identified only in Fornax by Bersier & Wood (2002), but they might also be present in Carina. Figure 5 shows the predicted $V$, $(B-V)$ CMD of the scaled-solar metal-poor helium-burning sequence plotted in Figure 1, together with the blue edge for first-overtone pulsators and the red edge for fundamental pulsators. Using the pulsation
relation provided by Di Criscienzo et al. (2004), we found that the periods at the intersection between the ZAHB and the instability strip are $P_{F}^{Z} = 0.279$ and $P_{F} = 0.787$ days, where the former has been fundamentalized. This period range agrees quite well with the observed range of Carina RRLs. To further investigate the possibility either of evolved RRLs or P2C, we took into account the off-ZAHB evolution of two old HB stellar structures with stellar masses smaller than the typical masses of RRLs ($0.70 < M/M_{\odot} < 0.75$). The two green lines cross, as expected, the instability strip at higher luminosity, and therefore they produce RRLs with longer periods. The structure with $M/M_{\odot} = 0.65$ at the intersection between the ZAHB and the instability strip gives periods of $P_{F}^{Z} = 0.371$ and $P_{F} = 1.131$ days, while the structure with $M/M_{\odot} = 0.60$ gives periods of $P_{F}^{Z} = 0.558$ and $P_{F} = 1.530$ days. These findings further indicate that the periods of the two peculiar RRLs (V158, 0.632 days; V182, 0.778 days) are too short compared with the predicted ones. Indeed, pulsation and evolutionary prescriptions indicate that pulsators located close to the red edge of the instability strip and at least one-half magnitude brighter than typical RRLs should have periods longer than one day, i.e., they should be P2C of the BL Herculis type (Marconi & Di Criscienzo 2007; Marconi et al. 2011).

4.3. The Period–Wesenheit Relation

Additional insights about the evolutionary status of the four peculiar variables can be obtained by adopting the PW relation. The main advantage in using Wesenheit magnitudes is that they are reddening-free by definition, being estimated using both apparent magnitudes and colors linked by a coefficient given by an extinction law (see, e.g., Marconi et al. 2004 and references therein). Note that we do not expect, a priori, that foreground or internal reddening in Carina will be a serious issue for our work; at Galactic longitude and latitude ($260^\circ, -22^\circ$), the foreground extinction is expected to be small and indeed we have previously adopted $E(B - V) = 0.03$ mag for this direction (cf. Figure 2), and no interstellar material has yet been identified within Carina. A secondary advantage of the Wesenheit magnitude is that it also largely removes the dependence of period on temperature at fixed luminosity, resulting from the finite width of the instability strip: loci of constant period on the observational CMD are nearly parallel to the reddening vector (see, e.g., Stetson et al. 1998). The Wesenheit magnitude therefore produces a narrower period–apparent magnitude relation one based on simple $B$- or $V$-band magnitudes. The data plotted in Figure 6 show the $BV$ PW relations for Carina RRLs (left panel) and ACs (right panel). The solid lines show the predicted PW relations at constant mass and metallicity according to pulsational models for RRLs computed by Di Criscienzo et al. (2004) and for ACs computed by Marconi et al. (2004). The dotted lines display the intrinsic dispersion of the above relations. The left panel shows the Wesenheit magnitude versus the log $P_{F}^{W}$. This parameter depends on the period (RR_c variables were fundamentalized), the mass, and the metallicity according to the following relation:

$$
\log P_{F}^{W} = \log P_{F} + 0.54 \log M/M_{\odot} + 0.03 \log Z,
$$

where the symbols have their usual meaning (for more details, see Di Criscienzo et al. 2004). Adopting the iron abundance and the mean mass indicated in the left panel of Figure 6, we found a true distance modulus of $\mu_{0} = 20.09 \pm 0.07$ (intrinsic) $\pm 0.1$ (systematic) mag. The intrinsic error estimate accounts for uncertainties in the mean RRL magnitudes, the photometric zero points, and the intrinsic dispersion of the theoretical PW diagram. The systematic errors account for uncertainties in the pulsational models. The peculiar nature of the above variables is further indicated by the fact that they exhibit Wesenheit magnitudes that are, at fixed period, systematically brighter than typical RRLs. The difference is at the 3σ level, on average.

The empirical scenario becomes even more puzzling if we consider the PW relations of ACs. Two (V14 and V158) out of the four peculiar variables have Wesenheit magnitudes relatively close to the AC PW relation for the stellar mass and chemical composition indicated (Marconi et al. 2004), while the other two are on average 6σ fainter. However, the spread in magnitude of the AC PW relation is significantly larger than for RRL ($0.2$ versus $0.09$ mag), thus suggesting that this is not a robust diagnostic of the evolutionary status of intermediate-age helium-burning variable stars. This evidence is further supported by the fact that the candidate short-period classical Cepheids (brighter ACs) seem to obey the same PW relation. The width of the observed AC PW relation is mainly due to a dispersion in mass and partially to evolutionary effects and mode identification.

Finally, we decided to compare in more detail the Carina evolved variable stars with their counterparts in Fornax, even if the census of evolved variable stars in this system is still far from being complete (Bersier & Wood 2002). To this end, the apparent magnitudes of RRLs in Fornax were rescaled to the apparent magnitude of RRLs in Carina assuming a true distance modulus of $\mu_{0} = 20.62$ mag and a reddening of $E(B - V) = 0.025$ mag (Bersier 2000; Bersier & Wood 2002). The data plotted in the top left panel of Figure 7 show that the distribution of evolved variables in Fornax is significantly different from that observed in Carina. Canonical RRLs in Carina are separated from canonical ACs by almost 1 mag, while in Fornax there is an almost continuous transition between RRLs, ACs, and P2Cs. The lack of a clear separation between RRLs and ACs is suspicious, since evolutionary models predict a steady increase in luminosity when moving from the ZAHB to the intermediate-age helium-burning sequence and a minimum gap of $\approx 0.8$ mag between the ZAHB and the evolved variable magnitude level is
Figure 6. $BV$ PW relations for RRLs (left) and ACs (right) in Carina. The symbols are the same as in Figure 1. The solid lines show the predicted behavior at constant mass and metallicity according to pulsational models for RRLs by Di Criscienzo et al. (2004) and for ACs by Marconi et al. (2004). The dotted lines depict the intrinsic dispersion of the above relations. (A color version of this figure is available in the online journal.)

expected even in the most metal-poor regime (see Figure 7 in Caputo et al. 2004 for details). However, a spread in metallicity could cause a spread in visual magnitude, and in turn smear out the separation between RRLs and ACs.

To further investigate this interesting point, we performed the same comparison in the $V$-magnitude logarithmic period plane. Data plotted in the bottom panels show that Carina RRLs and ACs are well separated. On the other hand, the Fornax ACs split into two different groups: the short-period group ($\log P \leq -0.1$) overlaps with RRLs, while the long-period group ($\log P > -0.1$) is, at fixed period, brighter than the P2Cs. The long-period group has a canonical behavior, since ACs are approximately a factor of three more massive than P2C and, at fixed period, they should be brighter. The short-period group appears peculiar, since their periods (0.44–0.56 days) cover the same period range as the evolved RRLs (see the discussion concerning the nature of the two peculiar RRL candidates in Carina). This preliminary evidence, if supported by new and more detailed investigations on Fornax evolved variables, might explain the peculiar peak in the period distribution of Fornax ACs.

5. CONCLUSIONS AND FINAL REMARKS

We have presented a new census and analysis of helium-burning variable stars in the Carina dSph. Their observed properties have been compared with theoretical predictions to constrain their evolutionary and pulsational status and their distance. The main results of our analysis are the following.

1. We have identified eight new RRLs that are found to share the same general properties as the whole sample. In particular, they agree quite well with the predicted ZAHB and instability strip for a metallicity ranging from $[\text{Fe/H}] = -1.79$ to $-1.49$ dex. The RRL period distribution shows a remarkable similarity with the RRLs in Leo I, Fornax, and the LMC. Using the theoretical $BV$ PW relation for the metallicity and the stellar mass inferred from the comparison with the theoretical ZAHB, we found a true distance modulus $\mu_0 = 20.09 \pm 0.07 \pm 0.1$ mag that agrees quite well with previous estimates in the literature (Pietrzyński et al. 2003, 2009).

2. We have identified four new ACs with periods around one day. The comparison with evolutionary predictions suggests that the stellar mass of these objects ranges from $\sim 2.0$ to $\sim 2.4 M_\odot$. The current empirical evidence indicates that the bright tail of the distribution might be short-period classical Cepheids. This means that Carina and Leo I (Fiorentino et al. 2012) are good laboratories to study the transition from intermediate-mass stars characterized by quiescent central helium burning ($M/M_\odot > 2.2$), producing classical
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Figure 7. Top left: V, V−I CMD of Fornax evolved variable stars. The RRLs, ACs, and P2Cs were plotted using different symbols. Their apparent magnitudes were rescaled to Carina assuming for Fornax a true distance modulus of $\mu_0 = 20.65$ mag and a reddening of $E(B-V) = 0.025$ mag (Bersier 2000; Bersier & Wood 2002). The periods of FOs were fundamentalized. Top right: same as the left, but for Carina evolved variable stars and in the V, B−V CMD. Bottom left: same as the top left, but in V-magnitude–logarithmic period plane. Bottom right: same as the left, but for Carina variable stars.

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

Cepheids, to those burning helium in an electron-degenerate core ($M/M_\odot < 2.2$), producing ACs. We also found that the period distribution of ACs is quite different among nearby dwarf galaxies. This occurrence might indicate that the star formation history in the last few gigayears differs strongly from system to system. This finding supports recent results by Fiorentino et al. (2012).

3. We have investigated the properties of four already known variables that appear to be peculiar in the CMD, since their mean magnitudes are intermediate between RRLs and ACs. The comparison between predicted and observed periods indicates that they cannot be of the BL Her type, i.e., low-mass ($M/M_\odot \approx 0.50–0.60$) HB stars evolving from the blue (hot) to the red (cool) region of the CMD and crossing the instability strip at luminosities brighter than typical RRLs. We found that their periods are 30% shorter than predicted by pulsation models (typically in the range of 0.7–1.3 days). According to the Bailey diagram, two (V14 and V149) out of the four appear to be candidate ACs, whereas the variables V158 and V182 might be peculiar RRLs as already suggested by Monelli et al. (2003). It is also interesting to note that in the Bailey diagram the variable V158 is located very close to the prototype—RRLYR-02792—of a new group of variable stars recently discovered by Pietrzyński et al. (2012) and investigated by Smolec et al. (2013). This new group of variables mimics the properties of typical RRLs, but they have a mass that is a factor of two smaller. This suggests that they are intermediate-mass stars that have experienced violent mass-loss events.

4. A firm quantitative analysis of evolved variable stars in nearby dwarfs requires not only homogenous and accurate multiband photometry, but also time-series data that cover a broad time interval. Only these data can open the path to a thorough spectroscopic investigation that can allow us to investigate how the environment, the chemical composition, and the star formation history affect their evolutionary and pulsation properties.

The above findings further emphasize the key role that evolved variable stars in dSphs can play to constrain the evolutionary and pulsation properties of low- and intermediate-mass stars. The similarity of the old stellar populations traced by RRLs in nearby stellar systems indicates that the early star formation in these systems was quite homogeneous. On the other hand, the difference in the intermediate-age populations,
as traced by ACs, suggests that recent star formation events in these systems do differ strongly from system to system. It goes without saying that detailed investigations of the pulsational properties of evolved variables in nearby isolated systems can shed new light on their individual properties and on their environmental influences.

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