Near-IR period-luminosity relations for pulsating stars in ω Centauri (NGC 5139)[★]

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ABSTRACT

Aims. The globular cluster ω Centauri (NGC 5139) hosts hundreds of pulsating variable stars of different types, thus representing a treasure trove for studies of their corresponding period-luminosity (PL) relations. Our goal in this study is to obtain the PL relations for RR Lyrae and SX Phoenicis stars in the field of the cluster, based on high-quality, well-sampled light curves in the near-infrared (IR).

Methods. Observations were carried out using the VISTA InfraRed CAMera (VIRCAM) mounted on the Visible and Infrared Survey Telescope for Astronomy (VISTA). A total of 42 epochs in J and 100 epochs in K_s were obtained, spanning 352 days. Point-spread function photometry was performed using DoPhot and DAOPHOT crowded-field photometry packages in the outer and inner regions of the cluster, respectively.

Results. Based on the comprehensive catalog of near-IR light curves thus secured, PL relations were obtained for the different types of pulsators in the cluster, both in the J and K_s bands. This includes the first PL relations in the near-IR for fundamental-mode SX Phoenicis stars. The near-IR magnitudes and periods of Type II Cepheids and RR Lyrae stars were used to derive an updated true distance modulus to the cluster, with a resulting value of $(m - M)_0 = 13.708 \pm 0.035 \pm 0.10$ mag, where the error bars correspond to the adopted statistical and systematic errors, respectively. Adding the errors in quadrature, this is equivalent to a heliocentric distance of 5.52 ± 0.27 kpc.

Key words. stars: variables: RR Lyrae – stars: variables: Cepheids – stars: variables: delta Scuti – infrared: stars – surveys – globular clusters: individual: NGC 5139

1. Introduction

The globular cluster ω Centauri (NGC 5139, C1323-472) is the most luminous, massive, and biggest globular cluster (GC) in the Milky Way. Located at RA = 13:26:47.28 and Dec = −47:28:46.1 (J2000), it appears visible with the naked eye from the southern celestial hemisphere. It has been extensively studied, since it is bright ($M_V \sim -10.26$ mag), large (apparent size of 36'), and nearby, at a distance of only 5.2 kpc, according to the 2010 version of the Harris (1996, 2010) catalog of GC parameters. Additionally, it hosts millions of stars in a field covering $\sim 1.5 \times 1.5$ deg², which has led to numerous works devoted to its internal dynamics (van de Ven et al. 2006; van der Marel & Anderson 2010; D'Souza & Rix 2013), a suggested extragalactic origin, and its possible

associated tidal debris (e.g., Meylan et al. 2001; Dinescu 2002; Altmann et al. 2005; Meza et al. 2005; Bekki & Norris 2006; Da Costa & Coleman 2008; Valcarce & Catelan 2011; Fernández-Trincado et al. 2015; Navarrete et al. 2015a). Naturally, it has also been the subject of extensive variability studies, which is also the main subject of the present work.

In this context, ω Cen stands out as one of the three most RR Lyrae (RRL)-rich GCs known (Navarrete et al. 2015b). Moreover, it is the GC with the highest known number of SX Phe stars (74; Olech et al. 2005; Weldrake et al. 2007; Cohen & Sarajedini 2012). At the same time, while the number of type II Cepheids (T2Cs) that it is known to harbor (seven) may seem small in an absolute sense, ω Cen still holds the record as the most T2C-rich of any GC (Clement et al. 2001; Matsunaga et al. 2006). Also, even though anomalous Cepheids (ACEPs) are primarily found in nearby extragalactic environments (Catelan & Smith 2015), an ACEP classification has been

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advanced for some of the RRL stars in ω Cen (Nemec et al. 1994). The existence of ACEPs in ω Cen would thus be another indication of its possible extragalactic origin. However, none of the ACEP candidates has been confirmed or definitely rejected yet, probably because they are quite similar to the longest-period RRL stars in terms of periods and light curve shapes.

At least two stellar populations are known in ω Cen, with metallicity peaks centered at $[\text{Fe}/\text{H}] \approx -1.6$ and -1.1 dex (Bedin et al. 2004; Joo & Lee 2013), and additional peaks likely also being present (e.g., Johnson et al. 2009). Besides metallicity, it has been reported that these populations differ in their detailed chemistry and age, with the metal-rich stars likely being enhanced in helium by $\Delta Y \sim 0.17$ (Norris 2004; Piotto et al. 2005; Dupree et al. 2011; Dupree & Avrett 2013; Tailo et al. 2016, and references therein). Despite the strong evidence for large He-abundance spread among ω Cen's stars, Sollima et al. (2006a) did not detect variations in Y in their study of the pulsation properties (and spectroscopic metallicities) of the RRL stars in the cluster. Later, Marconi et al. (2011) studied the impact of the helium content on the RRL properties based on evolutionary and pulsational models, finding that the helium content has a marginal effect on the pulsation properties of these variable stars. Very recently, Tailo et al. (2016) claimed consistency between the predicted and observed properties of RRL stars in ω Cen but with a relatively small spread in helium, amounting to $\Delta Y \sim 0.03$.

In this context, the different, well-represented variability types that are simultaneously present in ω Cen offer us a unique opportunity to perform a comparison of their properties. In particular, the pulsating stars present in the cluster are well-known distance indicators, following period-luminosity (PL) relations that are often used to derive distances (Catelan & Smith 2015, and references therein). We note, in this sense, that PL relations at infrared wavelengths have some advantages compared to the ones derived at visible bands (first highlighted by McGonegal et al. 1983, in a study of the PL relations of Classical Cepheids): the amplitude of the variables is smaller, leading to a smaller error in the derived mean magnitudes, even when relatively few data points are available; the interstellar extinction is lower ($\mathcal{A}_K/\mathcal{A}_V \sim 1/10$); and the infrared luminosities are less sensitive to temperature changes, leading to tighter PL relations, compared to the visible regime. Among the pulsating variability types present in ω Cen, the primary distance indicators are the RRLs, which are not only relatively bright (being horizontal-branch [HB] stars) but also significantly more numerous than the other types of pulsators that are present in the cluster. RRL stars follow a well-defined PL relation at the near-IR, at odds with the visual where such a relation is not present (see, e.g., Catelan & Smith 2015). The near-IR PL relations were first discovered in the pioneering work by Longmore et al. (1986), based on the study of three globular clusters. A detailed theoretical derivation in the Johnson-Cousin-Glass *UBVRIJHK* system was performed by Catelan et al. (2004), who showed how the PL relation first appears in the *R* band, decreasing its scatter towards redder bands, becoming tightest in the *K* regime. From the observational side, Klein & Bloom (2014) studied RRLs from the field in 13 different photometric bandpasses, including the mid-infrared Wide-Field Infrared Survey Explorer (WISE) bands, confirming that the PL relation does become tighter in the infrared (see also Klein et al. 2014).

SX Phe stars are the faintest among the known pulsating stars in the cluster, and thus more challenging to observe than their brighter siblings – and yet, they are the second most numerous type of variable stars currently known in ω Cen.

The study of the PL relations for SX Phe and their Population I counterparts, the δ Scuti stars, is complicated by the need to properly identify the pulsation modes, as these stars are often pulsating in more than one mode simultaneously. In these cases, the dominant mode is often the radial fundamental, first, or second overtone, though non-radial *p* modes are often also present (Catelan & Smith 2015, and references therein). The PL relations of these stars have been investigated using theoretical models (e.g., Petersen & Christensen-Dalsgaard 1999; Templeton et al. 2002) and observational data in the optical (Nemec et al. 1994; McNamara 1995; Alcock et al. 2000; McNamara 2011; Cohen & Sarajedini 2012) alike, but a clear consensus has not yet been reached regarding, for instance, the impact of the metallicity on these PL relations. An extension of these PL studies to the near-IR regime has not been carried out yet, and in fact is expected to present some important challenges: since many SX Phe stars are small-amplitude pulsators (with amplitudes below 0.2 mag or so in *V*), their amplitudes in the near-IR could easily become similar to, or even lower than, the photometric errors at their corresponding magnitudes. Such small amplitudes are detrimental to the proper characterization of the (often multiple) pulsation modes of the star, as needed to cleanly establish their PL relations. On the other hand, the smaller amplitudes make it easier to compute representative average magnitudes and colors from the time-series data.

T2Cs are considerably fewer in number than either RRL or SX Phe, and only seven are known in ω Cen. Despite their brightness, the T2C PL relation has not been as extensively studied, undoubtedly due to the fact that they are so few in number (see Catelan & Smith 2015, for a review and extensive references). As in the case of the RRL stars, the PL relations for T2Cs have also been shown to become tighter at longer wavelengths (Matsunaga et al. 2006, and references therein). In the case of ACEPs, which are even fewer in number in GCs (but not in nearby dwarf galaxies, where they can be very numerous), PL relations in different bandpasses, including the near-IR, have recently been provided by Ripepi et al. (2014a).

Our team has performed a systematic monitoring, in the *J* and *K_S* bands, of ω Cen, with the main goal of obtaining a large number of well-defined light curves for the different types of variables present in this cluster. These well-defined light curves can play an important role as templates for the automated classification of variable stars in near-IR surveys (Angeloni et al. 2014), including, in particular, the VISTA Variables in the Vía Láctea (VVV; e.g., Minniti et al. 2010; Catelan et al. 2011; Saito et al. 2012; Catelan et al. 2013a,b) survey and the VISTA survey of the Magellanic Clouds system (VMC; e.g., Cioni et al. 2011; Ripepi et al. 2014a, 2016) both of which are time-resolved European Southern Observatory (ESO) Public Surveys conducted in the near-IR that run on ESO's VISTA telescope.

This paper is the second in a series dedicated to presenting the results of our ω Cen near-IR variability survey. In the first paper, Navarrete et al. (2015b) studied the RRL population (in terms of variability type, amplitudes, and membership). Here we present the near-IR PL relations for the different types of pulsating variable stars that are present in the cluster. In the next and final paper of the series, Navarrete et al. (in prep.) will present the derived near-IR photometric catalog for all detected variables in ω Cen, including not only the pulsating stars but also eclipsing binaries, ellipsoidal variables, and others.

This paper is organized as follows. The observations and data reduction are presented in the next section. Section 3 is devoted to the PL relations for the different types of pulsating stars in ω Cen. The implied pulsational distance modulus of the cluster

and the sources of uncertainties are discussed in Sect. 4. Conclusions are presented in Sect. 5.

2. Observations

The VIRCAM camera (Dalton et al. 2006), mounted on the VISTA telescope (Emerson & Sutherland 2010), was used to monitor ω Cen, obtaining 42 and 100 epochs in the J and K_S bands, respectively. The effective field of view (FoV) of VISTA ($1.1 \times 1.5 \text{ deg}^2$) is large enough to encompass all the pulsating stars known in the field of the cluster, except for four RRL located farther away than the cluster's tidal radius and which are thus likely non-members (Navarrete et al. 2015b).

The characteristics of the observations and data reduction are the same as those already explained in Navarrete et al. (2013, 2015b), and will accordingly not be repeated here. Point-spread function (PSF) photometry was performed using the photometry packages DoPhot (Schechter et al. 1993; Alonso-García et al. 2012) for the outer regions, and DAOPHOT II/ALLFRAME (Stetson 1987, 1994) for the central part of the cluster (i.e., the innermost $\sim 10'$). All the magnitudes are presented in the VISTA photometric system.

3. Results

From our time-series photometry, light curves with the clear signatures of variability were derived for 209 pulsating stars, including seven T2Cs, 89 fundamental-mode (ab-type) and 98 first-overtone (c-type) RRL, 12 SX Phe, and three stars of uncertain type. Intensity-averaged magnitudes were obtained for all of these stars, based on Fourier fits to their light curves. For an additional 62 SX Phe and four RRc stars, variability was not reliably recovered on the basis of our data alone, most likely due to these stars have very small amplitudes in the near-IR (they were previously classified as variables by Kaluzny et al. 2004, based on optical photometry). In these cases, the mean magnitudes were obtained directly from the photometric processing of the images, without any attempt to phase-fit the light curves.

In order to compare the magnitudes and periods with well-calibrated near-IR PL relations, both J and K_S magnitudes were de-reddened, adopting a color excess of $E(B - V) = 0.12 \text{ mag}$ from the Harris (1996, 2010) online catalog, and the ratios $A_X/E(B - V)$ of 0.866 and 0.364 for the VISTA J and K_S magnitudes, respectively (Catelan et al. 2011).

3.1. Type II Cepheids

Light curves for all the T2Cs present in the cluster were recovered, both in J and K_S . However, the RV Tau star V1 has a magnitude near the saturation limit in the detector where it was observed. In particular, to derive its light curve, aperture photometry measurements (provided by the Cambridge Astronomical Survey Unit [CASU] catalogs) instead of PSF photometry were used because in the latter V1 is considered a saturated star. Because of this, the individual magnitude measurements have photometric errors higher than for the other T2Cs, and the errors adopted for the intensity-averaged magnitude, in J and K_S , are twice as high as the error adopted for the intensity-average magnitudes of the other T2Cs. Figure 1 shows the intensity-averaged magnitudes versus $\log P$ for the seven T2Cs in ω Cen, for the J and K_S bands. Dashed and dotted lines show the empirical PL relation derived by Matsunaga et al. (2006), shifted by 13.62 and 13.708 mag, respectively. The former value corresponds to the distance modulus adopted by Matsunaga et al. for

Fig. 1. De-reddened J and K_S magnitudes versus period (in units of days) for the seven known T2Cs in ω Cen. The dashed lines correspond to the empirical PL relations derived by Matsunaga et al. (2006), shifted to the distance modulus of the cluster used in that study, 13.62 mag, while the dotted lines are the same relations, but shifted to our derived distance modulus of 13.708 mag (see Sect. 4). V60 and V92, with roughly the same period and magnitude, are labeled accordingly.

ω Cen, based on their adopted relation between HB luminosity and metallicity, while the latter one is the final distance modulus obtained in this study (see Sect. 4). As can be noted, all the variables closely follow a well-defined linear relation, irrespective of the distance modulus adopted, showing very little scatter (with a rms in the residuals of the weighted least-squares fit of 0.07 and 0.03 mag in the J and K_S bands, respectively) which is consistent with all of the T2Cs pulsating in the same pulsation mode, and with a negligible dependence of their PL relation on metallicity (and helium). Indeed, Matsunaga et al. (2006) found that all T2Cs in Galactic GCs pulsate in the fundamental mode, and a similar conclusion was reached by Ripepi et al. (2015) in a study of 130 T2Cs in the Large Magellanic Cloud. Matsunaga et al. also found that the metallicity dependence of the PL relation is not very significant, with a zero point dependence of only $(-0.1 \pm 0.06) \text{ mag/dex}$ in the K_S band. Based on theoretical models for BL Her stars (the short-period T2Cs), Di Criscienzo et al. (2007) similarly found a dependence of only ~ 0.04 and $0.06 \text{ mag dex}^{-1}$ in J and K_S , respectively.

While Fig. 1 is consistent with all T2Cs pulsating in the fundamental mode, the previous study of Nemec et al. (1994) claimed that V1, V43, and V60 are actually first-overtone pulsators, while V29, V48, V61, and V92 pulsate in the fundamental mode. However, Fig. 1 does not show parallel sequences occupied by the different stars, as would be expected if they pulsated in different modes (Catelan & Smith 2015). In fact, the pair represented by V60 and V92 overlap in Fig. 1, the former being brighter than the latter by only 0.15 and 0.05 mag in J and K_S , respectively.

Interestingly, V43 and V60 appear consistently brighter than the other stars at the same period (by 0.079 and 0.052 mag in J and K_S , respectively) when the PL relation of Matsunaga et al. (2006) is adopted, shifted to the distance modulus derived with the fundamental-mode candidates. We note that V1 deviates more dramatically from the Matsunaga et al. relation, being brighter by $\sim 0.25 \text{ mag}$ in J and $\sim 0.12 \text{ mag}$ in K_S , but this is likely to be, at least in part, due to saturation (see above). Whether the measured shifts for V43 and V60 would be

Table 1. ω Cen weighted-average distance modulus, based on T2Cs.

Sub-sample	$N_{\star}$	$(J - M_J)_0$ (mag)	$(K_S - M_{K_S})_0$ (mag)
T2Cs (all)	7	13.659 ± 0.121	13.646 ± 0.066
T2Cs (all minus V1)	6	13.663 ± 0.073	13.646 ± 0.061
Fundamental-mode candidates only	4	13.686 ± 0.049	13.664 ± 0.061

consistent with the stars pulsating in the first overtone should be further investigated by theoretical modeling of the PL relation for these stars.

Adopting the calibrated PL relation derived by Matsunaga et al. (2006), the distances for the seven T2Cs can be obtained from their intensity-averaged de-reddened J and K_S magnitudes. Table 1 shows the true distance modulus of the cluster, determined using the weighted average of individual measurements in each bandpass, in three cases: (1) using all the T2Cs of the cluster; (2) discarding V1 (the only RV Tau star) due to the aforementioned saturation effects; (3) considering only the fundamental-mode candidates according to Nemec et al. (1994; i.e., V29, V48, V61, and V92). Reassuringly, and as can be seen from the table, the final derived distance modulus does not depend on either the selected sub-sample or the adopted bandpass.

3.2. RR Lyrae stars

In order to conduct the most accurate study of the RRL PL relation, we first cleaned the sample, which contains 191 RRLs with measured J and K_S magnitudes, by applying the following cuts. First, the field RRL stars V168, V181, V183, and V283 from Kaluzny et al. (2004), and NV457 and NV458 from Navarrete et al. (2015b) were excluded, since they are not members of the cluster (Navarrete et al. 2015b). Next, V165 and V366 were also dropped, as they have periods of ~ 0.5 and 1.0 day, respectively, which does not allow the recovery of the full light curves. Finally, the RRC stars V349 and V351, which are located in the innermost region of the cluster and have inaccurate magnitudes, were discarded as well. As a result, a final sample of 83 RRab and 100 RRC stars was considered in our study of the PL relations in J and K_S . Their positions in the corresponding $\log P$ -magnitude diagrams are shown in Fig. 2.

The four brightest RRL stars with periods ~ 0.63 days ($\log P \sim -0.2$), namely V84, V118, V135, and V139, have been referred to as “overluminous” previously by Del Principe et al. (2006), but from the examination of the *Hubble* Space Telescope (HST) catalog of Anderson & van der Marel (2010), all but V84 have very near companions which could lead to unresolved blends (see Navarrete et al. 2015b). V52 and V143 were not included in the study of Del Principe et al. (2006) but were found to be brighter than other RRab stars because of marked blends (Navarrete et al. 2015b). From this point onwards, these five RRab stars will be discarded from our analysis. V84 is an almost isolated star and its brightness appears to be intrinsic, which could be because it is a foreground RRL or, as Nemec et al. (1994) commented, an ACEP candidate. This possibility will be addressed in Sect. 3.3 and, for now, the star will also be discarded from the RRL sample.

In Fig. 2 there are three RRC stars that appear a little above the other RRC stars with the same period. They are V261, V352, and V353, all with periods of about ~ 0.4 days ($\log P \sim -0.4$). If their magnitudes are well constrained, then their periods might be consistent with second-overtone pulsations, in which case

Fig. 2. De-reddened J and K_S magnitudes versus period for RRLs in ω Cen. RRab stars are shown in red, and RRC stars are shown in blue. The dashed lines correspond to the best least-squares fits to the measurements, carried out separately for the *ab*- and *c*-type RRL, once the labeled stars have been removed from the samples (see text).

they would be candidate RRe stars, for which one might expect $P_2/P_0 \approx 0.57$ (e.g., Catelan & Smith 2015). However, RRe stars are normally expected to be bluer than the RRC stars and to have short periods (Catelan & Smith 2015, and references therein), whereas the long-period V261 and V353 appear redder instead, and fall near the RRab stars in the color–magnitude diagram (CMD; Navarrete et al. 2015b). V352 appears brighter than the RRC stars, but not bluer. It is perhaps more likely that these stars are affected by blends, and should accordingly be discarded from our analysis. As these three stars do not have previous metallicity measurements, they were considered neither in the derivation of empirical PL– Z relations nor in the distance modulus calculation.

Table A.1 lists all the cluster member RRL stars with metallicity measurements from Rey et al. (2000) and/or Sollima et al. (2006a), including their equatorial coordinates, periods, J and K_S intensity-averaged mean magnitudes and their corresponding (statistical) errors, subtypes, and metallicities. Since the number of RRL stars with spectroscopic metallicity is large, our sample allows us to obtain purely empirical PL– Z relations both in J and K_S . To do this, we adopted the metallicities from Sollima et al. (2006a) and “fundamentalized” the periods of RRC stars using the relation $\log P_0 = \log P_1 + 0.127$, corresponding to a period ratio $P_1/P_0 = 0.746$, as adopted by Del Principe et al. (2006). We prefer the metallicities from Sollima et al. (2006a) instead of those derived by Rey et al. (2000) because the former were derived based on high-resolution spectra. The metallicities were transformed into $\log Z$ using the relation

$$\log Z = [\text{Fe}/\text{H}] + \log(0.362 + 0.638 f) + \log Z_{\odot} \quad (1)$$

Fig. 3. *Top panel:* de-reddened J magnitudes versus period with metallicities from Sollima et al. (2006a) in the color-bar. *Bottom panel:* the same as in the top panel, but for the K_S magnitude. Dashed lines are the empirical PL–Z relations derived from our data set, evaluated at the mean RR Lyrae $[\text{Fe}/\text{H}] = -1.67$ dex.

Table 2. Empirical PL–Z relations for RRL stars in ω Cen.

Band	a	b	c	R^2
$m_X = a \log P + b[\text{Fe}/\text{H}] + c$				
J	-1.774 ± 0.061	0.153 ± 0.027	13.079 ± 0.075	0.936
K_S	-2.232 ± 0.044	0.141 ± 0.020	12.752 ± 0.054	0.985

Notes. The relation has the form $m_X = a \log P + b[\text{Fe}/\text{H}] + c$, where X corresponds to the bandpass.

(Salaris et al. 1993), where the α -element enhancement factor $f = 10^{[\alpha/\text{Fe}]}$. For consistency with Catelan et al. (2004), $Z_\odot = 0.017$ and $f = 3$ were adopted. The coefficients and one standard deviation error of the least-squares fit are reported in Table 2. Figure 3 displays the sample used and the PL–Z relations obtained both for J and K_S , evaluated at the mean metallicity of the RRLs, $[\text{Fe}/\text{H}] = -1.67$ dex. As can be seen from the plot, the J -band relation presents more scatter than the K_S one, which is consistent with theoretical expectations (e.g., Catelan et al. 2004) and with the fact that the J -band light curves present higher amplitudes, which can induce more scatter in the corresponding average quantities. The value of the J -band $\log P$ slope a is in excellent agreement with the theoretical predictions, whereas there is a small disagreement in the case of K_S , with the predicted value of a being larger (in absolute value) by about 0.1 (see Table 3 in Coppola et al. 2011). As far as the metallicity dependence is concerned, our derived b slopes are significantly steeper than was reported in Sollima et al. (2006b), but only slightly steeper than predicted by the Catelan et al. (2004) models. Naturally, we anticipate that the *Gaia* mission (Clementini et al. 2016) will provide the accurate distances to RR Lyrae stars that are needed in order to establish the definitive slopes and zero points of the PL–Z relations. In the meantime, however, considering the reasonable agreement between the Catelan et al. (2004) model predictions and our results, we will employ the former in the remainder of our analysis.

In order to estimate the distance modulus of the cluster based on RRL stars, the calibrated theoretical PL–Z relations in the

Table 3. Distance moduli based on RRLs using spectroscopic metallicities and different pulsational modes.

	$(J - M_J)_0$ (mag)	$(K_S - M_{K_S})_0$ (mag)
Metallicities from Rey et al. (2000)		
RRab (64 stars)	13.728 ± 0.063	13.752 ± 0.043
RRc (53 stars)	13.685 ± 0.058	13.709 ± 0.047
RRab+RRc (117 stars)	13.698 ± 0.064	13.722 ± 0.049
Metallicities from Sollima et al. (2006)		
RRab (33 stars)	13.706 ± 0.042	13.746 ± 0.027
RRc (31 stars)	13.693 ± 0.047	13.728 ± 0.040
RRab+RRc (64 stars)	13.698 ± 0.046	13.735 ± 0.036

VISTA filter system for the J and K_S bands (Eqs. (1) and (3) in Alonso-García et al. 2015, which were adapted from Catelan et al. 2004) were used. PL relations for RRL stars have a non-negligible dependence on metallicity, even though the dependence is lower in the near-IR bands compared to the optical (e.g., Catelan et al. 2004). Using the metallicities spectroscopically derived for RRL stars in ω Cen by Rey et al. (2000) and Sollima et al. (2006a), the distance modulus for the cluster was calculated using: (1) only the RRab stars; (2) only the RRc stars; and (3) all RRab and RRc stars. The periods of RRc stars were fundamentalized, as noted previously. $[\text{Fe}/\text{H}]$ values for 64 and 53 RRab and RRc stars, respectively, are available in the catalog of Rey et al. (2000), while from Sollima et al. (2006a) the metallicities of 33 RRab and also 31 RRc stars were considered. Seven RRL from Rey et al. and four from Sollima et al. were not considered as they do not have reported errors in the metallicities, those measurements being highly uncertain. Both metallicity catalogs were compared by Sollima et al., who found a systematic offset of $\Delta[\text{Fe}/\text{H}]$ (Sollima et al. – Rey et al.) = -0.06 dex, with a dispersion of 0.3 dex. Because of that, the two metallicity sources were treated separately. The weighted-average distance modulus found with the J and K_S magnitudes of the individual RRLs in the three different cases are listed in Table 3.

Figure 4 shows the magnitude differences between the mean J (upper panels) and K_S (bottom panels) magnitudes and the derived PL–Z relations (listed in Table 3), as a function of the metallicity from Sollima et al. (2006a) and Rey et al. (2000). As expected, there is less scatter for the K_S magnitudes (right panels), compared to the residuals for the J band (left panels). The 3σ residuals are ~ 0.13 and 0.10 mag for J and K_S , respectively, considering the metallicities derived by Sollima et al. (2006a). When the metallicities of Rey et al. (2000) are adopted, the 3σ residuals are slightly larger, with 0.19 and 0.13 mag for J and K_S magnitudes, respectively. For both J and K_S , the residuals as a function of the $[\text{Fe}/\text{H}]$ values derived by Sollima et al. (2006a) are clustered around zero, and there is no evident trend with metallicity, proving that the metallicity term in the derived PL–Z relations is well represented by the fit. Nonetheless, for the metallicities derived by Rey et al. (2000), there seems to be a small correlation between metallicities and magnitudes. However, we emphasize that our relations (Table 2) were derived using the metallicities from Sollima et al. (2006a), who used high-resolution spectroscopy in their work, presumably leading to more accurate values than in the case of the ΔS method used by Rey et al. (2000).

Fig. 4. Difference between the observed mean magnitudes and the derived PL–Z relations as a function of metallicity. *Top panels:* show the residuals for J , while the residuals in K_S are shown in the *bottom panels*. *Left and right panels:* correspond to the metallicities derived by Sollima et al. (2006a) and Rey et al. (2000), respectively.

3.3. Anomalous Cepheids

Figure 2 shows that one R Rab star, namely V84, is brighter than any other R Rab that follows the PL relation, reaching the region where the R Rc stars are located. However, the position in the CMD is in agreement with a cluster member star (Navarrete et al. 2015b). The period was first derived by Bailey (1902) and confirmed by the J and K_S light curves, discarding an R Rc classification. However, Sandage (1990), Longmore et al. (1990), and Nemec et al. (1994) all proposed that V84 and also V15, V68 (the longest-period R Rc star in the cluster), and V99 could be ACEPs, rather than RRL stars.

Sparse measurements in the near-IR have been done for ACEPs. Only recently, Ripepi et al. (2014a) presented a large catalog of ACEPs in the Large Magellanic Cloud which have been gathered using near-IR observations performed by the VMC (Cioni et al. 2011).

Figure 5 shows the PL relation for the ACEPs at the ω Cen distance using the calibrated PL relation derived by Ripepi et al. (2014a), and adopting $\mu_0 = 13.708$ mag as ω Cen’s true distance modulus (see Sect. 4). The PL relation is shown as a dotted line and the dashed lines above and below it represent ± 0.1 mag deviations.

As can be noted, between $\log P \sim -0.35$ and ~ -0.18 , the ACEPs and R Rc PL relations cover a similar region of magnitudes, which does not allow us to cleanly separate both types of stars based on this diagram if they are both at the same distance. Thus, using the magnitudes from VISTA it is not possible to confirm or to reject the possibility that V68 and V84 are ACEPs in ω Cen. If V84 is not an ACEP, it should be a foreground R Rab. V15 and V99, the other R Rab stars proposed as ACEP candidates, follow closely the R Rab PL relation, as can also be seen in Fig. 3, discarding the possibility of being ACEP variables.

3.4. SX Phoenixis

The ω Cen field contains a large number of SX Phoenixis stars – larger, in fact, than for any other GC – thus providing an excellent opportunity to calibrate the SX Phe PL relation. Previous such studies have, however, been limited to the optical.

Fig. 5. De-reddened K_S magnitudes versus period around the locations of V68 and V84, two candidate ACEPs in ω Cen. The mean trend of R Rab and R Rc are denoted by the black dashed lines, whereas the dotted line shows the K_S –PL relation for ACEPs, as derived by Ripepi et al. (2014a), shifted to the adopted distance modulus of $\mu_0 = 13.708$ mag. The gray dashed lines represent ± 0.1 mag deviations around the latter relation.

Nemec et al. (1994) considered the B and V magnitudes of three SX Phe stars from ω Cen as well as 11 more from other GCs in order to derive observational PL relations. McNamara (2011) considered most of the known SX Phe in ω Cen (not including the five SX Phe stars from Weldrake et al. 2007), finding a high spread in the $\log P - \langle V \rangle$ diagram (see his Fig. 9), which may be partially explained by the variation of metallicity values in the cluster stars. Nevertheless, there are no previous metallicity measurements for the SX Phe stars in the cluster. According to McNamara (2011), the scatter can be reduced by selecting a subsample of SX Phe stars with long periods ($\log P \geq -1.47$), which he argues are likely to be metal-poor ($[\text{Fe}/\text{H}] \leq -1.0$), fundamental-mode pulsators.

When plotting the $\log P - J$ and $-K_S$ diagrams, the same situation as in McNamara (2011; i.e., high spread) is found, as can be seen in Fig. 6. The field SX Phe stars, namely the foreground star V65 and the background stars V297 and ID-92 from Weldrake et al. (2007), were not included in the diagram.

The large amount of scatter notwithstanding, Fig. 6 also reveals the presence of a tight “lower envelope” of stars, below which only a handful of faint stragglers are found. We conjecture that this may correspond to the sequence of fundamental-mode pulsators in the cluster. The five stars located below this lower envelope (V302, V307, V315, V323, and V324) are probably non-radial pulsators. The three stars with the shortest-periods (V294, V295, and V296, with $\log P < -1.6$) are likely high-overtone pulsators. The longest-period star, V328, is considered a fundamental-mode pulsator (Olech et al. 2005), but its magnitudes in the visible and in the J and K_S bands are fainter than the linear trend that the other stars at shorter periods define. Because of that, it will also be excluded to derive the fundamental-mode PL relation for SX Phe stars.

Table A.2 presents the variable ID, equatorial coordinates, periods, and intensity-averaged J and K_S magnitudes for the 45 SX Phe fundamental-mode candidates. The stars that exhibit light curves with clear evidence of variability are explicitly tagged as “Variability recovered” in this table. Figure 7 shows the thus selected 45 fundamental-mode candidates, in which

Fig. 6. De-reddened J and K_S magnitudes versus period for all the SX Phe stars that appear to be members of the cluster. Those from Kaluzny et al. (2004) are plotted as orange diamonds while the star symbols denote those discovered by Weldrake et al. (2007). The “lower-envelope” stars that tentatively follow a common trend and would correspond to fundamental-mode pulsators are shown in purple.

three of the four SX Phe stars from Weldrake et al. (2007) are included. In Fig. 7, the dotted lines represent the least-squares best fit to the fundamental-mode candidates, while the dashed lines are the expected PL relation for first-overtone pulsators, assuming that both relations are parallel and adopting a ratio of the first-overtone period to the fundamental-mode period of ~ 0.775 (McNamara 2011), which implies a magnitude shift (at fixed $\log P$) of 0.26 and 0.37 mag for J and K_S , respectively.

Based on these 45 selected SX Phe stars, observational PL relations for the fundamental mode candidates obtained are

$$J_0 = -(3.04 \pm 0.17) \log P + (12.10 \pm 0.22), \quad (2)$$

$$\sigma = 0.09 \text{ mag},$$

$$K_{S,0} = -(3.39 \pm 0.24) \log P + (11.51 \pm 0.30), \quad (3)$$

$$\sigma = 0.11 \text{ mag}.$$

The dispersion around both these relations are quite similar and smaller than that associated to the V -band relation derived by McNamara (2011), being the latter 0.13 mag. This difference is mainly due to the intrinsic dispersion of the optical PL relations compared to the near-IR for any type of pulsating variable star (Catelan & Smith 2015). Despite the fact that most of the light curves of the SX Phe stars could not be fully recovered, their behavior in the $\log P$ –magnitude diagram is consistent with most of them pulsating in the fundamental mode.

However, according to Olech et al. (2005), there are some first-overtone SX Phe among the ones that we have considered as fundamental-mode pulsators. Figure 8 shows the same stars as Fig. 7 but now the fundamental-mode and first-overtone candidates as derived by Olech et al. are plotted as purple circles and yellow triangles, respectively. The diagram includes the four SX Phe (members of the cluster) discovered by Weldrake et al., after the study of Olech et al. was published (open stars).

From the figure, the SX Phe found by Weldrake et al. (2007) are consistent with three of them pulsating in the fundamental mode. On the other hand, the one with the longest period, namely ID-7 (at $\log P \sim -1.16$), appears as a bona fide first-overtone pulsator. The other SX Phe stars, despite being considered first-overtone pulsators by Olech et al. (2005), follow the PL relations

Fig. 7. Fundamental-mode SX Phe candidates from which observational J_0 and $K_{S,0}$ PL relations were derived. The dotted lines correspond to the best least-squares fit associated to each filter. The dashed lines correspond to the expected position of the first-overtone pulsators, assuming that fundamental and first-overtone PL relations are parallel.

as given by Eqs. (2) and (3), suggesting that they too may be fundamental-mode pulsators.

4. On the ω Cen pulsational distance modulus

4.1. Systematic errors

Before we adopt a pulsational distance modulus for ω Cen, based on the different values obtained using T2Cs and RRL stars, the different sources of systematic errors will be evaluated.

In the case of T2Cs, one possible source of systematic error in the distance modulus values is that some first-overtone pulsators could be considered as pulsating in the fundamental mode. To estimate the error associated to this, we could consider the difference between the distance modulus obtained when different stars are used, as listed in Table 1. Adopting the J and K_S -based true distance moduli derived using W Vir and BL Her stars, the systematic errors should be at least 0.04 and 0.03 mag, respectively. The metallicity term could constitute an additional source of systematic errors but, given the low metallicity dependence of the T2C PL relation, we expect that these errors are lower than 0.01 mag, both in J and in K_S .

In the case of RRL stars, one source of systematic error could be provided by the sample choice, that is, including or not fundamental and first-overtone pulsators simultaneously in the fits. Del Principe et al. (2006) found, based on synthetic HB models, that the relations for fundamental and first-overtone RRL are not exactly parallel, and that the use of fundamentalized RRL periods produces an increase (by a factor of two) in the uncertainty of the zero points and slopes of their relations. Nevertheless, Catelan et al. (2004) still found tight near-IR PL relations, considering RRab and (fundamentalized) RRC at the same time.

Table 3 lists the three possible cases, that is, using only RRab, only RRC (with fundamentalized periods), and RRL stars from both pulsational modes (again with RRC periods fundamentalized). The metallicities derived by Sollima et al. (2006a) seem to be more accurate (i.e., close to the actual metallicity of the stars) than the ones derived by Rey et al., in the sense that more precise distance moduli are obtained. The fact that the results are always consistent (to within the errors), irrespective of the adopted subsample, suggests that RRab and (fundamentalized)

Fig. 8. Fundamental (in purple circles) and first-overtone (in yellow triangles) SX Phe as classified by Olech et al. (2005), based on their frequency spectrum. The dotted lines are the PL relations derived previously. As can be seen, there are some claimed first-overtone pulsators that also follow the relations defined by fundamental-mode pulsators.

Table 4. Adopted distance moduli based on T2Cs and RRL stars.

	$\mu_0(J)$ (mag)	σ_{total} (mag)	$\mu_0(K_s)$ (mag)	σ_{total} (mag)
T2Cs	13.675	0.042	13.652	0.031
RRLs	13.701	0.024	13.733	0.017

RRL stars do indeed follow closely the same PL relation in the near-IR.

Comparison between the different distance moduli obtained using the two different sources of metallicity in Table 3 suggests to us that the metallicity scale can be one source of systematic error in the final derived distance modulus. Based on these results, we adopt a value of 0.02 and 0.01 mag for J and K_s respectively, as representative of the main identified sources of systematic errors affecting the ω Cen distance modulus, as derived on the basis of the near-IR PL relations for RRL stars. Moreover, the individual metallicities for RRL stars have errors of the order of ~ 0.19 and 0.31 dex, as reported by Rey et al. (2000) and Sollima et al. (2006a), respectively. These uncertainties, propagated into the PL–Z relations used to derive the distance modulus, add the following errors: 0.04 and 0.03 mag for J and K_s distance modulus, with metallicities from Rey et al., and 0.06 and 0.05 mag for the J and K_s values derived with the metallicities from Sollima et al. At the same time, results from previous studies (e.g., Cacciari & Clementini 2003; Del Principe et al. 2006; Feast et al. 2008; Gran et al. 2015) suggest that distances derived on the basis of such relations can probably not yet be considered accurate to better than about ± 0.1 mag. Thus, we adopt the latter value as a conservative estimate of the systematic error affecting the distance moduli provided in our study.

4.2. Pulsational distance modulus from T2Cs and RRL stars

Table 4 lists the weighted-average distance modulus values from T2Cs and RRL stars and sigma as the dispersion around the mean. The weights for each individual distance modulus values were defined as the inverse of the squared of the total error, including statistical and systematic errors (summed up

in quadrature). As expected, the error is lower for the K_s –PL relations compared to J , since the former have lower intrinsic dispersion, and is based on a more extensive dataset. Comparing both variability types, T2Cs lead to a less accurate distance modulus, probably because they are few in number, which increases the statistical error, and they have higher systematic errors since the effect of metallicity and pulsation mode separation in the derivation of the PL relations is not completely established.

Considering the distance modulus values found using T2Cs stars as well as RRL stars, both in J and K_s , the weighted-average distance modulus to ω Cen was determined, leading to a final value of $\mu_0 = 13.708 \pm 0.035$ mag, where the error bar corresponds to the standard deviation of the mean. Given the discussion of systematic errors in the previous section, our final adopted distance modulus is $\mu_0 = 13.708 \pm 0.035 \pm 0.10$ mag, where the error bars correspond to the adopted statistic and systematic errors, respectively. Adding the errors in quadrature (as recommended, for instance, by Barlow et al. 2002), this corresponds to a heliocentric distance of 5.52 ± 0.27 kpc.

As a further check, we have also explored the results of Feast (2011), who suggested that T2Cs and RRL follow basically the same PL relation in K . Using metallicities for the T2Cs from Gonzalez & Wallerstein (1994) and van Loon et al. (2007), and assuming that the same near-IR relation as for the RRL applies also to the T2Cs, we obtain for the latter a distance modulus of $\mu_0 = 13.70 \pm 0.04$ mag (standard deviation of the mean), in excellent agreement with the previously derived value. On the other hand, carrying out the same analysis using the J -band data does not provide similarly consistent results, with a resulting distance modulus that is shorter by about 0.3 mag. This suggests that the T2Cs and RRL stars may indeed follow the same PL relation in K_s , but not in J .

Table 5 lists some of the true distance modulus values for ω Centauri found in the literature. In order to put all of them in the same system, the color excess was set as $E(B - V) = 0.12$ mag, a standard extinction law with $R_V = 3.1$ was adopted, and the apparent V distance moduli were converted accordingly. The work of Caputo et al. (2002) listed some of ω Cen’s distance moduli derived in the literature and compared them, considering the influence of the metallicity spread as well as the possible helium enhancement associated to second-generation stars in the cluster. Distance modulus values based on PL–HB type relations were derived for different α -enhancement levels by Del Principe et al. (2006), and compared with other values from the literature.

The distance modulus found in this work appears in excellent agreement with most of the values listed in Table 5. The distance modulus derived by Del Principe et al. (2006), using a combination of near-IR light curves and 2MASS single-epoch magnitudes for different RRL stars in the cluster, appears quite similar to the average value found using our fully phase-folded light curves derived from VISTA filters.

4.3. Difference between T2C- and RRL-based distance moduli

The ω Cen distance modulus values derived using T2Cs appear shorter than those found with the RRL stars, by an amount ranging from 0.03 mag in J to 0.08 mag in K_s (see Table 4). Such a difference could not be explained by the metallicity term in the T2Cs PL relations as, if included, the corresponding distance moduli would be even lower.

Table 5. Distance modulus for ω Cen from the literature.

Method	μ_0 (mag) ^a	Reference
<i>B</i> and <i>V</i> PL relations for Pop. II stars	13.53 ± 0.20	Nemec et al. (1994)
High-amplitude δ Sct stars	14.05 ± 0.10	McNamara (2000) ^b
Detached eclipsing binary (V212)	13.68 ± 0.11	Thompson et al. (2001)
Detached eclipsing binary (V212)	13.72 ± 0.04	Kaluzny et al. (2002)
A_V -log <i>P</i> models for RRab stars	13.64 ± 0.11	Caputo et al. (2002)
M_V -log <i>P</i> models for RRC stars	13.71 ± 0.11	Caputo et al. (2002)
M_V – [Fe/H] relation (RRL stars)	13.72 ± 0.11	Del Principe et al. (2006) ^c
M_V – [Fe/H] relation (RRL stars)	13.62 ± 0.11	Del Principe et al. (2006) ^d
PL– $Z(K_S)$	13.77 ± 0.07	Del Principe et al. (2006) ^e
PL– $\tau_{HB}(K_S, f = 3, \tau_{HB} = 0.940)$	13.69 ± 0.06	Del Principe et al. (2006)
PL– $\tau_{HB}(J, f = 3, \tau_{HB} = 0.940)$	13.70 ± 0.10	Del Principe et al. (2006)
PL– $\tau_{HB}(K_S, f = 3, \tau_{HB} = 0.934)$	13.72 ± 0.06	Del Principe et al. (2006) ^f
PL– $\tau_{HB}(J, f = 3, \tau_{HB} = 0.934)$	13.76 ± 0.10	Del Principe et al. (2006)
Cluster dynamics	13.41 ± 0.14	van de Ven et al. (2006)
M_V – [Fe/H] relation (RRL stars)	13.68 ± 0.27	Weldrake et al. (2007)
SX Phe log <i>P</i> – <i>V</i> relation	13.76 ± 0.06	McNamara (2011)
Optical Period–Wesenheit relations (RRL stars)	13.71 ± 0.08	Braga et al. (2016)
Weighted average	13.72 ± 0.13	
Weighted-average PL relations (T2Cs and RRLs)	13.708 ± 0.035	This work

Notes. ^(a) Most of the error estimates do not consider the contribution of systematic errors, which in the case of T2Cs and RRL stars can reach values of order ≈ 0.10 mag. ^(b) The listed error was determined considering the internal uncertainties of the mean distance modulus value, ± 0.02 mag, and the observational error, ± 0.1 mag, as described by McNamara (2000). ^(c) Based on the M_V -[Fe/H] relation from Bono et al. (2003) and mean *V* magnitudes from Kaluzny et al. (2004). ^(d) Based on the M_V -[Fe/H] relation of Catelan et al. (2004) and *V* magnitudes from Kaluzny et al. (2004). ^(e) Based on the semi-empirical *J*-band PL– Z relation from Bono et al. (2003). ^(f) Based on the PL– τ_{HB} relations from Catelan et al. (2004).

One possible explanation for the difference could rest on the multiple populations in ω Cen and the associated helium enhancement (Caputo et al. 2002; Sollima et al. 2006a; Marconi et al. 2011). He-rich stars are expected to populate the bluest part of the HB, where the T2C progenitors are thought to be located, thus those stars affect the magnitudes and pulsational periods of T2Cs with respect to the expected ones for stars with primordial helium abundance.

Nonetheless, Marconi et al. (2011) developed evolutionary and pulsational models in order to derive the number of variable stars in the HB of ω Cen considering different helium abundances. The authors compared the number fraction of T2Cs over the number of variable stars in the instability strip as predicted by the models and the observed one. For $Y = 0.24$, 2% of T2Cs are found with the models, in good agreement with the observational 3%. Helium enhancement is taken into account considering two stellar populations with primordial initial helium abundances (80% of the stars) and enhanced-helium ($Y = 0.3$, 20% of the stars). It was found that the percentage of expected T2Cs, 5%, would be higher than the one actually observed. This suggests that T2C stars in ω Cen are predominantly not He-enhanced.

For RRL stars, the authors found that the minimum fundamentalized period predicted by the models is in good agreement with the observed values of 0.34 days when the primordial helium abundance is considered. At higher helium abundance values, the shortest fundamentalized period increases, which is not observed. This also suggests that RRL stars in ω Cen are not He-enhanced.

We thus conclude that other sources of systematic error will have to be investigated, in order to explain the origin of the difference in distance moduli obtained on the basis of the T2C and RRL near-IR PL relations.

5. Conclusions

We have presented the implications of our recent, extensive time-series photometry of ω Cen (Navarrete et al. 2015b) for the near-IR (VISTA *J* and K_S) PL relations of different types of pulsators along the “classical” instability strip. These include T2Cs, ACEPs, RRL, and SX Phe stars. For the T2Cs and RRL stars, for which the corresponding near-IR relations had previously been calibrated, we use the results to obtain a new distance modulus estimate for the cluster, $\mu_0 = 13.708 \pm 0.035 \pm 0.10$ mag, where the error bars correspond to the adopted statistical and systematic errors, respectively. Adding the errors in quadrature, this is equivalent to a heliocentric distance of 5.52 ± 0.27 kpc, which is in excellent agreement with previous results from the literature¹. An offset between the T2C and RRL-based result, at the level of a few hundredths of a magnitude (with the T2Cs implying a smaller distance), is however present, for reasons which are not completely clear at present.

The sizable number of RRL stars in the cluster allows us to derive new empirical near-IR PL– Z relations in the *J* and K_S bandpasses. Adopting as the true distance modulus of the cluster $\mu_0 = 13.708$ mag, the PL– Z relations presented in Table 2, in

¹ After we submitted our paper, Bhardwaj et al. (2017) published new near-IR PL and Period–Wesenheit relations for T2Cs, using template-fit *I* and K_S light curves. Combining both relations, the authors derived a true distance modulus for ω Cen of $\mu(K_S) = 13.70 \pm 0.11$ mag, in good agreement with our derived distance modulus based on RRL stars, but slightly different from the distance modulus derived by Matsunaga et al. (2006) using T2Cs and the K_S -band relation.

terms of the absolute magnitude, are given by

$$M_J(\text{RRL}) = -(1.77 \pm 0.06) \log P \\ + (0.15 \pm 0.03)[\text{Fe}/\text{H}] - (0.63 \pm 0.08), \quad (4)$$

$$M_{K_S}(\text{RRL}) = -(2.23 \pm 0.04) \log P \\ + (0.14 \pm 0.02)[\text{Fe}/\text{H}] - (0.96 \pm 0.05). \quad (5)$$

For the ACEPs, we show that their expected positions in the near-IR PL relations are very similar to those of RRc stars. This makes it difficult to properly establish their pulsation status on the basis of our near-IR data alone.

For the SX Phe stars, we provide, for the first time, a calibration of their near-IR PL relation. Using a true distance modulus of $\mu_0 = 13.708$ mag for the cluster, and combining with Eqs. (2) and (3), we obtain

$$M_J(\text{SX Phe}) = -(3.04 \pm 0.17) \log P - (1.60 \pm 0.22), \quad (6)$$

$$M_{K_S}(\text{SX Phe}) = -(3.39 \pm 0.24) \log P - (2.19 \pm 0.30). \quad (7)$$

In the next (and final) paper of this series (Navarrete et al., in prep.), we will present our full near-IR catalog of variable stars in the ω Cen field.

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References

- Alcock, C., Allsman, R. A., Alves, D. R., et al. 2000, *ApJ*, **536**, 798
- Alonso-García, J., Mateo, M., Sen, B., et al. 2012, *AJ*, **143**, 70
- Alonso-García, J., Dékány, I., Catelan, M., et al. 2015, *AJ*, **149**, 99
- Altmann, M., Catelan, M., & Zoccali, M. 2005, *A&A*, **439**, L5
- Anderson, J., & van der Marel, R. P. 2010, *ApJ*, **710**, 1032
- Angeloni, R., Contreras Ramos, R., Catelan, M., et al. 2014, *A&A*, **567**, A100
- Bailey, S. I. 1902, *Annals of Harvard College Observatory*, **38**, 1
- Barlow, R., Cahn, R., Cowan, G., et al. 2002, BABAR Analysis Document, 318, 1
- Bedin, L. R., Piotto, G., Anderson, J., et al. 2004, *ApJ*, **605**, L125
- Bekki, K., & Norris, J. E. 2006, *ApJ*, **637**, L109
- Bhardwaj, A., Macri, L. M., Rejkuba, M., et al. 2017, *AJ*, **153**, 154
- Bono, G., Caputo, F., Castellani, V., et al. 2003, *MNRAS*, **344**, 1097
- Braga, V. F., Stetson, P. B., Bono, G., et al. 2016, *AJ*, **152**, 170
- Cacciari, C., & Clementini, G. 2003, in *Stellar Candles for the Extragalactic Distance Scale*, eds. D. Alloin, & W. Gieren (Berlin: Springer Verlag), *Lect. Notes Phys.*, **ASP Conf. Ser.**, **635**, 105
- Caputo, F., degl'Innocenti, S., & Marconi, M. 2002, in *Omega Centauri, A Unique Window into Astrophysics*, eds. F. van Leeuwen, J. D. Hughes, & G. Piotto, *ASP Conf. Ser.*, **265**, 185
- Catelan, M., & Smith, H. A. 2015, *Pulsating Stars* (Wiley-VCH)
- Catelan, M., Pritzl, B. J., & Smith, H. A. 2004, *ApJS*, **154**, 633
- Catelan, M., Minniti, D., Lucas, P. W., et al. 2011, in *RR Lyrae Stars, Metal-Poor Stars, and the Galaxy*, ed. A. McWilliam, Carnegie Observatory Series, **5**, 145
- Catelan, M., Dékány, I., Hempel, M., & Minniti, D. 2013a, *BAAA*, **56**, 153
- Catelan, M., Minniti, D., Lucas, P. W., et al. 2013b, in *40 Years of Variable Stars: A Celebration of Contributions by Horace A. Smith*, eds. K. Kinemuchi et al., **141**
- Cioni, M.-R. L., Clementini, G., Girardi, L., et al. 2011, *A&A*, **527**, A116
- Clement, C. M., Muzzin, A., Dufton, Q., et al. 2001, *AJ*, **122**, 2587
- Clementini, G., Ripepi, V., Leccia, S., et al. 2016, *A&A*, **595**, A133
- Cohen, R. E., & Sarajedini, A. 2012, *MNRAS*, **419**, 342
- Coppola, G., Dall'Ora, M., Ripepi, V., et al. 2011, *MNRAS*, **416**, 1056
- Da Costa, G. S., & Coleman, M. G. 2008, *AJ*, **136**, 506
- Dalton, G. B., Caldwell, M., Ward, A. K., et al. 2006, in *SPIE Conf. Ser.*, **6269**
- Del Principe, M., Piersimoni, A. M., Storm, J., et al. 2006, *ApJ*, **652**, 362
- Di Criscienzo, M., Caputo, F., Marconi, M., & Cassisi, S. 2007, *A&A*, **471**, 893
- Dinescu, D. I. 2002, in *Omega Centauri, A Unique Window into Astrophysics*, eds. F. van Leeuwen, J. D. Hughes, & G. Piotto, *ASP Conf. Ser.*, **265**, 365
- D'Souza, R., & Rix, H.-W. 2013, *MNRAS*, **429**, 1887
- Dupree, A. K., & Avrett, E. H. 2013, *ApJ*, **773**, L28
- Dupree, A. K., Strader, J., & Smith, G. H. 2011, *ApJ*, **728**, 155
- Emerson, J., & Sutherland, W. 2010, *The Messenger*, **139**, 2
- Feast, M. 2011, in *RR Lyrae Stars, Metal-Poor Stars, and the Galaxy*, ed. A. McWilliam, Carnegie Observatory Series, **5**, 170
- Feast, M. W., Laney, C. D., Kinman, T. D., van Leeuwen, F., & Whitelock, P. A. 2008, *MNRAS*, **386**, 2115
- Fernández-Trincado, J. G., Robin, A. C., Vieira, K., et al. 2015, *A&A*, **583**, A76
- Gonzalez, G., & Wallerstein, G. 1994, *AJ*, **108**, 1325
- Gran, F., Minniti, D., Saito, R. K., et al. 2015, *A&A*, **575**, A114
- Harris, W. E. 1996, *AJ*, **112**, 1487
- Harris, W. E. 2010, ArXiv e-prints [[arXiv:1012.3224](https://arxiv.org/abs/1012.3224)]
- Johnson, C. I., Pilachowski, C. A., Michael Rich, R., & Fulbright, J. P. 2009, *ApJ*, **698**, 2048
- Joo, S.-J., & Lee, Y.-W. 2013, *ApJ*, **762**, 36
- Kaluzny, J., Thompson, I., Krzeminski, W., et al. 2002, in *Omega Centauri, A Unique Window into Astrophysics*, ed. F. van Leeuwen, J. D. Hughes, & G. Piotto, *ASP Conf. Ser.*, **265**, 155
- Kaluzny, J., Olech, A., Thompson, I. B., et al. 2004, *A&A*, **424**, 1101
- Klein, C. R., & Bloom, J. S. 2014, ArXiv e-print [[arXiv:1404.4870](https://arxiv.org/abs/1404.4870)]
- Klein, C. R., Richards, J. W., Butler, N. R., & Bloom, J. S. 2014, *MNRAS*, **440**, L96
- Longmore, A. J., Fernley, J. A., & Jameson, R. F. 1986, *MNRAS*, **220**, 279
- Longmore, A. J., Dixon, R., Skillen, I., Jameson, R. F., & Fernley, J. A. 1990, *MNRAS*, **247**, 684
- Marconi, M., Bono, G., Caputo, F., et al. 2011, *ApJ*, **738**, 111
- Matsunaga, N., Fukushi, H., Nakada, Y., et al. 2006, *MNRAS*, **370**, 1979
- McGonegal, R., McAlary, C. W., McLaren, R. A., & Madore, B. F. 1983, *ApJ*, **269**, 641
- McNamara, D. H. 1995, *AJ*, **109**, 1751
- McNamara, D. H. 2000, *PASP*, **112**, 1096
- McNamara, D. H. 2011, *AJ*, **142**, 110
- Meylan, G., Sarajedini, A., Jablonka, P., et al. 2001, *AJ*, **122**, 830
- Meza, A., Navarro, J. F., Abadi, M. G., & Steinmetz, M. 2005, *MNRAS*, **359**, 93
- Minniti, D., Lucas, P. W., Emerson, J. P., et al. 2010, *New Astron.*, **15**, 433
- Navarrete, C., Catelan, M., Contreras Ramos, R., et al. 2013, *IBVS*, **6078**, 1
- Navarrete, C., Chanamé, J., Ramírez, I., et al. 2015a, *ApJ*, **808**, 103
- Navarrete, C., Contreras Ramos, R., Catelan, M., et al. 2015b, *A&A*, **577**, A99
- Nemec, J. M., Nemec, A. F. L., & Lutz, T. E. 1994, *AJ*, **108**, 222
- Norris, J. E. 2004, *ApJ*, **612**, L25
- Olech, A., Dziembowski, W. A., Pamyatnykh, A. A., et al. 2005, *MNRAS*, **363**, 40
- Petersen, J. O., & Christensen-Dalsgaard, J. 1999, *A&A*, **352**, 547
- Piotto, G., Villanova, S., Bedin, L. R., et al. 2005, *ApJ*, **621**, 777
- Rey, S.-C., Lee, Y.-W., Joo, J.-M., Walker, A., & Baird, S. 2000, *AJ*, **119**, 1824
- Ripepi, V., Marconi, M., Moretti, M. I., et al. 2014a, *MNRAS*, **437**, 2307
- Ripepi, V., Moretti, M. I., Marconi, M., et al. 2015, *MNRAS*, **446**, 3034
- Ripepi, V., Marconi, M., Moretti, M. I., et al. 2016, *ApJS*, **224**, 21
- Saito, R. K., Hempel, M., Minniti, D., et al. 2012, *A&A*, **537**, A107
- Salaris, M., Chieffi, A., & Straniero, O. 1993, *ApJ*, **414**, 580
- Sandage, A. 1990, *ApJ*, **350**, 603
- Schechter, P. L., Mateo, M., & Saha, A. 1993, *PASP*, **105**, 1342
- Sollima, A., Borissova, J., Catelan, M., et al. 2006a, *ApJ*, **640**, L43
- Sollima, A., Cacciari, C., & Valenti, E. 2006b, *MNRAS*, **372**, 1675
- Stetson, P. B. 1987, *PASP*, **99**, 191
- Stetson, P. B. 1994, *PASP*, **106**, 250
- Tailo, M., Di Criscienzo, M., D'Antona, F., Caloi, V., & Ventura, P. 2016, *MNRAS*, **457**, 4525
- Templeton, M., Basu, S., & Demarque, P. 2002, *ApJ*, **576**, 963
- Thompson, I. B., Kaluzny, J., Pych, W., et al. 2001, *AJ*, **121**, 3089
- Valcarce, A. A. R., & Catelan, M. 2011, *A&A*, **533**, A120
- van der Marel, R. P., & Anderson, J. 2010, *ApJ*, **710**, 1063
- van de Ven, G., van den Bosch, R. C. E., Verolme, E. K., & de Zeeuw, P. T. 2006, *A&A*, **445**, 513
- van Loon, J. T., van Leeuwen, F., Smalley, B., et al. 2007, *MNRAS*, **382**, 1353
- Weldrake, D. T. F., Sackett, P. D., & Bridges, T. J. 2007, *AJ*, **133**, 1447

Appendix A: Catalog

Table A.1. Catalog of RR Lyrae stars in ω Cen field, used to derive the empirical PL relations.

ID	RA (J2000.0) hh:mm:ss.ss	Dec (J2000.0) dd:mm:ss.s	P (days)	J (mag)	e (mag)	K_s (mag)	e (mag)	Type	[Fe/H] (R00)	[Fe/H] (S06)
V3	13:25:56.14	-47:25:54.2	0.841258	13.152	0.008	12.821	0.003	RRab	-1.54 ± 0.05	
V4	13:26:12.91	-47:24:19.2	0.627320	13.376	0.051	13.059	0.005	RRab	-1.74 ± 0.05	
V5	13:26:18.31	-47:23:12.8	0.515274	13.626	0.032	13.362	0.005	RRab	-1.35 ± 0.08	-1.24 ± 0.11
V7	13:27:01.02	-47:14:00.1	0.713000	13.290	0.012	12.947	0.003	RRab	-1.46 ± 0.08	
V8	13:27:48.43	-47:28:20.7	0.521329	13.575	0.013	13.275	0.004	RRab	-1.91 ± 0.28	
V9	13:25:59.57	-47:26:24.4	0.523315	13.694	0.025	13.399	0.006	RRab	-1.49 ± 0.06	
V10	13:26:06.99	-47:24:37.0	0.375125	13.493	0.007	13.271	0.003	RRc	-1.66 ± 0.10	
V11	13:26:30.54	-47:23:01.9	0.564798	13.415	0.008	13.168	0.004	RRab	-1.67 ± 0.13	-1.61 ± 0.22
V12	13:26:27.17	-47:24:06.6	0.386769	13.467	0.004	13.234	0.002	RRc	-1.53 ± 0.14	
V14	13:25:59.66	-47:39:09.9	0.377114	13.567	0.004	13.317	0.002	RRc	-1.71 ± 0.13	
V15	13:26:27.08	-47:24:38.4	0.810642	13.133	0.013	12.824	0.002	RRab	-1.64 ± 0.39	-1.68 ± 0.18
V16	13:27:37.71	-47:37:35.2	0.330202	13.675	0.005	13.453	0.002	RRc	-1.29 ± 0.08	-1.65 ± 0.46
V18	13:27:45.06	-47:24:56.9	0.621689	13.372	0.014	13.079	0.003	RRab	-1.78 ± 0.28	
V19	13:27:30.12	-47:28:05.7	0.299551	13.857	0.004	13.632	0.002	RRc	-1.22 ± 0.05	
V20	13:27:14.03	-47:28:06.9	0.615559	13.379	0.017	13.091	0.003	RRab		-1.52 ± 0.34
V21	13:26:11.15	-47:25:59.3	0.380812	13.535	0.011	13.358	0.003	RRc	-0.90 ± 0.11	
V22	13:27:41.05	-47:34:08.1	0.396127	13.508	0.005	13.257	0.002	RRc	-1.63 ± 0.17	-1.60 ± 0.99
V23	13:26:46.48	-47:24:39.6	0.510870	13.678	0.023	13.407	0.004	RRab	-1.08 ± 0.14	-1.35 ± 0.58
V24	13:27:38.33	-47:34:15.0	0.462278	13.361	0.005	13.085	0.002	RRc	-1.86 ± 0.03	
V25	13:26:25.49	-47:28:23.7	0.588466	13.386	0.021	13.147	0.004	RRab	-1.57 ± 0.14	
V26	13:26:23.61	-47:26:59.9	0.784720	13.163	0.009	12.856	0.002	RRab	-1.68 ± 0.10	-1.81 ± 0.12
V27	13:26:26.04	-47:28:16.0	0.615680	13.499	0.012	13.193	0.003	RRab	-1.50 ± 0.26	-1.16 ± 0.14
V30	13:26:15.91	-47:29:56.5	0.404410	13.440	0.005	13.217	0.002	RRc	-1.75 ± 0.17	-1.62 ± 0.28
V32	13:27:03.34	-47:21:39.2	0.620347	13.365	0.026	13.076	0.007	RRab	-1.53 ± 0.16	
V33	13:25:51.57	-47:29:06.1	0.602324	13.426	0.015	13.122	0.004	RRab	-2.09 ± 0.23	-1.58 ± 0.42
V35	13:26:53.24	-47:22:34.9	0.386841	13.487	0.005	13.254	0.002	RRc	-1.56 ± 0.08	-1.63 ± 0.36
V36	13:27:10.19	-47:15:29.5	0.379683	13.515	0.007	13.261	0.002	RRc	-1.49 ± 0.23	
V38	13:27:03.23	-47:36:30.4	0.779061	13.205	0.006	12.859	0.002	RRab	-1.75 ± 0.18	-1.64 ± 0.40
V39	13:27:59.82	-47:34:42.3	0.393374	13.533	0.004	13.271	0.002	RRc	-1.96 ± 0.29	
V40	13:26:24.54	-47:30:46.7	0.634072	13.352	0.025	13.068	0.004	RRab	-1.60 ± 0.08	-1.62 ± 0.19
V41	13:27:01.37	-47:31:02.0	0.662942	13.302	0.021	13.005	0.004	RRab	-1.89 ± 0.48	
V44	13:26:22.38	-47:34:35.7	0.567545	13.587	0.013	13.274	0.003	RRab	-1.40 ± 0.12	-1.29 ± 0.35
V45	13:25:30.85	-47:27:20.9	0.589116	13.441	0.016	13.134	0.004	RRab	-1.78 ± 0.25	
V46	13:25:30.23	-47:25:51.7	0.686971	13.292	0.008	12.967	0.002	RRab	-1.88 ± 0.17	
V47	13:25:56.47	-47:24:12.3	0.485123	13.309	0.010	13.068	0.006	RRc	-1.58 ± 0.31	
V49	13:26:07.73	-47:37:55.9	0.604627	13.475	0.013	13.138	0.003	RRab	-1.98 ± 0.11	
V50	13:25:53.92	-47:27:36.2	0.386172	13.584	0.003	13.307	0.003	RRc	-1.59 ± 0.19	
V51	13:26:42.58	-47:24:21.6	0.574152	13.429	0.023	13.142	0.004	RRab	-1.64 ± 0.21	-1.84 ± 0.23
V52 ^a	13:26:35.16	-47:28:03.8	0.660386	12.854	0.022	12.650	0.007	RRab	-1.42 ± 0.04	
V54	13:26:23.50	-47:18:48.1	0.772915	13.196	0.008	12.855	0.003	RRab	-1.66 ± 0.12	-1.80 ± 0.23
V55	13:25:45.11	-47:42:20.0	0.581724	13.582	0.014	13.266	0.004	RRab	-1.23 ± 0.31	
V56	13:25:55.44	-47:37:44.4	0.568023	13.629	0.010	13.302	0.003	RRab	-1.26 ± 0.15	
V57	13:27:49.42	-47:36:50.7	0.794402	13.190	0.003	12.846	0.002	RRab	-1.89 ± 0.14	
V58	13:26:13.03	-47:24:03.4	0.369880	13.529	0.005	13.317	0.002	RRc	-1.37 ± 0.18	-1.91 ± 0.31
V59	13:26:18.41	-47:29:47.2	0.518506	13.622	0.010	13.363	0.006	RRab	-1.00 ± 0.28	
V62	13:26:26.57	-47:27:55.9	0.619770	13.330	0.018	13.062	0.004	RRab	-1.62 ± 0.29	
V63	13:25:07.87	-47:36:53.8	0.825943	13.171	0.005	12.819	0.002	RRab	-1.73 ± 0.09	
V64	13:26:02.16	-47:36:19.6	0.344458	13.627	0.005	13.382	0.002	RRc	-1.46 ± 0.23	
V66	13:26:33.02	-47:22:25.5	0.407461	13.441	0.004	13.200	0.002	RRc	-1.68 ± 0.34	
V67 ^c	13:26:28.56	-47:18:47.2	0.564451	13.557	0.010	13.271	0.003	RRab	-1.10	-1.19 ± 0.23
V68	13:26:12.79	-47:19:36.1	0.534696	13.175	0.005	12.896	0.002	RRc	-1.60 ± 0.01	
V69	13:25:10.94	-47:37:33.2	0.653221	13.367	0.015	13.061	0.003	RRab	-1.52 ± 0.14	
V70	13:27:27.75	-47:33:43.3	0.390625	13.513	0.009	13.267	0.004	RRc	-1.94 ± 0.15	-1.74 ± 0.30

Notes. ^(a) Stars not considered to derive the PL–Z relations because their mean magnitudes are brighter than the mean locus of RRab or RRc stars (see Fig. 2). These “over-luminous” stars are due to unresolved companions and blending. ^(b) The J and K_s light curves have a considerable gap in the observations because of the one day period. This star was not considered to derive the PL–Z relations. ^(c) Stars with metallicity measurements without error reported were not included to derive the PL–Z relations.

Table A.1. continued.

ID	RA (J2000.0) hh:mm:ss.ss	Dec (J2000.0) dd:mm:ss.s	P (days)	J (mag)	e (mag)	K_s (mag)	e (mag)	Type	[Fe/H] (R00)	[Fe/H] (S06)
V71	13:27:08.05	-47:27:52.2	0.357544	13.535	0.021	13.310	0.007	RRc		-1.74 ± 0.28
V72	13:27:33.02	-47:16:22.7	0.384522	13.524	0.004	13.278	0.002	RRc	-1.32 ± 0.22	
V73	13:25:53.65	-47:16:10.7	0.575215	13.470	0.009	13.193	0.003	RRab	-1.50 ± 0.09	
V74	13:27:07.25	-47:17:34.3	0.503209	13.600	0.022	13.308	0.004	RRab	-1.83 ± 0.36	
V75	13:27:19.69	-47:18:46.9	0.421980	13.390	0.005	13.125	0.002	RRc	-1.49 ± 0.08	-1.82 ± 0.99
V76	13:26:57.27	-47:20:07.9	0.337962	13.632	0.004	13.412	0.002	RRc	-1.45 ± 0.13	
V77 ^c	13:27:20.87	-47:22:06.0	0.426136	13.423	0.004	13.146	0.002	RRc	-1.81	-1.84 ± 0.43
V79	13:28:25.08	-47:29:24.8	0.608276	13.439	0.017	13.116	0.003	RRab	-1.39 ± 0.18	
V81	13:27:36.72	-47:24:48.4	0.389392	13.507	0.004	13.255	0.002	RRc	-1.72 ± 0.31	-1.99 ± 0.43
V82	13:27:35.58	-47:26:30.8	0.335758	13.599	0.005	13.375	0.002	RRc	-1.56 ± 0.20	-1.71 ± 0.56
V83	13:27:08.42	-47:21:34.4	0.356612	13.594	0.004	13.359	0.002	RRc	-1.30 ± 0.22	
V84	13:24:47.47	-47:29:56.2	0.579873	13.043	0.006	12.719	0.003	RRab	-1.47 ± 0.10	
V85	13:25:06.60	-47:23:33.6	0.742758	13.245	0.010	12.907	0.003	RRab	-1.87 ± 0.31	
V86	13:27:15.17	-47:26:11.6	0.647844	13.357	0.015	13.043	0.003	RRab	-1.81 ± 0.18	-1.99 ± 0.23
V87	13:26:57.47	-47:25:35.6	0.396488	13.479	0.007	13.246	0.003	RRc	-1.44 ± 0.19	
V88	13:26:55.89	-47:25:16.5	0.690211	13.262	0.021	12.985	0.007	RRab	-1.65 ± 0.23	
V89	13:26:45.95	-47:26:01.1	0.375110	13.574	0.017	13.325	0.005	RRc	-1.37 ± 0.28	-1.66 ± 0.23
V90 ^c	13:26:45.72	-47:26:23.6	0.603404	13.396	0.025	13.103	0.005	RRab	-2.21	-1.78 ± 0.31
V91	13:26:50.58	-47:26:15.7	0.895225	13.010	0.008	12.686	0.004	RRab	-1.44 ± 0.17	-1.81 ± 0.30
V94	13:25:57.07	-47:22:46.4	0.253936	13.977	0.006	13.811	0.002	RRc	-1.00 ± 0.11	
V95	13:25:24.90	-47:28:52.9	0.405067	13.502	0.005	13.223	0.002	RRc	-1.84 ± 0.55	
V96 ^c	13:26:39.27	-47:27:03.2	0.624527	13.327	0.024	13.054	0.004	RRab	-1.22	
V97	13:27:08.48	-47:25:31.4	0.691898	13.300	0.013	12.988	0.003	RRab	-1.56 ± 0.37	-1.74 ± 0.17
V98	13:27:05.83	-47:26:57.1	0.280566	13.893	0.006	13.704	0.003	RRc	-1.05 ± 0.12	
V99	13:27:02.21	-47:27:49.6	0.766181	13.110	0.024	12.838	0.004	RRab	-1.66 ± 0.14	-1.91 ± 0.25
V100	13:27:04.01	-47:27:33.8	0.552745	13.619	0.025	13.328	0.005	RRab	-1.58 ± 0.14	
V101	13:27:30.22	-47:29:51.6	0.340946	13.644	0.006	13.402	0.002	RRc	-1.88 ± 0.32	
V102	13:27:22.08	-47:30:12.9	0.691396	13.281	0.010	12.977	0.003	RRab	-1.84 ± 0.13	-1.65 ± 0.16
V103	13:27:14.26	-47:28:36.9	0.328852	13.600	0.004	13.403	0.002	RRc	-1.92 ± 0.11	-1.78 ± 0.27
V104	13:28:07.80	-47:33:44.7	0.866308	13.168	0.006	12.824	0.003	RRab	-1.83 ± 0.18	
V105	13:27:46.03	-47:32:44.3	0.335328	13.740	0.004	13.501	0.002	RRc	-1.24 ± 0.18	
V106	13:26:59.16	-47:28:12.9	0.569903	13.362	0.025	13.148	0.005	RRab	-1.50 ± 0.23	-1.90 ± 0.26
V107	13:27:14.02	-47:30:58.5	0.514102	13.670	0.016	13.386	0.003	RRab	-1.36 ± 0.11	
V108	13:27:04.66	-47:29:26.1	0.594458	13.328	0.011	13.078	0.004	RRab	-1.93 ± 0.23	-1.63 ± 0.13
V109	13:27:01.52	-47:29:37.0	0.744098	13.193	0.020	12.907	0.003	RRab	-1.51 ± 0.25	-1.70 ± 0.07
V110	13:27:02.04	-47:30:07.1	0.332107	13.641	0.008	13.451	0.003	RRc	-2.14 ± 0.16	-1.65 ± 0.52
V111	13:26:48.99	-47:28:40.5	0.762905	13.184	0.014	12.866	0.003	RRab	-1.66 ± 0.04	-1.79 ± 0.09
V112	13:26:54.24	-47:30:23.6	0.474359	13.574	0.027	13.354	0.006	RRab	-1.81 ± 0.26	
V113	13:26:56.29	-47:31:47.9	0.573375	13.447	0.025	13.192	0.005	RRab	-1.65 ± 0.34	
V114	13:26:50.10	-47:30:21.4	0.675307	13.292	0.015	12.997	0.004	RRab	-1.32 ± 0.30	-1.61 ± 0.99
V115	13:26:12.27	-47:34:17.9	0.630474	13.389	0.015	13.095	0.004	RRab	-1.87 ± 0.01	-1.64 ± 0.32
V116	13:26:35.47	-47:28:07.2	0.720133	13.231	0.018	12.980	0.006	RRab	-1.27 ± 0.44	-1.11 ± 0.17
V117	13:26:19.88	-47:29:21.6	0.421641	13.439	0.005	13.191	0.003	RRc	-1.68 ± 0.25	
V119	13:26:38.27	-47:31:18.3	0.305876	13.695	0.004	13.516	0.002	RRc	-1.61 ± 0.10	
V120	13:26:25.51	-47:32:49.0	0.548537	13.560	0.021	13.291	0.005	RRab	-1.39 ± 0.06	-1.15 ± 0.16
V121	13:26:28.15	-47:31:51.0	0.304182	13.636	0.004	13.455	0.002	RRc	-1.46 ± 0.13	-1.83 ± 0.40
V122	13:26:30.30	-47:33:02.5	0.634929	13.340	0.020	13.062	0.004	RRab	-2.02 ± 0.18	-1.79 ± 0.21
V123	13:26:51.07	-47:37:13.3	0.473884	13.389	0.005	13.110	0.002	RRc	-1.64 ± 0.01	
V124	13:26:54.38	-47:39:07.6	0.331860	13.650	0.005	13.433	0.002	RRc	-1.33 ± 0.23	
V125	13:26:48.98	-47:41:03.7	0.592888	13.416	0.011	13.145	0.003	RRab	-1.67 ± 0.22	-1.81 ± 0.38
V126	13:28:08.14	-47:40:46.5	0.341891	13.646	0.006	13.403	0.002	RRc	-1.31 ± 0.13	
V127	13:25:19.43	-47:28:37.6	0.305274	13.738	0.004	13.518	0.002	RRc	-1.59 ± 0.08	
V128	13:26:17.72	-47:30:13.5	0.834988	13.076	0.008	12.761	0.003	RRab	-1.88 ± 0.04	
V130	13:26:10.00	-47:13:40.0	0.493250	13.675	0.008	13.406	0.003	RRab	-1.46 ± 0.17	
V131	13:26:30.04	-47:29:41.1	0.392123	13.402	0.006	13.180	0.003	RRc	-1.56 ± 0.20	-1.66 ± 0.48
V132	13:26:39.18	-47:29:10.0	0.655656	13.267	0.022	12.990	0.005	RRab	-1.91 ± 0.20	
V134	13:25:13.33	-47:12:28.4	0.652903	13.339	0.018	13.040	0.006	RRab	-1.80 ± 0.41	
V135 ^a	13:26:28.06	-47:29:18.3	0.632527	12.877	0.029	12.536	0.011	RRab	-2.20	-1.57 ± 0.18
V136	13:26:31.06	-47:27:40.9	0.391945	13.397	0.007	13.182	0.005	RRc	-1.83 ± 0.47	-1.64 ± 0.37

Table A.1. continued.

ID	RA (J2000.0) hh:mm:ss.ss	Dec (J2000.0) dd:mm:ss.s	P (days)	J (mag)	e (mag)	K_s (mag)	e (mag)	Type	[Fe/H] (R00)	[Fe/H] (S06)
V137	13:26:31.52	-47:27:04.6	0.334205	13.557	0.007	13.352	0.002	RRc	-1.19 ± 0.18	
V139 ^a	13:26:37.75	-47:27:35.4	0.676871	13.022	0.028	12.707	0.008	RRab	-1.46 ± 0.04	-1.83 ± 0.20
V140	13:26:42.15	-47:30:07.5	0.619849	13.355	0.019	13.087	0.006	RRab		-1.72 ± 0.15
V141	13:26:40.87	-47:29:28.2	0.697363	13.221	0.019	12.915	0.007	RRab	-1.55 ± 0.36	-2.20 ± 0.36
V142	13:26:42.63	-47:28:42.9	0.375877	13.520	0.014	13.284	0.006	RRc		-1.81 ± 0.24
V144	13:26:43.02	-47:28:18.0	0.835320	13.044	0.008	12.742	0.004	RRab	-1.71 ± 0.12	
V145	13:26:51.21	-47:31:08.8	0.373214	13.542	0.005	13.317	0.002	RRc	-1.58 ± 0.07	
V147	13:27:15.88	-47:31:10.3	0.422615	13.387	0.006	13.166	0.002	RRc	-1.66 ± 0.14	
V149	13:27:32.85	-47:13:43.3	0.682728	13.297	0.013	12.997	0.003	RRab	-1.21 ± 0.24	
V150	13:27:40.23	-47:36:00.4	0.899302	13.086	0.008	12.766	0.003	RRab	-1.76 ± 0.34	
V151	13:28:25.31	-47:16:00.0	0.407756	13.470	0.003	13.213	0.002	RRc	-1.30 ± 0.24	
V153	13:26:49.65	-47:26:23.8	0.386245	13.511	0.006	13.281	0.003	RRc	-1.38 ± 0.19	
V154	13:27:03.11	-47:30:32.4	0.322340	13.618	0.007	13.462	0.002	RRc	-1.39 ± 0.12	-1.49 ± 0.23
V155	13:26:53.64	-47:24:42.8	0.413925	13.428	0.006	13.187	0.003	RRc	-1.46 ± 0.09	
V156	13:26:47.87	-47:31:52.6	0.359067	13.513	0.009	13.320	0.004	RRc	-1.40 ± 0.04	-1.51 ± 0.38
V157	13:26:46.45	-47:27:17.7	0.406578	13.493	0.006	13.260	0.003	RRc	-1.49 ± 0.10	
V158	13:26:45.30	-47:30:40.4	0.367276	13.543	0.009	13.336	0.003	RRc	-1.25 ± 0.06	-1.64 ± 0.49
V160 ^c	13:25:36.08	-47:12:32.3	0.397527	13.497	0.004	13.237	0.002	RRc	-1.66	
V163	13:25:49.47	-47:20:21.8	0.313196	13.701	0.005	13.493	0.002	RRc	-1.18 ± 0.27	
V169	13:27:20.45	-47:23:59.6	0.319116	13.713	0.003	13.502	0.001	RRc		-1.65 ± 0.19
V261 ^a	13:27:15.40	-47:21:29.9	0.402512	13.358	0.005	13.049	0.002	RRc		-1.50 ± 0.35
V263	13:26:13.11	-47:26:10.2	1.012158	12.970	0.004	12.625	0.002	RRab		-1.73 ± 0.19
V265	13:26:30.19	-47:28:45.6	0.422600	13.384	0.02	13.129	0.004	RRc		-2.00 ± 0.29
V267	13:26:40.18	-47:26:36.0	0.315822	13.624	0.008	13.456	0.002	RRc		-1.62 ± 0.63
V268	13:26:35.11	-47:26:11.2	0.8129220	13.145	0.006	12.822	0.002	RRab		-1.76 ± 0.24
V271	13:26:47.10	-47:30:04.3	0.4432000	13.337	0.008	13.100	0.003	RRc		-1.80 ± 0.21
V275	13:26:49.72	-47:27:37.4	0.3778970	13.526	0.009	13.314	0.003	RRc		-1.66 ± 0.36
V341	13:26:54.63	-47:28:48.4	0.3061360	13.621	0.017	13.366	0.015	RRc		-1.78 ± 0.59
V342	13:27:18.72	-47:28:22.6	0.3083890	13.687	0.005	13.485	0.002	RRc		-1.71 ± 0.55
V346	13:26:46.91	-47:28:14.3	0.3276230	13.581	0.012	13.402	0.004	RRc		-1.52 ± 0.54
V347	13:26:50.82	-47:27:46.2	0.3288490	13.637	0.025	13.459	0.009	RRc		-1.66 ± 0.27
V350	13:26:56.44	-47:30:50.2	0.3791080	13.442	0.012	13.236	0.005	RRc		-1.45 ± 0.40
V353 ^a	13:26:43.61	-47:27:57.6	0.4010200	13.245	0.026	12.977	0.014	RRc		-1.93 ± 0.31
V354	13:26:38.58	-47:25:10.2	0.4200900	13.419	0.009	13.182	0.004	RRc		-1.73 ± 0.23
V357	13:26:17.73	-47:30:23.0	0.2977750	13.690	0.005	13.510	0.003	RRc		-1.64 ± 0.99
V366 ^b	13:26:41.54	-47:31:42.2	0.9999100	12.748	0.007	12.423	0.004	RRab		-1.61 ± 0.14
V399	13:26:29.51	-47:30:03.0	0.3097820	13.659	0.007	13.495	0.003	RRc		-1.70 ± 0.67

Table A.2. Catalog of fundamental-mode candidate SX Phe stars in ω Cen, used to derive the empirical PL relations.

ID	RA (J2000.0) hh:mm:ss.ss	Dec (J2000.0) dd:mm:ss.s	P (days)	J (mag)	e (mag)	K_s (mag)	e (mag)	Remarks ^a
V194	13:27:53.95	-47:31:54.2	0.0471777	16.237	0.007	16.106	0.006	1
V195	13:27:15.63	-47:24:34.9	0.0654912	15.808	0.006	15.591	0.005	1
V196	13:25:01.21	-47:25:29.6	0.0574000	16.080	0.009	15.858	0.010	1
V197	13:26:20.40	-47:31:59.7	0.0471210	16.153	0.044	15.980	0.067	2
V198	13:26:34.53	-47:31:03.7	0.0481817	16.348	0.044	16.212	0.058	2
V199	13:26:28.63	-47:28:38.4	0.0622866	15.669	0.007	15.468	0.004	1
V201	13:26:11.09	-47:15:54.1	0.0506500	16.250	0.029	16.061	0.054	2
V202	13:26:38.97	-47:11:51.2	0.0464200	16.319	0.018	16.125	0.037	2
V204	13:27:07.90	-47:37:05.4	0.0493757	16.110	0.008	15.960	0.008	1
V217	13:26:16.91	-47:27:25.9	0.0532600	16.076	0.029	15.859	0.037	2
V218	13:26:11.22	-47:17:54.1	0.0437393	16.335	0.019	16.177	0.035	2
V219	13:26:08.43	-47:19:24.6	0.0386681	16.544	0.022	16.455	0.048	2
V220	13:26:48.61	-47:21:42.4	0.0528868	16.127	0.007	15.936	0.006	1
V222	13:26:18.52	-47:41:12.5	0.0389100	16.475	0.022	16.350	0.039	2
V225	13:27:02.28	-47:24:36.8	0.0486381	16.055	0.011	15.918	0.008	1
V226	13:26:10.47	-47:29:57.3	0.0378524	16.529	0.027	16.422	0.049	2
V227	13:26:14.36	-47:23:54.2	0.0382255	16.508	0.027	16.346	0.047	2
V228	13:26:40.48	-47:33:46.6	0.0398531	16.456	0.027	16.347	0.056	2
V229	13:27:12.60	-47:23:58.9	0.0375333	16.524	0.023	16.351	0.039	2
V231	13:27:19.03	-47:35:54.4	0.0374850	16.601	0.024	16.479	0.048	2
V232	13:26:17.32	-47:11:49.9	0.0369700	16.647	0.022	16.506	0.042	2
V233	13:26:47.28	-47:20:32.0	0.0365377	16.478	0.027	16.386	0.056	2
V237	13:25:52.88	-47:23:56.0	0.0656024	15.905	0.007	15.675	0.004	1
V238	13:27:33.96	-47:29:23.4	0.0408004	16.484	0.021	16.372	0.044	2
V249	13:25:46.27	-47:26:28.8	0.0349468	16.624	0.025	16.425	0.041	2
V250	13:27:31.74	-47:35:42.1	0.0406269	16.548	0.024	16.388	0.045	2
V252	13:27:29.71	-47:29:00.5	0.0466226	16.398	0.019	16.178	0.031	2
V253	13:27:22.13	-47:27:52.3	0.0399687	16.421	0.023	16.285	0.044	2
V260	13:24:52.73	-47:25:22.0	0.0462600	16.271	0.018	16.073	0.028	2
V299	13:27:00.30	-47:22:29.9	0.0344409	16.654	0.034	16.477	0.063	2
V300	13:25:46.55	-47:24:00.7	0.0347301	16.640	0.023	16.437	0.040	2
V304	13:26:19.57	-47:20:01.6	0.0361405	16.488	0.028	16.314	0.045	2
V305	13:27:51.42	-47:19:51.4	0.0365673	16.474	0.022	16.266	0.035	2
V306	13:27:10.99	-47:28:24.8	0.0384044	16.551	0.033	16.364	0.069	2
V308	13:27:50.03	-47:21:16.1	0.0389852	16.480	0.022	16.324	0.037	2
V311	13:26:58.75	-47:29:49.9	0.0414133	16.295	0.078	15.976	0.118	2
V313	13:26:38.28	-47:31:37.3	0.0418484	16.443	0.034	16.277	0.065	2
V316	13:26:14.84	-47:31:10.8	0.0424040	16.405	0.025	16.264	0.041	2
V319	13:26:28.52	-47:31:02.9	0.0489421	16.304	0.028	16.139	0.056	2
V320	13:26:49.43	-47:34:29.1	0.0471934	16.351	0.028	16.181	0.038	2
V322	13:26:38.85	-47:27:39.1	0.0479562	16.009	0.037	15.853	0.052	2
V326	13:26:40.17	-47:24:55.7	0.0569058	15.994	0.026	15.817	0.035	2
V419/W22	13:28:53.57	-47:19:29.7	0.0410000	16.403	0.020	16.236	0.032	2
V420/W23	13:28:44.57	-47:24:51.0	0.0370000	16.472	0.021	16.322	0.036	2
V445/W131	13:24:54.09	-47:41:03.5	0.0470000	16.350	0.020	16.146	0.030	2

Notes. ^(a) 1: Variability recovered in our data; 2: variability not recovered in our data.