Variable stars in Local Group Galaxies - II. Sculptor dSph

C. E. Martínez-Vázquez1,2,⋆ P. B. Stetson3, M. Monelli1,2, E. J. Bernard4, G. Fiorentino5, C. Gallart1,2, G. Bono6,7, S. Cassisi8, M. Dall’Ora9, I. Ferraro7, G. Iannicola7, and A. R. Walker10

1 Instituto de Astrofísica de Canarias (IAC), E-38205 La Laguna, Tenerife, Spain
2 Universidad de La Laguna (ULL), Dpto. Astrofísica, E-38206 La Laguna, Tenerife, Spain
3 Herzberg Astronomy and Astrophysics, National Research Council Canada, 5071 West Saanich Road, Victoria, BC V9E 2E7, Canada
4 Laboratoire Lagrange, Observatoire de la Côte d’Azur, 06304 Nice Cedex 4, France
5 INAF-Osservatorio Astronomico di Bologna, via Ranzani 1, 40127, Bologna, Italy
6 Dipartimento di Fisica, Università di Roma Tor Vergata, Via della Ricerca Scientifica 1, 00133 Roma, Italy
7 INAF-Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monteporzio Catone, Italy
8 INAF-Osservatorio Astronomico di Teramo, Via M. Maggini, 64100 Teramo, Italy
9 INAF-Osservatorio Astronomico di Capodimonte, Via Moiariello 16, 80131 Napoli, Italy
10 Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, Casilla 603, La Serena, Chile

Accepted 2016 July 28. Received 2016 July 28; in original form 2016 March 31

ABSTRACT

We present the identification of 634 variable stars in the Milky Way dSph satellite Sculptor based on archival ground-based optical observations spanning ~24 years and covering ~2.5 deg². We employed the same methodologies as the “Homogeneous Photometry” series published by Stetson. In particular, we have identified and characterized one of the largest (536) RR Lyrae samples so far in a Milky Way dSph satellite. We have also detected four Anomalous Cepheids, 23 SX Phoenicis stars, five eclipsing binaries, three field variable stars, three peculiar variable stars located above the horizontal branch – near to the locus of BL Herculis – that we are unable to classify properly. Additionally we identify 37 Long Period Variables plus 23 probable variable stars, for which the current data do not allow us to determine the period. We report positions and finding charts for all the variable stars, and basic properties (period, amplitude, mean magnitude) and light curves for 574 of them. We discuss the properties of the RR Lyrae stars in the Bailey diagram, which supports the coexistence of subpopulations with different chemical compositions. We estimate the mean mass of Anomalous Cepheids (∼1.5M⊙) and SX Phoenicis stars (∼1M⊙). We discuss in detail the nature of the former. The connections between the properties of the different families of variable stars are discussed in the context of the star formation history of the Sculptor dSph galaxy.

Key words: stars: variables: general – galaxies: evolution – galaxies: individual: Sculptor dSph – Local Group – galaxies: stellar content

1 INTRODUCTION

Pulsating variable stars are powerful tools to investigate the evolution of their host galaxy, as they trace the age and the metallicity of the parent population. Most importantly, the coexistence of different types of variable stars provides, thanks to their pulsational properties, independent constraints not only on the star formation history and the chemical evolution, but also on the distance of the system. Indeed, because pulsations occur at specific evolutionary stages that depend on the stellar mass, variable stars trace the spatial distribution of stellar populations of given ages. Therefore they can be used as markers of spatial trends across the galaxy under examination (e.g., Gallart et al. 2004). Moreover, even the range of pulsational properties among individual stars of a particular type can trace some differences in the age and metallicity of the corresponding population (e.g., Bernard et al. 2008; Martínez-Vázquez et al. 2015).

This paper focuses on the variable-star content of the Local Group dwarf spheroidal (dSph) Sculptor. Sculp-
tor is one of the “classical” Milky Way dSph satellites. After the Magellanic Clouds, it was the first to be discovered along with Fornax (Shapley 1938). Sculptor’s stellar content has been investigated in a large number of papers, using different techniques. Large scale and/or deep photometric surveys provided colour-magnitude diagrams (CMDs) showing an extended horizontal branch (HB; Majewski et al. 1999; Hurley-Keller et al. 1999; Harbeck et al. 2001), and a wide colour spread of the red giant branch first mentioned by Da Costa (1984). While it is well established that Sculptor is composed of a predominantly old population (Monkiewicz et al. 1999; de Boer et al. 2011), it clearly presents some age spread (Tolstoy et al. 2004; de Boer et al. 2012). The chemical enrichment history of Sculptor has been investigated through spectroscopy of its RGB (Tolstoy et al. 2004; Kirby et al. 2009; Starkenburg et al. 2013; Skúladóttir et al. 2015) and HB stars (Clementini et al. 2005), revealing a large range in metallicity, of the order of 1 dex. In Martínez-Vázquez et al. (2015) (hereafter Paper I), based on the pulsational properties of RR Lyrae (RRL) stars, we showed that a similar metallicity spread (∼0.8 dex) was already in place at an early epoch (>10 Gyr), imprinted in the parent population that we observe today as RRL stars.

The first investigation of the variable-star content in Sculptor dates back to the work by Baade & Hubble (1939) and Thackeray (1950). However it was not until van Agt (1978) that a conspicuous population of 602 candidate variable stars was discovered and periods for 64 of them were provided.

The most complete catalogue of variable stars (in terms of providing pulsational properties) in Sculptor is that of Kalluzny et al. (1995). They investigated the central region of the Sculptor dSph (∼15′×15′) as a side-program of the OGLE I project. They identified 231 variable stars that were classified as 226 RRL, 3 Anomalous Cepheids (AC), and 2 long period variable (LPV) stars. Their properties are consistent with a metal-poor population ([Fe/H] < −1.7).

A spectroscopic follow-up made by Clementini et al. (2005) confirmed this result through low resolution (R=800) spectroscopy of 107 variables using the ∆S method. In particular, they found that the metallicity peaks at [Fe/H] ∼ −1.8.

In Paper I we reported on the detection of a large metallicity spread and spatial gradients within the population of Sculptor’s RRL star population. In this work we present the full catalog of variable stars detected in this galaxy employing the same methodologies as the “Homogeneous Photometry” series (Stetson et al. 1998a; Stetson 2000; Stetson et al. 2003; Stetson 2005; Stetson et al. 2005, 2014). In § 2 we present the extensive data set of 4,404 images used in this analysis. In § 3 we discuss the variable-star detection and classification. We later discuss in detail different families of variable stars: RRL stars (§ 4), AC (§ 5), SX Phoenicis (SX Ph);§ 6), and other groups (peculiar, binaries, long period and probable variable stars, § 7). In § 8 we discuss the properties of the old populations of Sculptor, analysing its RRL stars in detail. A summary of our conclusions (§ 9) closes the paper. We highlight that in the online version of the paper we provide full details on all the variable stars discussed: time series photometry, light curves, mean photometric and pulsational properties and finding charts.

2 PHOTOMETRIC DATA SET

The photometric data set used for this study consists of 5,149 individual CCD images obtained during 21 observing runs between 1987 October and 2011 August (i.e., over nearly 24 years). It covers an area over the sky of ∼4.7 deg² centred on the Sculptor dSph galaxy. However, only 4,404 images (within ∼2.5 deg²) were calibrated photometrically, while the area with a significant number of epochs for the variability study is further reduced to ∼2.0 deg². These data were acquired with a variety of cameras on a number of different telescopes at the European Southern Observatory, Cerro Tololo Interamerican Observatory, and Las Campanas Observatory as detailed in the accompanying Table 1. For each of the observing runs the table specifies the beginning and ending dates of the run (although it is not necessarily true that Sculptor was observed on all the nights during any given run). Table 1 also identifies the telescope and the detector system used for each of the runs, as well as the number of separate exposures obtained in the B, V, R, I, and “other” filter passbands. The “multiplex” column indicates the number of individual disjoint CCDs in each instrument. For instance, the ESO/MPI Wide Field Imager used during run, “wfi33”, has eight adjacent CCDs; the six individual exposures obtained during this run produced 6×8 = 48 separate CCD images that contributed to our overall total of 5,149. However, no individual star was contained in more than six of the 48 images from that run, since the different CCDs map to non-overlapping areas on the sky. Similarly, the SUSI camera on the ESO NTT telescope had two adjacent CCDs, so the 45 individual exposures obtained during run 4,“susi9510,” comprised 90 separate CCD images.

All 5,149 CCD images were processed to produce instrumental magnitudes for individual stars using the DAOPHOT/ALLSTAR/ALLFRAME package of programs (e.g., Stetson 1987, 1994); those which could be were then calibrated using the protocols described by Stetson (2000, 2005). These methods have by now been used in a large number of refereed papers by members of our collaboration, and more elaborate details are not needed here. The few exposures that we have designated as being obtained with “other” filters in Table 1 are not used photometrically here, but they were included in the ALLFRAME reductions to exploit the information they could provide toward the completeness of the star list and the quality of the astrometry.

From two of the observing runs, 7 = wfi36 and 21 = leel, we inferred at least some magnitudes on the standard Landolt photometric system from observations that were obtained in non-standard filters. In particular, in run 7 (wfi36) 13 exposures were obtained using the standard Wide-Field Imager “B” filter and 13 were obtained with the standard “R” filter. However, an additional nine exposures were obtained using a DDO51 (magnesium hydride) filter (MB#516/16_ESO071, central wavelength 516.5 nm, width 16.2 nm) and another ten were obtained with a Washington M filter. (In a quick search on the internet we were unable to locate the filter properties for the ESO/WFI M filter, but the defining M filter has central wavelength 508.5 nm and width 105.0 nm: Cantera 1976) By simple trial we learned that, allowing for quadractic colour terms in the calibrating transformation equations, we were able to use these filters to predict Landolt-system V-band magnitudes with a star-to-
star reliability $\sigma \sim 0.05$ mag from the DDO51 magnitudes, and $\sim 0.02$ mag from the $M$ magnitudes. In our opinion, this precision is good enough to use these observations to help define the variable-star light curves, but we would hesitate to use these in calibrating our best CMD for Sculptor.

Similarly, in the run we have identified as “lecl” (our number 21), the observations were made in the Strömgren $b$ and $y$ filters, and in a Calcium $H$+$K$ filter. (We were unable to locate the filter characteristics of the Ca filter then in use with the CTIO 4.0m Mosaic Camera, but the filter used on the smaller CTIO telescopes is described as having central wavelength 396.0 nm and width 10.0 nm.) We made no attempt to calibrate the Ca observations photometrically, but we found that with quadratic colour coefficients $b$ could be transformed to $B$ with a star-to-star reliability of 0.03 mag, and $y$ transformed to $V$ with a reliability of 0.02 mag. Again, we feel that these are good enough to employ for the variable-star light curves, but would hesitate to include them in the CMD.

The individual $B$, $V$ and $I$ measurements for all of the detected variables in the calibrated field of Sculptor are listed in Table 2. They were named with the prefix “scl- CEMV” (which refers to the name of the galaxy and the current work), followed by a number which increases in order of increasing right ascension.

### 3 VARIABLE STAR IDENTIFICATION AND COLOUR-MAGNITUDE DIAGRAM

We performed the variability search over the full data set, using an updated version of the Welch-Stetson variability index (Welch & Stetson 1993; Stetson 1996) which identifies candidate variable stars on the basis of our multi-band photometry. From the list of 663 variable candidates, we have identified 574 as actual variable stars (i.e., we can derive periods, amplitudes and mean magnitudes in $BVI$), 60 as likely variable stars, and 29 as non-variable stars. Figure 1 presents the $(V, B-V)$ CMD of Sculptor, with the detected variable stars highlighted. Most of them belong to Sculptor and are located in the instability strip (IS), spanning a wide range of luminosities. In particular, from the brightest to the faintest, we identified four A0s (red circles), three peculiar HB variable stars (orange squares, similar variables were detected in Coppola et al. 2013), 536 RRL stars (blue star symbols), five eclipsing binaries (magenta diamonds) and 23 SX Phe stars (green bowties). Moreover, a sample of 31 probable LPVs (brown triangles) are found near the tip of the Sculptor’s giant branch, plus six more LPVs are spread over the CMD. The three grey open circles mark the position of variable stars that we believe are located along the line of sight of the Sculptor dSph with the other one is a possible field RRc.

We derived pulsational properties for all the variable stars using our $BVI$-Johnson/Cousins photometry. An initial period search was carried out using a simple string-length algorithm (Stetson et al. 1999b). The intensity-averaged magnitudes and amplitudes of the mono-periodic light curves were obtained by fitting the light curves with a set of templates partly based on the set of Layden et al. (1999) following the method described in Bernard et al. (2009).

Fig. 2 presents the spatial distribution of the detected variable stars (inside of $\sim 2$ deg$^2$), superimposed on the photometric.
Table 2. Photometry of the variable stars in Sculptor dSph.

| MHJD$^a$ | $B$ | $\sigma_B$ | MHJD$^a$ | $V$ | $\sigma_V$ | MHJD$^a$ | $I$ | $\sigma_I$ |
|----------|-----|------------|----------|-----|------------|----------|-----|------------|
| 54734.613281 | 19.636 | 0.011 | 54734.609375 | 19.429 | 0.014 | 54734.675000 | 19.460 | 0.014 |
| 54734.656250 | 19.809 | 0.017 | 54734.660156 | 19.592 | 0.013 | 54734.698438 | 19.475 | 0.038 |
| 54734.718750 | 20.076 | 0.026 | 54734.710938 | 19.800 | 0.026 | 54734.902444 | 19.403 | 0.034 |
| 54734.520000 | 20.314 | 0.311 | 54734.777344 | 19.920 | 0.010 | 54734.914082 | 19.806 | 0.363 |
| 54734.824219 | 20.536 | 0.011 | 54735.328125 | 20.238 | 0.016 | 54735.726562 | 20.512 | 0.039 |
| 54735.707031 | 20.681 | 0.014 | 54736.550781 | 20.371 | 0.020 | 54736.730469 | 19.450 | 0.058 |
| 54736.54888 | 20.794 | 0.020 | 54736.742188 | 19.536 | 0.010 | 54736.875000 | 19.450 | 0.058 |
| 54736.746094 | 19.746 | 0.010 | 54736.816406 | 19.732 | 0.012 | 54736.859375 | 19.921 | 0.020 |
| 54737.707031 | 20.681 | 0.014 | 54738.550781 | 20.371 | 0.020 | 54738.730469 | 19.450 | 0.058 |
| 54738.54888 | 20.794 | 0.020 | 54738.742188 | 19.536 | 0.010 | 54738.875000 | 19.450 | 0.058 |

$^a$ Modified Heliocentric Julian Date of mid-exposure: HJD - 2,400,000

(This table is a portion of its entirely form which will be available in the online journal.)

Table 3. Summary of the detected variable stars inside $\sim 2$ deg$^2$ centred on Sculptor dSph.

| Type of variable | Total | Fundamental Mode | First Overtone | Second Overtone | Double Mode |
|------------------|-------|------------------|----------------|----------------|-------------|
| ACTUAL           |       |                  |                |                |             |
| AC               | 4     | 4                | 0              | 0              |             |
| RR Lyrae (RRL)   | 536   | 289              | 197            | 0              | 50          |
| SX Phe           | 23    | $^*$             | $^*$           | $^*$           | 23          |
| Eclipsing binary | 5     |                  |                |                |             |
| Field            | $2^a$ + $1^b$ |                  |                |                |             |
| Peculiar HB      | $^c$  |                  |                |                |             |
| LIKELY           |       |                  |                |                |             |
| Long-Period Variable (LPV) | $31^a + 6^b$ |                |                |                |             |

$^a$ See § 6 for a detailed discussion of the classification mode.
$^b$ Compatible with being field $\delta$ Scuti.
$^c$ In § 7.1, the reader have the explanation of why these stars are considered peculiars.
$^d$ LPV stars near the tip of the red-giant branch.
$^e$ LPV stars out of the tip of the red-giant branch.
$^f$ Variable stars for which a proper light curve and a reliable classification is difficult to obtain.
Figure 1. Colour-magnitude diagram of Sculptor with the identification of the all detected variable stars. Green bowtie symbols represent the SX Phoenicis stars. Magenta diamonds are the probable eclipsing binaries. Blue stars are the RR Lyrae stars. Orange square are the three peculiar variables detected in Sculptor. Red circles are anomalous cepheids. Grey open circles are probable eclipsing binaries. Blue stars are the RR Lyrae stars. The edges of the Instability Strip are those presented in Fiorentino et al. (2006) extended to low luminosities (light grey lines).

...tometrically calibrated part of the field. The solid ellipses mark the core and tidal radii (the latter is only partially visible in the south-west corner). As the present database consists of a large selection of observations collected from different projects, the number of phase points is not constant over the field and increases towards the centre of Sculptor. The dashed ellipse marks the area corresponding to the elliptical radius (equivalent distance along the semi-major axis) of 27.5', where we estimate the completeness to be homogeneous (discussed below) in the variable star detection, at least in the magnitude and period range typical of RRL stars. The inner square marks the area covered by the Kaluzny et al. (1995) RRL stars. It is worth mentioning that the covered area is nearly similar to that observed by van Agt (1978). He identified 95 percent of his candidates (602) inside of our current area. However, van Agt (1978) provided periods only for a few (64). On the other hand, we note that, given the large tidal radius of Sculptor, many RRL stars are likely still to be discovered.

Focusing on the homogeneity of the sample, Fig. 3 shows the number of phase points for each identified RRL star as a function of the elliptical radius for the $B$, $V$, and $I$ filters (blue, green, and red dots, respectively). The plot shows that the $V$ band has the largest number of points in the central regions (greater than 170 for elliptical radius < 5' and lower than 100 for elliptical radius > 5' and < 20'). The number of observations above 50 out to 27.5'. The number of $I$ band points is relatively constant (~15) out to the same distance and then slowly declines. Given the large number of independent observing runs and the large time baseline, we are confident that we have a high and relatively homogeneous completeness for detection of RRL stars out to 27.5'. This is shown as a dashed ellipse in Fig. 2.

4 RR LYRAE STARS

4.1 Classification

Based on the pulsational properties, light curves (LCs), and positions on the CMD, we identify 536 RRL stars. Of these, 390 were flagged by van Agt (1978) as candidate variables (but periods were provided for only 53 of them), and 65 were discovered by Kaluzny et al. (1995); the remaining 81 are new discoveries. Kaluzny et al. (1995) presented the analysis of 226 RRLs, although we show in § 4.4 that 10 of these are probably not RRLs. Here we provide the pulsation parameters (period, mean magnitude and amplitude) for 320 RRLs for the first time.

We sub-classify the sample of RRL stars as: i) 289 RRab, pulsating in the fundamental mode; 20 of them are suspected Blazhko stars, (Blazhko 1907); ii) 197 RRc, pulsating in the first-overtone mode; and iii) 50 possible multimode RRd stars, pulsating in both modes simultaneously. The classification of the latter was uncertain in some cases due to their relatively noisy or (very) poor light curves.

The LCs of all the RRL stars are presented in Fig. 4 and their basic properties (position, period, amplitude and mean magnitude in $B$, $V$, and $I$ Johnson/Cousins bands) are detailed in Table 4. The mean (maximum) number of points in the light-curves of the RRL stars are 52, 83, and 21 (115, 182 and 28) respectively in $B$, $V$, and $I$.

Fig. 1 shows that a few RRLs stars appear far from their expected location, presumably due to the poor coverage of the LC causing erroneous mean magnitudes in the different photometric bands. To avoid these outliers, following the procedure of Paper I we selected those (520) with mean $V$ magnitude within 2.5σ from the average of the population (20.13 mag); these define the full sample that will be adopted in the analysis throughout the paper. On the other hand, a more restrictive selection was performed based on the quality of the phase coverage of the photometry over the entire pulsation cycle based on visual inspection of the individual light curves and the period-magnitude diagram, resulting in the sample of 290 RRL stars that we defined as the clean sample (tinted background in Fig. 4). In summary,
we have identified 276 (167) RRab + 195 (123) RRc + 49 (0) candidate RRd variables in the full (clean) sample.

4.2 Periods and Amplitudes

Fig. 5 presents a comparison between the amplitudes in the $B$ vs $V$ (upper panel) and $V$ vs $I$ bands (lower panel) for the clean sample of RRLs. We used them to perform a linear fit. The red symbols show the outliers rejected with a 3-$\sigma$ clipping selection and not used in the linear fit. The derived values for the amplitude ratios, given by the slopes of the red lines, are $1.229\pm0.002$ ($A_B/A_V$) and $1.483\pm0.003$ ($A_V/A_I$). These values are in good agreement both with theoretical predictions (Bono et al. 1997b) and with observations of RRLs in Galactic globular clusters (Di Criscienzo et al. 2011). This supports the accuracy of our derived pulsation properties for Sculptor’s RRL stars.

In Fig. 6, we present the Bailey (period-amplitude) diagrams (top panels) and the period distributions (bottom panels) for the full (left panels) and the clean (right panels) samples of RRL stars. Galactic globular clusters (GGCs) with RRLs can be classified into two groups (Oosterhoff 1939), according to the mean period of their RRab stars (Oo-I: 0.55 d, Oo-II: 0.64 d) and RRc stars (Oo-I: 0.32 d, Oo-II: 0.37 d). In the case of Sculptor, we find that the mean periods of the RRab and RRc stars are: $\langle P_{ab}\rangle=0.602\pm0.004$ d ($\sigma=0.08$) and $\langle P_{c}\rangle=0.340\pm0.003$ d ($\sigma=0.04$) for the full sample, and $\langle P_{ab}\rangle=0.609\pm0.006$ d ($\sigma=0.07$) and $\langle P_{c}\rangle=0.345\pm0.003$ d ($\sigma=0.03$) for the clean sample, thus placing Sculptor squarely in the so-called Oosterhoff gap (see Fig. 5 from Catelan 2009). Therefore, on the basis of the mean period of the RRab (and RRc) stars, Sculptor could be classified as an Oo-intermediate system, as is normal among Local Group dwarf galaxies (Kuehn et al. 2008; Bernard et al. 2009, 2010;

---

Figure 2. Spatial distribution of the detected variable stars in and around the Sculptor dSph based on our current photometry database. Static stars are represented by gray dots. The RRL stars, AC, SX Phe, eclipsing binary, field variable stars, LPV, the three peculiar variables and the probable variable are shown, with the same symbols as in Fig. 1. The innermost ellipse represents the core ($r_c=5.8$ arcmin; Mateo 1998). The outermost ellipse (of which only a small arc appears in the south-west corner) corresponds to the tidal radius ($r_t=76.5$ arcmin; Irwin & Hatzidimitriou 1995). The dashed ellipse is the radius ($\sim27.5$ arcmin) from which the number of points per light curve of RRL is lower than 40 in the $B$ and $V$ bands. The field of view of the study presented in Kaluzny et al. (1995) ($15'\times15'$) is represented by the inner square. This field ($\sim2$ deg$^2$) covers the area where van Agt (1978) detected the $95$ percents of his candidates.
also provides constraints on the old galaxy stellar population: (i) The fraction of RRc stars in the full sample, \( f_{RRc} = \frac{N_{RRc}}{N_{total}} = 0.41 \) (for the clean sample of RRLs) in agreement with Kaluzny et al. 1995, is relatively higher than in the rest of the other dSph galaxies (see Table 6 of Garofalo et al. 2013; Stetson et al. 2014; Cusano et al. 2015; Ordoñez & Sarajedini 2016).

Another tool used to classify GGCs in Oo-type is the Bailey diagram. Oo-I and Oo-II clusters commonly follow the two distinct curves shown in Fig. 6 (top panels) and defined in Cacciari et al. (2005). The RRLs in Sculptor present a significantly wider distribution than either Oo- or I-type. In fact, for each given amplitude stars cover a large period range around both Oo-lines, with a minor fraction populating the intermediate region. It is clear that an Oo-intermediate classification does not necessarily mean that stars are predominantly between the Oo-I and Oo-II loci; the distribution also extends to and beyond those loci. Consequently, a classification based only on the mean periods for RRab-type (and/or RRc-type) stars is clearly insufficient to characterize the range of properties among the RRL stars in Sculptor.

As we demonstrated in Paper I, the RRL stars show a spread in \( V \) magnitude of \( \sim 0.35 \) mag, significantly larger than the typical uncertainties in the mean magnitude (\( \sigma = 0.03 \) mag), and larger than the spread expected from the simple ageing of a mono-metallic population. We also show that the vast majority of the RRLs span a significant metallicity spread of \( \sim 0.8 \) dex, bracketed between \( \sim 2.3 \) and \( \sim 1.5 \) dex. When splitting the sample of RRLs at \( \langle V_{RRL} \rangle = 20.155 \) mag, thus defining a bright (\( B \)) and a faint (\( F \)) sample, the spread in metallicity is reflected in the two groups. In Martínez-Vázquez et al. (2016, Paper II), we show that the \( B \) sample is, on average, more metal-poor (\( \langle [Fe/H]_B \rangle = -2.03 \) ) than the \( F \) stars (\( \langle [Fe/H]_F \rangle = -1.74 \) ).

The Bailey diagram (Fig. 6) shows the \( B \) and \( F \) samples with blue and orange symbols, respectively. Interestingly, stars selected in the CMD are clearly separated in the Bailey diagram as well: \( B \)-metal-poor RRL stars are closer to the Oo-II sequence, while \( F \), more metal-rich RRL stars follow a distribution similar to an Oo-I system. This is also reflected in the mean periods of the \( B \) and \( F \) groups, which are similar to those defining the OoI and OoII systems, respectively (see Table 5). This supports the conclusion that simplified systems such as Sculptor, characterized by an important chemical evolution at an early epoch, the Oosterhoff classification must be treated cautiously, and that the mean period alone does not provide a full characterization of the target stellar sample.

Fig. 6 also provides constraints on the old galaxy stellar population:
(ii) The shortest period found for the RRab stars is 0.48230141 days (with $A_V = 1.280$ mag, star: scl-CEMV397). The lack of High Amplitude Short Period fundamental RRL stars (HASP; $A_V \geq 0.75$ mag, $P \leq 0.48$ (log $P \leq -0.32$) Fiorentino et al. 2015a) suggests that Sculptor does not host a significant metal-rich ([Fe/H] $\geq -1.5$) old stellar population, as has been confirmed in our analysis of Paper I.

### 4.3 Distance to Sculptor from the RRL stars

In Paper I we estimated the true distance modulus from the full sample as well as the clean sample of RRLs. The distance estimates to Sculptor were derived using the three different subsamples (RRab, RRc, and RRab+RRc fundamentalized). The use of three photometric bands and two period-Wesenheit relations (PWR) in $V$, $B$–$V$, and $V$, $B$–$I$ (these are reddening-free and are only minimally affected by the metal content, Marconi et al. 2015) allowed us to provide a very accurate distance. Table 3 in Paper I summarizes the individual distance moduli obtained applying different calibrations. The errors on individual distance moduli are never larger than 0.03 mag in both $B$ and $I$ bands.

Finally, we adopted a mean true distance modulus ($\mu$) of 19.62 mag with $\sigma = 0.04$ (see § 4 of Paper I for more details). This estimate is in good agreement with values based on other reliable indicators (Rizzi 2002; Pietrzynski et al. 2008).

---

**Table 5.** Mean period of the Bt and Ft groups for both full and clean RRL samples.

|          | $(P_{ab})$     | $(P_c)$     |
|----------|----------------|-------------|
| **FAINT (Ft)** |                |             |
| full     | $0.560 \pm 0.004$ d ($\sigma = 0.05$) | $0.325 \pm 0.007$ d ($\sigma = 0.03$) |
| clean    | $0.560 \pm 0.006$ d ($\sigma = 0.05$) | $0.322 \pm 0.003$ d ($\sigma = 0.03$) |
| **BRIGHT (Bt)** |                |             |
| full     | $0.639 \pm 0.006$ d ($\sigma = 0.08$) | $0.356 \pm 0.006$ d ($\sigma = 0.03$) |
| clean    | $0.647 \pm 0.007$ d ($\sigma = 0.07$) | $0.362 \pm 0.004$ d ($\sigma = 0.03$) |

---

**Figure 3.** Number of phase points for each identified RRL star as a function of the elliptical radius for the $B$ (blue dots), $V$ (green dots), and $I$ (red dots) filters. Asterisks represent the mean value of each of them every 5’ (with exception of the last one that covers 10’, from 55’ to 65’).

**Figure 4.** Sample of light curves of the RRL stars in the $B$ (blue), $V$ (green) and $I$ (red) bands, phased with the period in days given in the lower right-hand corner of each panel. The name of the variable is given in the left-hand corner of each panel. Open symbols show the bad data points, i.e., with errors larger than 3\(\sigma\) above the mean error of a given star; these were not used in the calculation of the period and mean magnitudes. For clarity, the $B$ and $I$ light curves have been shifted by 0.4 mag downward and upward, respectively. Tinted backgrounds mark those RRL stars classified as members of the clean sample. All light curves are available as Supporting Information with the online version of the paper.
Figure 5. $B$-amplitude versus $V$-amplitude diagram (top) and $V$-amplitude versus $I$-amplitude diagram (bottom). The slopes obtained here are in good agreement with those predicted for the RRLs of the Galactic GCs (Di Criscienzo et al. 2011). In both cases, the linear fit was performed through the clean sample of RRLs in Sculptor, applying least squares fit and a 3σ clipping.

4.4 Comparison with the Kaluzny catalogue

Kaluzny et al. (1995) published a list of 226 RRL stars covering the central 15′×15′ of Sculptor. We matched the two catalogues in order to check the consistency of the derived pulsational properties. 216 of Kaluzny’s RRL stars are included in our sample. It is worth mentioning that the work of Kaluzny et al. (1995) includes 226 sources, but we realized that: i) 5 of these stars were duplicated (K1926=K406, K2558=K2058, K2559=K2059, K3345=K1439, K4233=K2423); ii) one (K403) is not variable in our photometry; iii) the variability of K5081 is not certain based on our data; iv) one more star is possibly misclassified, and we catalogue it as probable eclipsing binary (K3710, Clementini et al. 2005); v) for two of the Kaluzny’s stars (K737, K4780) we are not able to derive a reliable period. The 3 AC (K3302-V25, K734-V119, and K5689) and the 2 LPV (K274 and K687) analysed in Kaluzny et al. (1995) were also found in our catalogue so, in total, we matched 224 variable stars (216 RRL + 3 AC + 2 LPV + 1 eclipsing binary + 2 probable variable stars).

The individual and global properties they found are in good agreement with the values we redetermined. In particular, 90 percent of the stars matched have the same periods in both catalogues, within 0.001 days. The global properties are also in good agreement, despite the fact that the two surveys cover a different fraction of Sculptor’s main body. Kaluzny et al. (1995) found that the mean period of the fundamental pulsators and the frequency of first overtones are, respectively, $<P_{ab}> = 0.585$ d, $<P_c >= 0.338$ d, and $f_c = 0.40$. In this work, the mean periods of the 289 RRab and 197 RRc are $<P_{ab} >= 0.580 ± 0.004$ d ($σ = 0.08$), and $<P_c >= 0.340 ± 0.003$ d ($σ = 0.04$), respectively. The fraction of RRc variables is equal to $f_c = 0.41$ and becomes 0.46 if we also include the RRd, i.e., $f_{cd} = 0.46$. It has to be stressed...
that roughly 2/3 of the OGLE images are included in our sample. The few outliers with discrepant periods in the two studies can be ascribed to an aliasing problem, which is more likely solved by our larger database. Nevertheless, the overall excellent agreement is further independent proof of the quality of the OGLE data and observing strategy, even with a limited number of phase points as in this case.

5 ANOMALOUS CEPHEID STARS

We confirm the existence of 4 Anomalous Cepheids (ACs) in Sculptor, as previously found by Smith & Stryker (1986) and Kaluzny et al. (1995). In Table 6 we summarize the properties of these stars. Two of them (scl-CEMV284 and scl-CEMV388) were discovered by Baade & Hubble (1939) and analysed for the first time by Swope (1968), obtaining periods of 0.926 and 1.346 days, respectively. Another (scl-CEMV160) was discovered by Thackeray (1950), who obtained a period of 1.15 days. All three of these variables were included in the van Agt (1978) catalogue, with similar periods. The fourth AC, scl-CEMV447, was discovered and classified as such by Kaluzny et al. (1995), with a period of 0.85541 days. These previous determinations of the periods for the four ACs are in agreement with those presented here (see the sixth column in Table 6).

ACs can form through two different channels (Bono et al. 1997a; Cassisi & Salaris 2013). They can be the progeny of coalesced binary stars, thus evolved blue straggler stars (BSS) tracing the old population (Renzini et al. 1977; Hild Press 1980; Sills et al. 2009). Alternatively, they can be on a life stage of metal-poor (Z < 0.006; Fiorentino et al. 2006), single stars with mass between 1.2 and 2.2 M⊙ and age between 1 and 6 Gyr (Demarque & Hild Press 1975; Norris & Zinn 1975; Castellani & Degl’Innocenti 1995; Caputo et al. 1999). Given the predominantly old stellar population of Sculptor (de Boer et al. 2012), it is unlikely that ACs proceed from such a young, elusive population (if any), in agreement with the analysis of the BSS population (Mapelli et al. 2009) which excludes the occurrence of such young stars in Sculptor.

The classification of the pulsation mode of ACs is not trivial and cannot be easily determined from the morphology of the light curves (Fig. 7) or from the period-amplitude diagram alone. Theoretical predictions indicate that for the same luminosity and colour, first-overtone (FO) pulsators are less massive than fundamental (F) pulsators. Therefore, determining the correct pulsational mode is important for obtaining a reliable mass estimate. To distinguish between FO and F pulsators we follow two approaches. First, the different pulsation modes follow different period-luminosity relations – which are also different from those of classical and type II Cepheids. Their location in the PL diagram can therefore be used to constrain their pulsation mode (see, e.g., Bernard et al. 2013). We find that all four ACs in Sculptor fall squarely on the sequence corresponding to the fundamental mode ACs. The second approach has been presented in Fiorentino & Monelli (2012), and is based on the method described in Marconi et al. (2004). It is known that ACs obey well-defined mass-dependent period-luminosity-amplitude (MPLA) and period-luminosity-colour (MPLC) relations (Marconi et al. 2004):

\[
\log \frac{M_{\text{MPLA,F}}}{M_\odot} = (0.01 - 0.188 \cdot A_V - \log P - 0.41 \cdot M_V)/0.77 \quad (1)
\]

\[
\log \frac{M_{\text{MPLC,F}}}{M_\odot} = -(M_V + 1.56 + 2.85 \log P - 3.51 \cdot (M_B - M_V))/1.88 \quad (2)
\]

\[
\log \frac{M_{\text{MPLC,FO}}}{M_\odot} = -(M_V + 1.92 + 2.90 \log P - 3.43 \cdot (M_B - M_V))/1.82 \quad (3)
\]

However, the MPLA relation is only valid for F pulsators, whereas MPLC relations exist for both pulsation modes.

In order to assign a pulsation mode and a mass to each AC, we proceed as follows. We first estimate the mass using both the MPLA and MPLC relations for F pulsators. Then, when these two values agree with each other within 2σ, we classify the star as F mode and take the mean mass as the true value. If instead the two mass estimates are not consistent, we assume that the star is a FO pulsator and we use the corresponding MPLC relation for the mass estimation. This method confirms independently that all ACs are F pulsators (see Table 7).

Smith & Stryker (1986) provided a mass value for two Sculptor ACs: scl-CEMV284 (2.0+0.4 \ 2.0M⊙) and scl-CEMV388 (0.6+0.2 \ 0.6M⊙) from a linear pulsation theory assuming that they pulsate in the F mode with a pulsational constant of Q=0.0034 (Wallerstein & Cox 1984). The first value is in agreement within the errors with our estimate, but the second one is different at the 3-σ level. Nevertheless, as Smith & Stryker (1986) noted, both their mass estimates have substantial uncertainties due to their photometry, and our improved data make us more confident in our determinations.

Fig 8 is a zoom-in of the CMD on the region of AC stars that shows a comparison of theoretical evolutionary tracks for different masses (1.5 - 3.0 M⊙) and [Fe/H] (-2.0 and -1.8). The adopted stellar models have been retrieved from the BaSTI library (Pietrinferni et al. 2004) or—when not available in the database—have been computed for this specific project using a theoretical framework fully consistent with the BaSTI assumptions. In more detail, the models shown in Fig. 8 are based on a scaled-solar heavy element mixture, assume a canonical (no overshooting) physical framework, and a mass loss efficiency on the RGB with the free parameter η entering in the Reimers (1975) law set to 0.4. The models were shifted using the distance modulus µ=19.62 mag (Paper I) and foreground reddening E(B-V)=0.018 mag (Pietrzyński et al. 2008), and assuming the standard extinction law from Cardelli et al. (1989). The blue lines show the zero-age helium-burning (ZAHB) loci for stars with masses from ~1 to 3 M⊙. Green dashed and black solid lines correspond to the core He-burning evolutionary tracks for stellar models ignoring triple-α nuclear reactions at the tip of the RGB under conditions of partial electron degeneracy (initial mass lower than ~2.0 M⊙) and no-electron degeneracy, respectively (see Cassisi & Salaris 2013 for a detailed review on this topic). The termination of the core He-burning stage (central He abundance equal to 10 percent of the initial value) is marked as green

\[
\log \frac{M_{\text{MPLA,F}}}{M_\odot} = (0.01 - 0.188 \cdot A_V - \log P - 0.41 \cdot M_V)/0.77 \quad (1)
\]

\[
\log \frac{M_{\text{MPLC,F}}}{M_\odot} = -(M_V + 1.56 + 2.85 \log P - 3.51 \cdot (M_B - M_V))/1.88 \quad (2)
\]

\[
\log \frac{M_{\text{MPLC,FO}}}{M_\odot} = -(M_V + 1.92 + 2.90 \log P - 3.43 \cdot (M_B - M_V))/1.82 \quad (3)
\]
Table 6. Parameters of the AC stars in Sculptor dSph.

| CEMV+2016 name  | Original name | Alternative name | RA (J2000) | DEC (J2000) | Period (current) | <B> | <V> | <I> | A_B | A_V | A_I | Q1 | Q2 | Type |
|-----------------|--------------|------------------|------------|------------|-----------------|-----|-----|-----|-----|-----|-----|----|----|------|
| scl-CEMV160     | V119         | K734             | 00 59 33.93 | -33 39 31.0 | 1.5757836       | 19.221 | 18.880 | 18.284 | 0.703 | 0.647 | 0.543 | 0 | 1 | F    |
| scl-CEMV284     | V25          | K3302            | 01 00 16.64 | -33 47 57.4 | 1.3460388       | 19.097 | 18.623 | 18.097 | 1.045 | 0.863 | 0.536 | 0 | 1 | F    |
| scl-CEMV447     | K5689        |                  | 01 00 30.32 | -33 41 42.5 | 0.8554217       | 19.472 | 19.133 | 18.617 | 0.941 | 0.715 | 0.381 | 2 | 0 | F    |

See the caption of Table 4 for a description of the Q1 and Q2 parameters.

Table 7. Parameters of the AC stars in Sculptor dSph.

| CEMV+2016 name  | M_{MP LC,FU} M_{DO} | M_{MP LC,FU} M_{DO} | M_{MP LC,FU} M_{DO} | MODE_{max} | <M>^* |
|-----------------|---------------------|---------------------|---------------------|-------------|-------|
| scl-CEMV160     | 0.56 ±0.18          | 1.25 ±0.06          | 0.77 ±0.04          | 1.40±0.19   | F     |
| scl-CEMV284     | 0.68 ±0.19          | 1.50 ±0.07          | 0.94 ±0.04          | 1.55±0.21   | F     |
| scl-CEMV388     | 0.57 ±0.18          | 1.65 ±0.08          | 1.02±0.05           | 1.61±0.20   | F     |
| scl-CEMV447     | 0.64 ±0.19          | 1.45 ±0.07          | 0.90 ±0.04          | 1.54±0.20   | F     |

*The final mean value is the mean of the fundamental estimates.

Figure 7. Sample of light curves of the AC stars in the B (blue), V (green) and I (red) bands, phased with the period in days given in the lower right-hand corner of each panel. The name of the variable is given in the left-hand corner of each panel. Open symbols show the bad data points, i.e., with discrepancies larger than 3σ above the standard error of a given star; these were not used in the calculation of the period and mean magnitudes. For clarity, the B and I light curves have been shifted by 0.4 mag down- and upward, respectively.

black stars, respectively. The gray lines correspond to the boundaries of the instability strip (Fiorentino et al. 2006).

The left panel of Fig. 8 shows that a metallicity of [Fe/H]=−2.0 provides a good match between the location of three of the observed stars and the tracks with mass value in the range 1.60–1.80 M_{⊙}. These masses are in good agreement, within the errors, with the mean mass estimated above: < M_{AC } > =1.54 M_{⊙} (σ_{gs}=0.20 M_{⊙}, σ_{ran} = 0.08 M_{⊙}). However, the brightest AC is ∼ 0.1 mag brighter than expected at this metallicity. An increase in metallicity by 0.2 dex (right panel) provides a good fit of all four stars, but implies slightly larger stellar masses of ∼1.90 M_{⊙} that is in agreement, for the adopted theoretical scenario, within 2-σ.

These two low metallicities are in agreement with previous estimates by Smith & Stryker (1986), who gave a mean value close to [Fe/H]=−1.9 (σ = 0.3 dex)² as the mean of three out the four ACs (scl-CEMV284, scl-CEMV388 and scl-CEMV160).

6 SX PHOENICIS STARS

Fig. 9 shows the light curves of the 23 variable stars identified in the relatively faint part of the CMD of Sculptor, where the IS crosses the MS and the sub-giant branch for masses typically larger than 1 M_{⊙} (see Fig. 1). In this region, variable stars are characterized by short periods (from minutes to a few hours) and low amplitudes (a few tenths of a magnitude). They typically present several pulsation modes simultaneously, both radial and non-radial (Santolamazza et al. 2001; Poretti et al. 2008). These properties make them elusive targets in external galaxies, as the intrinsic faint brightness makes them difficult to detect, given that the long exposure times required to have good measurements conflict with their short periods. Commonly, these variable stars are classified as 8 Scuti when they are population I (young and more metal-rich stars), or SX Phoenix (SX Phe) when they are population II metal-poor counterparts. The latter are typically observed in GCs, and they are associated with the BSS that, leaving the MS, cross the IS above the main-sequence turnoff of the cluster population. SX Phe stars are important because their pulsational properties allow us to derive their distances (McNamara 2011) and structural parameters such as the BSS mass (Fiorentino et al. 2014, 2015b), which is a key ingredient in deriving the dynamical friction in globular clusters (Ferraro et al. 2012).

In the case of dwarf galaxies the situation is more complicated. On the one hand, dwarf galaxies that are composed of old populations only (> 10 Gyr, or fast systems according to the nomenclature introduced by Gallart et al. 2015) appear similar to GCs: the colour of the main-sequence turnoff (MSTO) stars is redder than the red edge of the IS. Therefore, only BSS stars (bluer and brighter than the MSTO stars) can cross the IS at this magnitude level when moving redward after central H exhaustion. On the other hand, slow dwarf galaxies characterized by star formation at all epochs can host a mix of different variable stars in this region of the metallicity for the ACs through an adaptation of the ΔS method for RRLs.

² Smith & Stryker (1986) used the ΔS parameter to measure the
Figure 8. Optical ($B-V$, $V$) CMDs of Sculptor, zoom-in on AC stars, where theoretical predictions from BaSTI library (Pietrinferni et al. 2004) are over-plotted. Solid grey lines represent the theoretical instability strip (Fiorentino et al. 2006). The red dots indicate the 4 ACs found in Sculptor. The blue lines show the zero-age helium-burning (ZAHNeB) loci for stars with masses in the range between $\sim 1.0$ and $3.0$ $M_{\odot}$. Evolutionary tracks for AC stars for the labelled metallicities: [Fe/H]=2.0 (left), [Fe/H]=−1.8 (right). Green and black lines indicate models that ignite helium in the core in degenerate and non-degenerate conditions, respectively. These stellar tracks represent the path from the ZAHNeB to the central helium exhaustion (10 percent of the initial abundance), indicated by an open star symbol, at different stellar masses. For the theoretical analysis we used scaled-solar evolutionary models, with a fixed $\Delta Y/Y = 0.245$, assumed a distance modulus of $\mu = 19.62$ mag (Paper I) and a reddening of 0.018 mag (McConnachie 2012).
masses are in good agreement with the evolutionary stellar models (BaSTI, Pietrinferni et al. 2004) as shown in Figure 11. Incidentally, we note that the age of a single star of such a mass is about 4 Gyr. Interestingly, in the star-formation history of fast galaxies it is common to detect a peak of star formation at this age, which is interpreted as the contribution of the BSS (Monelli et al. 2010b,a, 2016).

7 OTHER VARIABLE STARS

7.1 Peculiar HB variable stars

We have identified three peculiar variable stars, with periods and LCs similar to those of RRL, but located quite above the HB. They are \( \sim 0.3 \) mag brighter than the brightest RRL stars of the full sample, but \( \sim 0.6 \) mag fainter than the faintest ACs. The properties of these stars, which we could not classify convincingly – see below – are summarized in Table 9, while their LCs are presented in Fig. 12.

From an inspection of the CMD these stars are unlikely to be ACs, which are typically more than \( 1 \) mag brighter that the HB in the \( V \) band. Their location suggests they are either RRL affected by blending or stars evolving off from the blue part of the HB, i.e., stars on the verge to become BL Herculis (BL Her) variables. The first hypothesis is not convincing since these objects are located far from the galaxy centre (see Fig. 2). Furthermore their amplitudes (see Table 9) and their amplitude ratios \( (A_R/A_V \sim 1.34 \text{ and } A_{\lambda}/A_{\lambda} \sim 1.57) \) are similar to that expected for normal RRL stars (Di Criscienzo et al. 2011) thus not supporting a possible blend effect. The second hypothesis is also unlikely, since BL Her typically have periods \( >1 \) day (e.g., Wallerstein 2002; Sozzetti et al. 2010; Marconi et al. 2011; Sozzetti et al. 2015), while these have periods \( <0.8 \) day.

Besides, according to the current evolutionary scenario the time spent within the Instability Strip by a star with such a luminosity after the central Helium burning is very short (\(<10 \text{ Myr}; \text{ e.g., Pietrinferni et al. 2004})\), which means that only in systems with a prominent extreme BHB can we expect to observe BL Her stars (e.g., Maas et al. 2007).

We therefore cannot classify these variables convincingly, but note that similar peculiar objects have been detected in other galaxies (e.g., Carina: Dall’Ora et al. 2003; Coppola et al. 2013, Cetus and Tucana: Bernard et al. 2009).

7.2 Eclipsing binaries

Five eclipsing binaries have been detected. The LCs for five of them are shown in Fig. 13, and the properties are summarized in Table 10. It is worth noting that, for scl-CEMV398, despite the fact that its LC is very similar to one RRc, we classified this star as eclipsing binary based on both the flattening of the brighter part of its LC and on the period \( (P=0.474 \text{ d, unusually long for a RRc-type star}) \). Note also the classification provided by Clementini et al. (2005), who classified it as “suspected binary system”.

7.3 Field variable stars

We have identified three variable stars compatible with being foreground field stars. Their LCs are shown in Fig. 14, and the properties are summarized in Table 11. Two are compatible with being field \( \delta \)Scultri stars.

7.4 Likely candidates

A sizeable sample of 37 LPV and 23 probable variable stars has been detected in Sculptor. For the case of the LPV stars, due to their long periods, a large number of phase points together with an appropriately long temporal coverage are needed to define the shape of their LCs. Despite our large data set, we have not been able to characterize the properties of these stars. We consider a star to be a candidate LPV when we obtain concordant magnitude measurements within individual nights and individual observing runs, but average
results from observing runs separated by many months or many years are highly discrepant.

For the case of the probable variables, the insufficient data and the inability to achieve a good light curve makes the classification and the period determination of such stars difficult to do. Based on these facts, we named them “likely candidates”. Table 12 shows the list of these stars. We note that: i) 31 out of 37 LPV stars are located near the tip of the RGB; and ii) out of the 23 probable variable stars, 4 could be possibly eclipsing binaries, and 2 could be RRC stars.

7.5 Non-variable stars

The comparison with previous work on variable stars in Sculptor discloses that we do not detect any trace of variability in a number of sources previously catalogued as variable, mostly from the van Agt (1978) paper, and a few from the Kaluzny et al. (1995). The list is presented in Table 13.

8 DISCUSSION: THE FAST EARLY CHEMICAL EVOLUTION OF SCULPTOR AND TUCANA

In this work, we presented the most complete and updated catalogue of variable stars in the Sculptor dSph. This is so far one of the largest RRL star samples in external galaxies of similar morphological type. As demonstrated in Paper I, the combination of a large sample together with high quality and multi-band photometry, allowed us to set tight constraints on the metallicity distribution of the old stellar component, and revealed the presence of a significant metallicity spread within the RRL star population (t > 10 Gyr). This implies that Sculptor underwent substantial chemical enrichment fast enough to be imprinted in the population we observe today as RRL stars. This manifests itself through a large luminosity spread of the RRL stars (~0.35 mag) that is inconsistent with the evolution of a monometallic population (Paper I). Moreover, we showed that, when splitting the sample of RRL stars according to their luminosity relative to the mean < V > mag, the brighter and the fainter subsamples follow different spatial distributions, the latter being more centrally concentrated than the former. If we interpret the bright and faint components in terms of metallicity, the latter is consistent with being more metal-rich. This result is consistent with he spectroscopic results of Tolstoy et al. (2004). This implies that, in agreement with what is generally found in dwarf galaxies, the youngest and chemically more evolved population is located in the innermost regions, surrounded by a more uniform older and more metal-poor one, suggesting a metallicity gradient. In the present work (see § 4.2) we showed that the Bailey diagram is quite complex, with stars populating the region around and intermediate to the typical Oo-I and Oo-II loci. Interestingly, we found that the bright, metal-poor, more extended population preferentially follows the location of the Oo-II (typically more metal-poor) GCs, while the faint, more metal-rich, more centrally concentrated RRL stars have a distribution closer to that of Oo-I clusters.

A surprisingly similar empirical result was found in the Tucana dSph. Bernard et al. (2008) disclosed that the pulsational properties of the RRL stars in this galaxy trace a spatial gradient in the metallicity of its individual stars, which therefore must have appeared very early on in the history of this galaxy. As in Sculptor, fainter RRLs are more centrally concentrated than the brighter RRLs. This was the first time that a spatial variation of pulsational properties was observed in a dwarf galaxy, thanks to the large spatial coverage and number of variables discovered. Fig. 15 compares the Bailey diagram and the period distribution of the RRL stars populations in Sculptor and Tucana. The distribution of the RRab-type shows the same general characteristics, with a large period dispersion at fixed amplitude. This is reflected in the normalized histogram in the lower panel,
Table 12. Parameters of the candidates variable stars with problems of classification in Sculptor dSph.

| CEMV+2016 name | Original name | Alternative name | RA (J2000) | DEC (J2000) | Note |
|----------------|---------------|------------------|------------|-------------|------|
| scl-CEMV003    | V579          | —                | 00 56 29.94 | -33 56 03.9 | probable variable |
| scl-CEMV004    | V303          | —                | 00 56 32.41 | -33 54 52.4 | probable variable |
| scl-CEMV007    | V443          | —                | 00 56 57.55 | -33 50 21.1 | probable variable |
| scl-CEMV009    | —             | —                | 00 57 14.08 | -33 48 19.6 | probable variable; probable RRC but unable to determine period |
| scl-CEMV011    | V570          | —                | 00 57 37.90 | -33 58 57.0 | probable variable |
| scl-CEMV017    | V546          | —                | 00 57 59.79 | -33 55 58.1 | probable variable |
| scl-CEMV023    | V581          | —                | 00 58 15.63 | -33 47 57.4 | probable variable; possible eclipsing binary |
| scl-CEMV075    | —             | —                | 00 59 04.80 | -33 38 44.2 | LPV |
| scl-CEMV082    | —             | —                | 00 59 08.58 | -33 41 52.7 | LPV |
| scl-CEMV101    | —             | —                | 00 59 15.76 | -33 42 48.6 | LPV |
| scl-CEMV121    | —             | —                | 00 59 23.33 | -33 38 37.3 | LPV |
| scl-CEMV136    | —             | —                | 00 59 27.67 | -33 40 35.6 | LPV |
| scl-CEMV140    | —             | —                | 00 59 28.28 | -33 42 07.4 | LPV |
| scl-CEMV159    | —             | —                | 00 59 33.95 | -33 38 37.3 | LPV |
| scl-CEMV164    | K734          | —                | 01 00 00.06 | -33 38 34.3 | LPV |
| scl-CEMV168    | —             | —                | 01 00 01.13 | -33 40 21.3 | probable variable |
| scl-CEMV194    | V204          | —                | 01 00 06.15 | -33 40 21.3 | probable variable; multimode? |
| scl-CEMV196    | V539          | —                | 01 00 05.66 | -33 40 21.3 | probable variable; possible eclipsing binary, but unable to determine period |
| scl-CEMV221    | K687          | —                | 01 00 12.12 | -33 40 21.3 | probable variable |
| scl-CEMV228    | —             | —                | 01 00 18.19 | -33 40 21.3 | LPV |
| scl-CEMV231    | —             | —                | 01 00 18.19 | -33 40 21.3 | LPV |
| scl-CEMV244    | —             | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV254    | V97           | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV269    | V544          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV296    | —             | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV303    | V551          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV343    | V80           | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV346    | V539          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV368    | —             | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV372    | K4780         | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV395    | —             | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV412    | —             | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV450    | —             | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV470    | V575          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV482    | V575          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV496    | V575          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV503    | V80           | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV504    | V303          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV530    | V303          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV534    | V303          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV543    | V303          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV550    | V303          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV566    | V303          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV573    | V303          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV578    | V303          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV586    | V303          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV591    | V303          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV608    | V303          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV613    | V480          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV628    | V530          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV629    | V577          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV631    | V577          | —                | 01 00 30.72 | -33 40 21.3 | LPV |
| scl-CEMV633    | V587          | —                | 01 00 30.72 | -33 40 21.3 | LPV |

which clearly shows that the period coverage is essentially the same.

Indeed, the old population of the two systems presents striking similarities, which are unique among the low-mass galaxies of the LG. No other dSph investigated so far shows such clear evidence of chemical evolution imprinted in their population of RRL stars. This may suggest that the early conditions of the two galaxies, and in particular the mass and star formation histories may have been similar, in order to explain that both systems were able to retain enough nucleosynthesis products to provide early enrichment as observed today. Nonetheless, Sculptor and Tucana also exhibit important differences.

At present, Tucana is a very isolated dSph at the edge of the Local Group (\( \sim 870 \) kpc from the MW versus \( \sim 84 \) kpc for Sculptor). Given its current location in the Local Group and its relatively high recession velocity, Tucana seems to have been an isolated Local Group galaxy during the majority of its lifetime, except perhaps for a close encounter with the MW or M31 at early epochs (Fraternali et al. 2009). On the contrary, with an apogalactic distance of 122 kpc and orbital period of 2.2 Gyr (Piatek et al. 2006), Sculptor spent most of its existence within the halo of the MW. Under these conditions, theoretical investigations indicate that tidal stripping, stirring, and ram-pressure stripping (Blitz & Robishaw 2000; 2016).
Mayer et al. (2006), as well as the local UV radiation from the primary galaxy (Mayer et al. 2007) all act to remove dark matter and/or baryons from the dwarf, implying that satellite galaxies such as Scl may have been up to ten times more massive in the past (Kravtsov et al. 2004). However, Sculptor is considerably more massive than Tucana at the present time (M \( \simeq -11.1 \) versus –9.6 for Tucana). If Sculptor had been ten times as massive as we observe it today, the mass-metallicity relation would suggest a larger increase in metallicity at early times. However, this is in contrast with the lack of HASP RRL stars, which are solid tracers of an old stellar population more metal-rich than [Fe/H] \( \gtrsim 1.5 \). Moreover, Coleman et al. (2005) demonstrated that beyond the tidal radius (from both photometric and spectroscopic data) there is no evidence of extra-tidal structure, suggesting the absence of strong tidal interaction. This argues against substantial mass loss along Sculptor’s history and may suggest that, possibly, Sculptor has quietly and passively evolved during its revolutions around the Milky Way. The similarity of the stellar populations of Sculptor and Tucana, including at early times, provides support to the scenario about the origin of the dwarf galaxy types introduced by Gallart et al. (2015), in which dwarf galaxy types may be imprinted by the early conditions of formation rather than only being the result of a recent or secular morphological transformation driven by environmental effects. In this particular case, both Sculptor and Tucana may have formed in the relatively high density environment close to the centre of what would become the Local Group, and this would be instrumental in becoming fast galaxies, i.e., galaxies whose star formation history is dominated by en early and short star formation event, with little star formation afterwards. The subsequent sustained interaction of Sculptor with the Milky Way would have had a minor effect in its star formation history and mass characteristics, and thus Sculptor and Tucana remain galaxies with similar mass and star formation history today despite the substantially different secular evolution.

9 SUMMARY AND CONCLUSIONS

We have presented the largest catalogue (so far) of variable stars in the Sculptor dSph galaxy. This work is based on the homogeneous photometric analysis of 4,404 images in the B, V, and I bands collected over 24 years in 21 different observing runs and using 6 different telescopes and 7 different instruments, employing the same methodologies as the “Homogeneous Photometry” series. The main results of this work are:

- Basic properties (period, amplitude, mean magnitude, position) have been made available for all the stars, together with the light curves and the finding charts (see Appendix A).

- In total, we have discovered 147 variable stars in the calibrated portion of the Sculptor dSph, among which 81 are RRLs, 21 SX Phe, one peculiar, one eclipsing binary and 38 “likely candidates” (31 of them are probable LPV stars, one is a possible eclipsing binary, two are probable RRc and four more are possible variables of uncertain type).

- Out of the 634 detected variables in the current work, 334 (301 RRLs) have their periods identified for the first time, and 354 (320 RRLs) have their pulsation parameters also given for the first time.

- We have detected 536 RR Lyrae variable stars. Out of these, 289 are RRab type stars, 197 are RRC, and 50 stars are suspected RRd double-mode pulsators. We have discussed the distribution of stars in the Bailey diagram, showing that the metallicity spread among RRL stars discussed in Paper I reflects not only in the luminosity spread

Table 13. Parameters of non-variable stars in Sculptor dSph.

| Original name | Alternative name | RA (J2000) | DEC (J2000) | Note |
|---------------|------------------|------------|-------------|------|
| V574          |                  | 00 56 38.63 | -33 25 23.7 | not variable? |
| V397          |                  | 00 57 24.12 | -33 38 02.5 | not variable? |
| V580          |                  | 00 57 33.20 | -33 52 00.2 | not variable? |
| V596          |                  | 00 57 49.52 | -33 32 23.3 | not variable? |
| V559          |                  | 00 58 12.31 | -33 37 50.4 | not variable? |
| V547          |                  | 00 58 36.48 | -34 02 11.9 | not variable? |
| V252          |                  | 00 58 45.65 | -33 32 12.8 | not variable? |
| V251          |                  | 00 59 00.13 | -33 38 50.9 | not variable? |
| V311          |                  | 00 59 21.44 | -33 48 48.6 | not variable? |
| V332          |                  | 00 59 32.85 | -33 57 44.4 | not variable? |
| V554          |                  | 00 59 35.22 | -33 29 04.3 | not variable? |
| K403          |                  | 00 59 36.61 | -33 46 05.7 | not variable? |
| V416          |                  | 00 59 44.35 | -33 55 19.3 | not variable? |
| V200          |                  | 00 59 47.20 | -33 33 37.0 | not variable? |
| V382          |                  | 00 59 57.66 | -33 46 56.5 | not variable? |
| V370          |                  | 01 00 06.99 | -33 52 25.7 | not variable? |
| V173          |                  | 01 01 17.17 | -33 56 06.4 | not variable? |
| V60           |                  | 01 00 21.78 | -33 39 07.7 | no bright star here; estimated position is 11.4 arcseconds from K4313 |
| V245          |                  | 01 00 24.43 | -33 55 09.7 | not variable? |
| V558          |                  | 01 00 24.75 | -33 51 06.6 | not variable? |
| V557          |                  | 01 00 26.14 | -33 41 07.3 | not variable? |
| V54           |                  | 01 00 28.99 | -33 51 52.5 | not variable? |
| K5081         |                  | 01 00 30.78 | -33 46 21.7 | not variable? |
| V54           |                  | 01 00 39.78 | -33 52 21.9 | not variable? |
| V532          |                  | 01 00 43.79 | -33 29 08.1 | not variable? |
| V424          |                  | 01 00 47.84 | -33 58 54.2 | not variable? |
| V340          |                  | 01 01 21.08 | -33 42 22.6 | not variable? |
| V571          |                  | 01 02 36.69 | -33 30 07.1 | not variable? |
| V307          |                  | 01 03 23.63 | -33 44 16.8 | not variable? |
We have discussed 23 newly discovered SX Phe stars. Using theoretical models developed by (Fiorentino et al. 2015b), and the distance derived from RRLs in Paper I, we classified them as 16(17) FO, 6(5) SO, assuming a mean metallicity of $Z=0.001$ ($Z=0.0001$). On the other hand, the empirical relations by McNamara (2011) instead suggest that 15(13) are F and 5(5) are FO. The discrepancy comes from the zero-point offset ($\sim$0.3 mag) between both relations. The mean mass derived for them is of about 1 $M_\odot$, if we assume that the entire sample of SX Phe comes from single star evolution, they might indicate a residual star formation $\sim$4 Gyr ago, or coalescence of very low mass stars.

- We also discuss the existence of three peculiar variable stars, located in the region of the CMD between the RRL star and the ACs, which have pulsation properties inconsistent with other classes of variable brighter than the HB, such as the BL Her stars. Their nature remains unclear.

- Five eclipsing binaries and 37 probable long period variables, and a few (3) field variable stars were also presented.

We have discussed the striking similarities between the properties of the old population in the Sculptor and Tucana dSph galaxies, which are imprinted in the complex populations of their RRL stars. Despite the large spatial coverage of the present work ($\sim$2.5 deg$^2$), a complete investigation of stellar variability over the full tidal radius of Sculptor is still lacking. Moreover, a direct confirmation of the metallicity spread among the RRL population through spectroscopic follow-up could provide further insight into the early chemical evolution of this galaxy. The future development of this project does require new precise and radial velocity.
measurements of both RG and HB stars to assess whether the two different populations show different kinematics and different chemical enrichment histories as recently suggested by (Fabrizio et al. 2015, 2016 AJ accepted) for Carina dSph. Note that the quoted approach took advantage of the \textit{CUHIT} index to separate stellar populations along the RGB. This means that deep and accurate U-band photometry is also urgently required.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure11.png}
\caption{Distribution of the 23 SX Phe stars in Sculptor dSph in the optical (B–V, V) CMD (with the same colour code as in Fig. 1). We have represented the standard scaled-solar evolutionary tracks from the BaSTI library (Pietrinferni et al. 2004) for different metallicities Z=0.001 (solid lines) and Z=0.0001 (dashed lines), and for the masses 0.9 M\odot (orange lines), 1.1 M\odot (blue lines) and 1.3 M\odot (magenta lines).}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure12.png}
\caption{Sample of light curves of the peculiar variable stars in the B (blue), V (green) and I (red) bands, phased with the period in days given in the lower right-hand corner of each panel. The name of the variable is given in the left-hand corner of each panel. Open symbols show the bad data points, i.e., with errors larger than 3\(\sigma\) above the mean error of a given star; these were not used in the calculation of the period and mean magnitudes. For clarity, the B and V light curves have been shifted by 0.4 mag down- and upward, respectively.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure13.png}
\caption{Sample of light curves of the eclipsing binary stars in the B (blue), V (green) and I (red) bands, phased with the period in days given in the lower right-hand corner of each panel. The name of the variable is given in the left-hand corner of each panel. Open symbols show the bad data points, i.e., with errors larger than 3\(\sigma\) above the mean error of a given star; these were not used in the calculation of the period and mean magnitudes. For clarity, the B and I light curves have been shifted by 0.4 mag down- and upward, respectively.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure14.png}
\caption{Sample of light curves of the field variable stars in the B (blue), V (green) and I (red) bands, phased with the period in days given in the lower right-hand corner of each panel. The name of the variable is given in the left-hand corner of each panel. Open symbols show the bad data points, i.e., with errors larger than 3\(\sigma\) above the mean error of a given star; these were not used in the calculation of the period and mean magnitudes. For clarity, the B and I light curves have been shifted by 0.4 mag down- and upward, respectively.}
\end{figure}

\section*{ACKNOWLEDGMENTS}

We thank the referee for his/her comments, careful reading and detailed report. CEM-V is grateful to the Rome Observatory and the Physics Department of the Tor Vergata University where part of this work has been carried out. CEM-V acknowledges the support by the ULL through a grant funded by the Agencia Canaria de Investigación, Innovación y Sociedad de la Información and co-funded by the Fondo Social Europeo (FSE) under the framework of Programa Operativo de Canarias (POC 2007-2013). This research has been supported by the Spanish Ministry of Economy and Competitiveness (MINECO) under the grant (project reference AYA2014-56795-P). EJB acknowledges support from the CNES postdoctoral fellowship program. GF has been supported by the Futuro in Ricerca 2013 (grant RBFR13J716).
For clarity, RRd stars do not appear in these diagrams, which only consider stars with well defined pulsational properties. The bottom panel shows the normalized distribution of RRab and RRc stars in both galaxies (red: Sculptor, blue: Tucana).

REFERENCES

Baade W., Hubble E., 1939, PASP, 51, 40
Bernard E. J., et al., 2008, ApJ, 678, 821
Bernard E. J., et al., 2009, ApJ, 699, 1742
Bernard E. J., et al., 2010, ApJ, 712, 1259
Bernard E. J., et al., 2015, MNRAS, 432, 3047
Blazhko S., 1907, Astronomische Nachrichten, 175, 327
Blitz L., Robishaw T., 2000, ApJ, 541, 675
Bono G., Caputo F., Santolamazza P., Cassisi S., Piersimoni A., 1997a, AJ, 113, 2209
Bono G., Caputo F., Cassisi S., Incerpi R., Marconi M., 1997b, ApJ, 483, 811
Cacciari C., Corwin T. M., Carney B. W., 2005, AJ, 129, 267
Canterna R., 1976, AJ, 81, 229
Caputo F., Cassisi S., Castellani M., Marconi G., Santolamazza P., 1999, AJ, 117, 2189
Cardelli J. A., Clayton G. C., Mathis J. S., 1989, ApJ, 345, 245
Cassisi S., Salaris M., 1993, Old Stellar Populations: How to Study the Fossil Record of Galaxy Formation
Castellani V., dell’Innocenti S., 1995, A&A, 298, 827
Catelan M., 2009, Ap&SS, 320, 261
Clementini G., Ripepi V., Bragaglia A., Martinez Fiorentino A. F., Held E. V., Gratton R. G., 2005, MNRAS, 363, 734
Coleman M. G., Da Costa G. S., Bland-Hawthorn J., 2005, AJ, 130, 1065
Coppola G., et al., 2013, ApJ, 775, 6
Coppola G., et al., 2015, ApJ, 814, 71
Cusano F., et al., 2015, ApJ, 806, 200
Da Costa G. S., 1984, ApJ, 285, 483
Dall’Ora M., et al., 2003, AJ, 126, 197

Figure 15. Top. Period-V amplitude diagram for Sculptor (top) and Tucana (middle, Bernard et al. 2009). For clarity, RRd stars do not appear in these diagrams, which only consider stars with well defined pulsational properties. The bottom panel shows the normalized distribution of RRab and RRc stars in both galaxies (red: Sculptor, blue: Tucana).
APPENDIX A: FINDING CHART

Fig. A1 displays a mosaic centred on Sculptor dSph, divided in 56 quadrants. In the electronic version we show finding charts for each quadrant in which we found variable stars. In this way, we make available the finding charts for the whole sample of variable stars detected. Fig. A2 shows the finding chart for the 28 quadrant of the mosaic of Sculptor (Fig. A1). The labelled numbers are those belonging to the numerical suffix from our assigned names (scl-CEMV+suffix).

This paper has been typeset from a TeX/\LaTeX\ file prepared by the author.
Figure A1. Mosaic of Sculptor.
Figure A2. Finding chart for the quadrant 28 of the Mosaic of Sculptor (A1). North is up and east to the left. The labelled numbers correspond to the numerical suffix from our assigned names (sc-l-CEMV+suffix). The other quadrants are in the electronic edition.