An Updated Census of RR Lyrae Stars in the Globular Cluster ω Centauri (NGC 5139)*

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ABSTRACT

Aims. ω Centauri (NGC 5139) contains large numbers of variable stars of different types and, in particular, more than a hundred RR Lyrae stars. A homogeneous (in terms of instrument, image quality, and time coverage) sample of high-quality near-infrared (NIR) RR Lyrae light curves could thus be gathered by performing an extensive time-series campaign aimed at this object. We have conducted a variability survey of ω Cen in the NIR, using ESO’s 4.1m Visible and Infrared Survey Telescope for Astronomy (VISTA). This is the first paper of a series describing our results.

Methods. ω Cen was observed using VIRCAM mounted on VISTA. A total of 42 and 100 epochs in J and Ks, respectively, were obtained, distributed over a total timespan of 352 days. Point-spread function photometry was performed using DAOPHOT and DoPhot in the inner and outer regions of the cluster, respectively. Periods of the known variable stars were improved when necessary using an ANOVA analysis.

Results. An unprecedented homogeneous and complete NIR catalogue of RR Lyrae stars in the field of ω Cen was collected, allowing us to study, for the first time, all the RR Lyrae stars associated to the cluster, except 4 located far away from the cluster center. Membership status, subclassifications between RRab and RRc subtypes, periods, amplitudes, and mean magnitudes were derived for all the stars in our sample. Additionally, 4 new RR Lyrae stars were discovered, 2 of them with high probability of being cluster members. The distribution of ω Cen stars in the Bailey (period-amplitude) diagram is also discussed. Reference lines in this plane, for both Oosterhoff type I (OoI) and Oosterhoff type II (OoII) components, are provided, both in J and Ks.

Conclusions. In the present paper, we clarify the status of many (candidate) RR Lyrae stars that had been unclear in previous studies. This includes stars with anomalous positions in the color-magnitude diagram, uncertain periods or/and variability types, and possible field interlopers. We conclude that ω Cen hosts a total of 88 RRab and 101 RRc stars, for a grand total of 189 likely members. We confirm that most RRab stars in the cluster belong to an OoII component, as previously found using visual data.

Key words. Stars: variables: RR Lyrae – Stars: variables: general – Stars: horizontal-branch – Galaxy: globular clusters: individual: ω Centauri (NGC 5139) – Infrared: stars – Surveys – Catalogs

1. Introduction

RR Lyrae stars (RRLs) are well known for being reliable distance indicators and tracers of the old stellar populations of galaxies (Smith 1995; Catelan 2009; Bono et al. 2011) and references therein). In the dawning era of time-series infrared (IR) photometric surveys, new observations in the near- and mid-IR have recently been providing large and homogeneous samples of RRLs in different environments (e.g., Dékány et al. 2013; Klein et al. 2014), which can be used to improve our understanding of this variability class and as tracers of structure in the nearby Universe.

Especially noteworthy, in this context, is the fact that RRLs follow well-defined period-luminosity (PL) relations in the IR (e.g., Longmore et al. 1990; Catelan et al. 2004). Furthermore, the interstellar extinction in Ks is approximately a tenth of the one in the optical, thus making it possible to observe RRLs even in the most obscured regions of our Galaxy, e.g., its inner bulge. Despite these advantages, there are still few extensive variability studies in the near-infrared (NIR), due to a number of factors, including the lack, until recently, of large-format detectors, which rendered NIR surveys extremely costly, in terms of observing time. In addition, the low amplitudes of many types of variables, including RRLs, in the NIR, compared to the optical, have hindered the detection of new variables using these filters. The situation has only recently started to change, particularly with the start of operations of ESO’s 4.1m Visible and Infrared Sur-
The VISTA Variables in the Vía Láctea (VVV) ESO Public Survey is an extensive variability study in the $K_S$-band of the Galactic bulge and an adjacent portion of the disk (see Minniti et al. 2010; Catelan et al. 2011, 2013, and references therein). In order to automatically classify the large samples of variable stars detected by this survey, our team started to build a database of well-defined, high-quality NIR light curves for various variability classes – the VVV Templates Project (Catelan et al. 2013; Angeloni et al. 2014). In this context, ω Centauri (NGC 5139) was identified early on as one of the most suitable targets to obtain template light curves, given that it hosts a large number and variety of variable stars.

ω Cen stands out as one of the three most RRL-rich globular clusters known, only surpassed by M3 (NGC 5272, with 230 RRLs; Clementini et al. 2004) and M62 (NGC 6626, with 224 RRLs; Contreras et al. 2005, 2010). From the several variability studies that have been carried out in the optical over the years with different telescopes and temporal baselines, a large (although still incomplete) catalogue of RRLs in ω Cen has been provided (Clement et al. 2001; C. M. Clement’s online catalogue [2013 edition, hereafter C13]). A wide-field, NIR variability survey of ω Cen allows us to derive and calibrate the NIR PL relations of several different types of stars, including SX Phoenicis, type II Cepheids, and RRL stars. In this sense, our study of ω Cen with VIRCAM@VISTA has provided the largest homogeneous NIR sample of RRL ever collected in any globular cluster, leading to tight PL relations, as described in our next papers in this series on ω Cen variables.

ω Cen is the most massive and luminous globular cluster in the Milky Way, and it may have been even more massive in the past (e.g., Valcarce & Catelan 2011 and references therein). Nowadays, ω Cen is well known for hosting at least two stellar populations with metallicity peaks centered at [Fe/H] $\sim$ −1.6 and −1.1 dex (Bedin et al. 2004; Joo & Lee 2013 and references therein). In addition to presenting variations in [Fe/H] that may be correlated with age, it has been found that ω Cen’s stars also present variations in the abundances of many other elements, both heavy and light, in addition to helium (at a level Δ$Y$ $\sim$ 0.17 dex) and age (e.g., Norris 2004; Piotto et al. 2005; Dupree et al. 2011 [Valcarce & Catelan 2011]).

Despite the fact that He enhancement appears to be required to explain the lower color-magnitude diagram (CMD) morphology of ω Cen, an impact on the cluster’s variable stars has not yet been established. Sollima et al. (2006) found that the RRL stars with metal-intermediate composition ([Fe/H] $\sim$ −1.2) fainter than the bulk of the dominant metal-poor population (with primordial helium abundances and [Fe/H] $\sim$ −1.7 dex), are in good agreement with the corresponding horizontal branch (HB) models with $Y = 0.246$. More recently, Marconi et al. (2011) studied the impact of the helium content on the RRL properties based on evolutionary and pulsation models, and again could not find evidence of He enhancement among the RRL stars. The most likely interpretation of these results is that any He-enhanced populations in the cluster likely end up far to the blue on the zero-age HB, thus being unlikely to populate the classical instability strip (e.g., Joo & Lee 2013).

In this paper, in addition to describing our VISTA observations, we also update the census of RRLs in ω Cen. In this sense, we provide, using our data and comparing with previous studies, a comprehensive assessment of their number, types, membership probabilities, and light curves, and also improved light curves for several RRL variables. We point out some erroneous cross-identifications between the Weldrake et al. (2007) and Kaluzny et al. (2004) catalogues, and propose a change in classification for a few stars. The membership status of all the suspected field stars is revisited. Last but not least, we present four new RRLs, two of which we classify as genuine cluster members. In future papers of this series, we will study the NIR PL relations for RRL, type II Cepheids, and SX Phe stars, and present the full updated catalogue of variable stars (including also eclipsing binaries) in the ω Cen field.

2. Observations

A total of 42 and 100 epochs in $J$ and $K_S$, respectively, were taken using VIRCAM (Dalton et al. 2006) mounted on VISTA (Emerson et al. 2006; Emerson & Sutherland 2010). All of the images were centered on the cluster center. The heart of the VIRCAM camera is a $4 \times 4$ array of Raytheon VIRGO IR detectors (2048 $\times$ 2048 pixels), with a pixel size of 0′′.34 (Dalton et al. 2006). The size of a uniformly covered field (also called a “tile”) is 1.501 deg$^2$, thus allowing unprecedented spatial coverage in the NIR bandpasses. The effective field of view (FoV) of the camera is larger than the previous studies of Kaluzny et al. (2004) and Weldrake et al. (2007), both carried out in the visible, but not large enough to cover ω Cen in its whole extension (its tidal radius is ≈52″; e.g., Ferraro et al. 2006 and references therein). Our observations have a baseline of 352 days, which provides an unprecedented phase coverage in the NIR.

The characteristics of the observations, data reduction and photometry extraction are the same as those explained in Navarrete et al. (2013). In particular, the images were reduced by the Cambridge Astronomy Survey Unit (CASU) and crowded-field, point-spread function (PSF) photometry was performed using the DAOPHOT II/ALLFRAME (Stetson 1987, 1994) and DoPhot (Schechter et al. 1993; Alonso-García et al. 2012) photometry packages for the cluster central (i.e., the innermost $\sim10'$) and outer regions, respectively.

The DoPhot and ALLFRAME photometries were calibrated independently, using in both cases the aperture photometry provided by CASU, which is in the VISTA photometric system. As described in detail in Minniti et al. (2010), the CASU pipeline determines the photometric zero points using 2MASS stars (Skrutskie et al. 2006) in the pawprint frames, then transforming these 2MASS magnitudes into VISTA magnitudes according to the equations derived by Hodgkin et al. (2009). Magnitudes for common stars derived using both packages were then compared, finding an excellent agreement in the magnitude calibration (at the level of RRL stars, the average $K_S$-band magnitude difference between the DoPhot and ALLFRAME magnitudes is $\sim0.01$ mag only).

3. Results

Time-series photometry of most of the previously known variable stars listed by C13 (from V1 to V410) and Weldrake et al. (2007) was recovered using a cross-match between those catalogues and our complete PSF photometric catalogue (i.e., photometry for all the stars at all the observed epochs). The matching radius was set at 1″. When one star was not recovered under this procedure, the Samus et al. (2009) catalogue was used as a reference.
reference. In the Samus et al. catalogue, variable stars from V1 to V293 are listed, most of them with updated coordinates based on 2MASS observations. The cross-match using the Samus et al. catalogues allowed us to recover 16 variable stars (including 8 RRL, 3 SX Phoenicis, 4 eclipsing binaries, and 1 spotted variable) that were not recovered using the C13 catalogue. When neither of these reference catalogues gave a match for a certain variable star, an increasing matching radius was used, until a known variable star was found. To pinpoint the latter, the time series for all stars that were inside the matching radius were phased using the star’s period as listed by C13, until reasonable agreement was found. As a consistency check, periods for those stars were also calculated using the ANOVA algorithm (Schwarzenberg-Czerny 1989), in an effort to determine if the known variable is present in the area covered by the matching radius but with a different period according to our observations. This approach led to the discovery of V411 as a new RRL star (Navarrete et al. 2013), which Weldrake et al. (2007) had previously (but incorrectly) claimed to be the same as V144 from the Kaluzny et al. (2004) catalogue.

Figure 1 shows the \( \omega \) Cen \( K_s \), \( J - K_s \) CMD, as obtained from our ALLFRAME photometry for the central regions (see Sect. 2). In this diagram, RRLs from the whole observed area are superimposed as red and blue circles for RRab (i.e., fundamental-mode) and RRc (first-overtone) types, respectively. Star symbols indicate variables from Weldrake et al. (2007) (see Sect. B), and new variables are shown as open circles (see Sect. 3.3). Most of the RRLs are located in the horizontal branch (HB), as expected for bona-fide cluster members, but a few stars fall close to the main sequence, or even at the turn-off point. A zoom-in around the RRL instability strip (IS) region is shown in the bottom panel of Figure 1 where there are also two type II Cepheids, marked as green triangles. All the RRL stars labeled in both figures were considered in our analysis and studied in terms of their periods, variability types, and cluster membership. In the following, we clarify the status of many of the RRL stars in \( \omega \) Cen that had been unclear in previous studies. This includes stars with anomalous CMD positions, uncertain periods or variability types, and possible field interlopers.

Table 1 lists the characteristics of 21 previously known RRL that either have anomalous positions in the CMD, were suggested as field stars by previous studies (and fall within our FoV), or do not have periods (or even variability type) listed in the literature. Column 1 lists the ID of the variables according to C13, except for the two stars from Weldrake et al. (2007), because they are not included in the C13 catalogue (ID-91, ID-99); columns 2 and 3 show the coordinates based on VISTA astrometry (which in turn is tied to the 2MASS system); columns 4 and 5 display the intensity-weighted mean \( J \) and \( K_s \) magnitudes, respectively; column 6 gives our derived periods, while the variability type (RRab, RRc, eclipsing binary [EB], or anomalous Cepheid [ACEP]) is given in column 7; the distance to the cluster center for each variable is listed in column 8. The membership probability for the stars, according to the two main proper motion studies of \( \omega \) Cen, are listed in columns 9 and 10, as provided by van Leeuwen et al. (2000) [hereafter Vl.00] and Bellini et al. (2009) [hereafter B09], respectively. Finally, column 11 shows the membership status according to our photometric study (m: member, f: field). A brief description of each of these variables is presented in the Appendix.

Fig. 1. Top: CMD of the central part of the cluster (11 arcmin\(^2\), grey dots). ab- and c-type RRL are marked as red and blue circles, respectively. RRL from Weldrake et al. (2007) are marked as star symbols. Open circles mark the new RRLs found in this work, with NV455 and NV456 (labeled) likely being cluster members (see Sect. 3.3). Field, blended, or erroneously classified stars are labeled and explained in the text. Bottom: Zoom-in around the RRL region in the CMD of \( \omega \) Cen, with a few noteworthy stars labeled. V43 and V60, marked with green triangles, are known type II Cepheids.

\( ^4 \) van Leeuwen et al. (2000) constructed a proper motion catalogue for stars in \( \omega \) Cen based on observations of photographic plates of the cluster, taken between 1931 and 1983 with the Yale-Columbia 66-cm telescope. The covered area has a radius of ~30’ (about 60% of the cluster’s tidal radius). The Bellini et al. (2009) proper motion catalogue was in turn derived from astrometry on CCD images taken with the Wide-Field Imager on the 2.2-m telescope at ESO La Silla, with a precision of ~7 mas. The B09 observations were carried out with a baseline of 4 years, and extend to a limiting magnitude of \( B \sim 20 \) mag, which is up to four magnitudes deeper than previous studies.
timespan of cases), and hint at amplitude modulations exceeding 0.1 mag in at least some stars, which could be either because the amplitude changes are too small in the NIR (notwithstanding the fact that Fig. 2 might show).

As shown by Clement & Rowe (2000) based on visual data, individual stars in ω Cen predominantly follow a locus on the Bailey diagram (period-amplitude plane) that is characteristic of Oosterhoff type II (OoII) systems, with individual RRL typically having longer periods at a given amplitude than their Oosterhoff type I (OoI) counterparts. The details, systematics, astrophysical interpretation and importance of the Oosterhoff phenomenon are extensively discussed in Catelan (2009).

Figure 2 shows, for the first time, the distribution of ω Cen RRL stars in the NIR Bailey diagram, both in the J (top panel) and in the Ks (bottom panel) bands. RRab stars with documented Blazhko effect (Blazhko 1907) in the catalogue of Kaluzny et al. (2004) are plotted as open red circles. Several features can be appreciated from these plots. First, the positions occupied by c- and ab-type RRL stars are clearly very different, as also seen in the visual. Second, there is significantly more scatter in the Ks-band Bailey diagram than is present in J. This is, at least in part, due to the smaller amplitudes in Ks, compared to J. Third, and as it is also commonly seen in the visible, the Blazhko stars tend to have smaller amplitudes, at a given period, than their non-Blazhko counterparts. This is particularly noteworthy as the actual amplitude modulation that is brought about by the Blazhko effect is not clearly seen in our NIR data for any of ω Cen’s RRab stars, which could be either because the amplitude changes are too small in the NIR (notwithstanding the fact that Fig. 2 might hint at amplitude modulations exceeding 0.1 mag in at least some cases), and/or because our time coverage is insufficient to reveal long-term modulation (recall that our observations have a timespan of ~300 days, with gaps). Indeed, to the best of our knowledge, there have been no clear-cut measurements of the Blazhko effect in the IR, even though Sollima et al. (2008) have reported increased scatter in their NIR light curves of RR Lyr itself, which they attribute to the star’s well-known Blazhko-type light curve modulation. Fourth, there is a tendency for the locus occupied by ab-type RRL to flatten out, as one moves from bluer to redder wavelengths. In fact, this trend appears to continue towards the mid-IR regime, where the relation eventually becomes completely flat (Gavrilenko et al. 2014). Fifth, and again as previously emphasized by Clement & Rowe (2000), most RRab stars in ω Cen tend to clump around a fairly well-defined locus, particularly in the J-band Bailey diagram. Based on our J amplitudes for the “OoII-like” RRab stars, this locus is fitted by the following expression:

As can be seen from Figure 3, there is a fairly tight relation between J- and Ks-band RRL amplitudes, which is described by the following expression:

As in the period is given in days. The amplitude-period correlation given by Equation [1] is plotted as a dashed line in the J-band Bailey diagram (Figure 2). That this indeed corresponds to Clement & Rowe’s OoII component can be seen by the fact that this line is significantly displaced towards longer periods, compared to the OoI reference line (also shown in Figure 2).

As can be seen from Figure 3, there is a fairly tight relation between J- and Ks-band RRL amplitudes, which is described by the following expression:

Equation [2] was used to obtain the Ks-band equivalent of Equation [1]. OoII reference loci obtained in this way are overplotted

Table 1. Properties of member and field RRLs with previously uncertain status

| ID   | RA   | DEC  | ⟨J⟩  | ⟨Ks⟩ | P(ab) | Type | d(b) | pV,1000 (μ) | pV,2000 (μ) | Membr. |
|------|------|------|------|------|-------|------|------|-------------|-------------|--------|
| V19  | 13:27:30.12 | -47:28:05.74 | 13.852 | 13.631 | 0.299551 | RRc  | 7.27 | 100 | 100 | m |
| V21  | 13:26:11.15 | -47:25:59.30 | 13.538 | 13.362 | 0.380812 | RRc  | 6.71 | 100 | 99 | m |
| V52  | 13:26:35.15 | -47:28:04.33 | 12.831 | 12.634 | 0.660386 | RRab | 2.16 | 53 | 45 | m |
| V56  | 13:25:55.44 | -47:37:44.44 | 13.612 | 13.301 | 0.568023 | RRab | 12.53 | 98 | 100 | m |
| V68  | 13:26:12.79 | -47:19:36.12 | 13.168 | 12.897 | 0.534699 | RRc/ACEP? | 10.87 | 100 | 100 | m |
| V80(c) | 13:28:54.96 | -47:30:16.42 | 13.568 | 13.360 | 0.37718 | RRc  | 21.62 | out | out | m |
| V84  | 13:24:47.47 | -47:49:56.18 | 13.031 | 12.712 | 0.579873 | RRab/ACEP? | 29.24 | 0 | out | m |
| V143 | 13:28:42.59 | -47:27:28.98 | 12.783 | 12.510 | 0.820734 | RRab | 1.51 | 90 | 99 | m |
| V151 | 13:28:25.31 | -47:16:00.01 | 14.355 | 13.211 | 0.407756 | RRc  | 20.94 | out | out | m |
| V165 | 13:28:52.74 | -47:32:03.19 | 14.164 | 13.916 | 0.321299 | RRc  | 9.78 | 0 | 0 | f |
| V172(d) | 13:27:55.04 | -47:04:38.50 | 13.220 | 12.927 | 0.7380 | RRab | 26.72 | out | out | m |
| V173 | 13:29:43.13 | -47:16:53.80 | 13.624 | 13.360 | 0.3590 | RRc  | 32.05 | out | out | m |
| V177(c) | 13:29:04.15 | -47:36:21.42 | 13.690 | 13.479 | 0.31469 | RRc  | 24.31 | out | out | m |
| V180 | 13:30:15.22 | -47:40:32.02 | 12.832 | 12.634 | 0.380812 | W Uma | 18.93 | 0 | out | f |
| V181 | 13:30:00.35 | -47:48:44.96 | 14.823 | 14.535 | 0.5884 | RRab | 38.17 | out | out | f |
| V183 | 13:29:39.50 | -47:30:18.36 | 14.690 | 14.449 | 0.29603 | RRc  | 29.13 | out | out | f |
| V268 | 13:26:35.11 | -47:26:11.15 | 13.168 | 12.827 | 0.812922 | RRab | 3.30 | 70 | 99 | m |
| V283 | 13:27:36.53 | -47:46:40.44 | 16.947 | 16.682 | 0.517233 | RRc  | 19.73 | out | out | m |
| V411(f) | 13:26:40.77 | -47:28:17.00 | 13.123 | 12.796 | 0.8449 | RRab | 1.20 | 100 | 99 | m |
| V433(g) | 13:29:03.59 | -47:48:58.25 | 14.737 | 14.151 | 0.6681 | ? | 30.58 | out | out | f |
| ID-91 | 13:26:14.03 | -47:16:00.01 | 14.355 | 13.211 | 0.407756 | RRc  | 20.94 | out | out | m |
| ID-99 | 13:24:40.44 | -47:45:22.54 | 15.777 | 15.275 | 0.670361 | RRab | 27.07 | out | out | f |

Notes. (a) Periods are from Kaluzny et al. (2004), except for V80, V172, V173, V177, V180, V181, V183 and V411, which were derived by us. (b) Distance to the cluster center was calculated using ω Cen’s center as reported by SIMBAD: RA = 13:26:47.28, DEC = -47:28:46.1, both in J2000. (c) ID-53 in Weldrake et al. (2007). (d) ID-18 in Weldrake et al. (2007). (e) ID-49 in Weldrake et al. (2007). (f) V411 has the same coordinates as ID-74 in Weldrake et al. (2007). (g) ID-18 in Weldrake et al. (2007).
Fig. 2. Bailey diagrams for all the RRL stars known in the ω Cen field, based on $J$- (top) and $K_s$-band bottom light curves. The overplotted lines define representative loci of “OoII-like” (dashed lines) and “OoI-like” (dotted lines) behavior for the ab-type RRL, obtained as described in the text. RRab stars with documented Blazhko effect are marked with open circles. Clearly, V180 has too large an amplitude for its claimed RRc status; instead, we believe that the star is a contact binary of the W UMa type with twice the alternative “RRc-like” period. V151 is clearly an RRc star.

on both panels of Figure 2 as dashed lines, clearly showing the expected period shift with respect to the (minority) “OoI-like” RRab stars in ω Cen.

Unfortunately, there are few stars in ω Cen that belong to the OoI component (Clement & Rowe 2000), and thus we can not define the OoI reference line reliably based solely on our data. Therefore, to obtain an OoI reference locus in the NIR, we have used as a reference the V-band OoI line from Cacciari et al. (2005) and Zorotovic et al. (2010), transformed into the NIR bandpasses by means of the following relations:

$$\mathcal{A}_J = 0.46 \mathcal{A}_V, \quad (3)$$

$$\mathcal{A}_{K_s} = 0.32 \mathcal{A}_V^{2/3}, \quad (4)$$

both of which are based on ω Cen RRab stars, with visual amplitudes coming from Kaluzny et al. (2004). The corresponding $J$- and $K_s$-band OoI lines are shown in Figure 2 as dotted lines. The presence of OoI-like RRL stars in ω Cen is confirmed, and is especially evident in the $J$-band Bailey diagram.

These interrelations involving $\mathcal{A}_V$, $\mathcal{A}_J$, and $\mathcal{A}_{K_s}$, compared to those previously presented by Feast et al. (2008), provide a description of the amplitudes that is physically better motivated, as they more properly describe their asymptotic behavior towards vanishing light-curve amplitudes.

It is still a matter of debate whether the position of stars on the Bailey diagram, and therefore the Oosterhoff type, is determined primarily by the metallicity of the cluster or by its HB morphology (Contreras et al. 2005, 2010; Clement & Rowe 2000; Rey et al. 2000, and references therein). In this respect, ω Cen provides an interesting test of the relative importance of HB morphology and [Fe/H] in defining the Oosterhoff classification, given that the cluster possesses a predominantly blue HB, as in the case of most OoI clusters, but it also shows at least two well-defined metallicity peaks, separated by ≈0.5 dex. To further investigate the possible impact of metallicity upon the distribution of RRL stars in the NIR Bailey diagrams, Figure 3 again shows the Bailey diagrams in both $J$ and $K_s$, but separating the RRL into three metallicity bins, based on [Fe/H] values from Sollima et al. (2006) and Rey et al. (2000). The bin sizes were chosen so as to ensure an equal number of RRab stars in each bin. For stars with [Fe/H] measurements in both catalogues, the metallicities of Sollima et al. were preferred.

As shown in Figure 2, ω Cen can still (not unexpectedly) be safely classified as predominantly an OoII GC, which is in perfect agreement with its predominantly blue HB morphology. This figure also shows that the NIR Bailey diagrams for ω Cen ab-type RRL stars is largely insensitive to metallicity, in the sense that the average OoII and OoI loci, defined as above, adequately represent the mean loci occupied by RRL in each individual metallicity bin also. It is interesting to note, however, that the OoI/OoII number ratio does change with metallicity: in the lowest-metallicity bin, there are virtually no RRL stars close to the OoI locus; conversely, in the highest-metallicity bin, RRab stars are more evenly divided between OoII and OoI subclasses. This largely confirms previous results from Rey et al. (2000) based on visual data, even though the impact of metallicity...
Fig. 4. As in Figure 2, but separating the RRL stars into three metallicity bins, from lowest (top) to highest (bottom). The sizes of the bins were chosen so as to include the same number of RRab stars in each.

... at low [Fe/H] was stronger in their case. Thus, HB morphology and metallicity appear both to be important in determining Oosterhoff type.

Interestingly, Figure 9 in [Rey et al. (2000)] suggests that the ω Cen ab-type RR Lyrae with the longest periods (i.e., $P \gtrsim 0.71$ d) all belong to the metal-intermediate bin, but this is not immediately obvious from our plot. We tested whether this difference is simply due to the different metallicity bins selected by [Rey et al.] and our study. Indeed, according to our analysis, even using the [Sollima et al. (2006)] metallicities, the long-period RRab's in ω Cen RRab’s do indeed occupy a very limited range in [Fe/H], between −1.81 and −1.64. This can be understood in terms of the evolutionary scenario proposed by [Lee (1991)], according to which the HB component over this metallicity range is extremely blue, thus preferentially producing overluminous, long-period RRL stars.

3.2. Low-amplitude RRc stars

Some RRc stars in ω Cen are known to have very low amplitudes in the visible, at the level of $A_V < 0.1$ mag [Kaluzny et al. (2004)]. Specific examples include V281 ($A_V \approx 0.07$ mag), V344 ($A_V \approx 0.07$ mag), and...
0.08 mag), V357 ($A_V \approx 0.05$ mag), and V399 ($A_V \approx 0.05$ mag). We do not expect to recover the variability of these stars from our NIR observations, because the amplitudes in the NIR are even lower than in the optical (Smith 1995). Indeed, none of these stars were found to be variable in our data.

In this context, we also note that clean light curves for V339 and V340 could not be recovered either, even though their $V$ amplitudes ($A_V \approx 0.11$ mag and 0.17 mag, respectively) are perhaps high enough that one might have expected non-negligible $J$ and $K_S$ amplitudes. A possible explanation for their non-detection in our data is their marked multiperiodic behavior, which renders even their $V$-band light curves somewhat noisy (Kaluzny et al. 2004).

### 3.3. New RR Lyrae stars

To detect additional, previously unknown variable stars in and around $\omega$ Cen, we performed a new search for variable stars over the complete area covered by our observations. Our procedure consisted in considering as candidate variables all those stars whose light curves implied root-mean-square magnitude deviations that were higher than the average trend for non-variable stars at the same magnitude. The search was independently performed in $J$ and $K_S$. With the goal of specifically detecting RRL and other periodic variables, the four most prominent periods for each star, as returned by the ANOVA algorithm (Schwarzenberg-Czerny 1989), were used to plot phase-folded variables. From this search, four variable candidate stars have periods and amplitudes in accordance with their being RRL stars. Figure 5 shows the finding chart for these new discovered RRL candidates. None of them appears to present the Blazhko effect. The remaining candidates, which may belong to different variability classes, will be discussed in future papers of this series.

Table 2 gives the ID (following the numbering scheme from the C13 online catalogue), coordinates, intensity-weighted mean $J$ and $K_S$ magnitudes, periods, type, and the distance to the center of the cluster. According to their position in the CMD, NV455 and NV456 are likely members of the cluster, whereas the other two stars deviate largely from the main HB locus – and since they are fainter, they are almost certainly field stars in the cluster background. $J$- and $K_S$-band light curves are presented in Figure 6. According to their light curve shapes, in addition to their periods (Table 2) and positions in the Bailey diagram (Fig. 2), we assign an RRc type to the new variable NV456, and an RRab type to variables NV455, NV457, and NV458. As it happens, NV455, with a period of about 0.932 d, is the RRab star with the third longest period known to date in $\omega$ Cen (see Fig. 2).

Recently, Fernández Trincado et al. (2013) also performed a variability search in the $V$-band over an area of 50 deg$^2$ around $\omega$ Cen, with the main aim to detect RRL stars and in this way find evidence for tidal debris from the putative dwarf galaxy progenitor of the cluster (e.g., Dinescu 2002; Altmann et al. 2005; Carretta et al. 2010; Valcarce & Catelan 2011). They found 29 new RRL stars, and recovered 7 previously known ones. Of these, a total of 11 are in the area covered by our observations, and they were all independently recovered in our study as well. Their remaining RRL are all outside $\omega$ Cen’s tidal radius, and they are reported further on in Fernández Trincado et al. (2014).

### 4. Summary

Based on previous $\omega$ Cen variability studies, from Bailey (1902) until Kaluzny et al. (2004), C13 report that there are 193 RRL stars in the field of the cluster. Among these, one finds 92 RRab, 100 RRc, and 1 star classified as RR? (V80). None of the 5 new RRL claimed by Weldrake et al. (2007) were included in the C13 catalogue, because, as we have shown, only two of them are really new discovered – and for these two stars, ID-91 and ID-99, an RRL classification still remains uncertain.

On the other hand, ID-74, which Weldrake et al. (2007) classified simply as “pulsating,” was included in the C13 catalogue as a possible RRL, based on its period (0.6671 d). In this way, it was also given the official ID V433 by C13. However, we have been unable to recover the star’s variability using our NIR data. Moreover, its NIR magnitude and color place the star close to but

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**Fig. 5.** Finding charts for the 4 new RRL candidates that were discovered in our VISTA images. North is up and East to the left, and each stamp covers a field of 1 arcmin$^2$. The discovered candidates are the stars at the center of each stamp. The first two stamps correspond to 2 new RRL members of $\omega$ Cen, based on their position in the CMD (Fig. 1), whereas the remaining ones, according to the same CMD, are field interlopers, in the cluster background.

**Table 2.** New RR Lyrae candidate stars$^{(a)}$

| ID   | RA (J2000) | DEC (J2000) | $〈J〉$  | $〈K_S〉$ | $P$  | Type  | $d$  | Membr. |
|------|------------|-------------|---------|----------|-----|-------|------|--------|
| NV455| 13:27:53.94| -46:55:43.93| 13.132  | 12.760   | 0.932469 | RRab | 34.92 | m     |
| NV456| 13:22:14.49| -47:24:21.64| 13.530  | 13.270   | 0.383516 | RRc  | 46.33 | m     |
| NV457| 13:29:54.56| -47:50:46.00| 15.530  | 15.265   | 0.508593 | RRab | 38.45 | f     |
| NV458| 13:30:00.09| -47:13:05.63| 14.772  | 14.441   | 0.620313 | RRab | 36.23 | f     |

Notes. $^{(a)}$ Columns have the same meaning as in Table 1.
to the red of the base of the red giant branch, rather than on the classical RS. Recently, [Navarrete et al. (2013)] found a misidentified RRab star, V411, in the [Weldrake et al.] catalogue. Therefore, prior to this publication, 194 RRL stars in all (93 and 100 RRab and RRc, respectively) have been listed for the ω Cen field, where we have not included any of the “new” candidates in the [Weldrake et al.] catalogue in this number count.

Considering the information obtained with the VISTA observations, the light curves of some RRLs were recovered for the first time, leading to changes in the variability classification. In particular, we have been able to provide the first light curves ever for V80, thus establishing that it is an RRc star, V151, V173, and V177, all of which had previously been considered ab-types, are shown to be RRc stars, according to our data. On the other hand, we have found that V180 is not an RRc, as previously thought, but rather a contact binary of the W UMa type. Furthermore, if we exclude V68 and V84 because of their controversial classification (with the distinct possibility that they may be ACEP stars, rather than RRLs), the final census of likely RRL members of ω Cen includes 88 RRab and 101 RRc stars, for a grand total of 189.

From these 197 RRLs, there are 4 RRab (V181, V283, NV457, and NV458) and 2 RRc (V168 and V183) stars that have magnitudes and colors consistent with being field interlopers. In addition, if we exclude V68 and V84 because of their controversial classification (with the distinct possibility that they may be ACEP stars, rather than RRLs), the final census of likely RRL members of ω Cen includes 88 RRab and 101 RRc stars, for a grand total of 189.

Fig. 6. J and $K_s$-band light curves of the newly discovered RRL stars that are likely cluster members.

It should be noted that it was not possible for our team to observe some distant RRLs such as V171, V178, V179, and V182, because they fall outside the VIRCAM@VISTA FoV; however, they are located outside the tidal radius of the cluster, and are therefore most probably field stars. It is expected that these numbers will increase further, once the new variables found by [Fer-

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Appendix A: Notes on individual RR Lyrae stars

V19 and V21: In the C13 catalogue, these variables are listed as possible non-members, based on their anomalous Fourier parameters compared with other variables with similar periods (Clement & Rowe 2009). However, and as indicated in Table 1, the proper motion studies of vL00 and B09 found a membership probability $P_M$ of (100%, 100%) and (100%, 99%) for V19 and V21, respectively. The membership status for these two stars is further supported by their position in our NIRM CMD, which locates them in the middle of the RRL IS (see the bottom panel of Fig. 1).

V52: This star appears to be much brighter than other RRab stars in $\omega$ Cen, as can be noted in Figure 1. Its light curve has high photometric errors despite its high luminosity, thus suggesting contamination due to blending. Indeed, vL00 reported that V52 may have an unresolved companion, which would account for the fact that it is brighter and has a lower amplitude than other RRab variables with the same period. According to vL00 and B09, the membership probability of this star is 42% and 53%, respectively. Based on its position in our NIRM CMD, the projected distance to the cluster center, $d$, and the high amount of noise in the light curve, V52 is most likely a member of the cluster in a very marked blend. Inspection of Hubble Space Telescope (HST) images (Anderson & van der Marel 2010) confirms the presence of a companion that is unresolved in our images, located just about 0.5″ from the RRL star, but brighter by about 0.5 mag in $V$, and bluer by about 0.25 mag in $B - V$.

V56 and V168: The field status of these two stars was based on a radial velocity study by Liller & Tokarz (1981). Subsequently, V56 was again considered a member of the cluster based on its high membership probability of 98% and 100% found by vL00 and B09, respectively — a status in excellent agreement with its position in our NIRM CMD. These inconsistent conclusions can probably be explained as follows. When assessing membership status of an RRL variable from its radial velocity, it is necessary to take into account the phase in its light and velocity cycle. Liller & Tokarz obtained this information from an epoch established in 1974. The observations of Liller & Tokarz were made in 1978. A period change study by Jurcsik et al. (2001) indicates that V56 undergoes random period changes. Thus it is highly likely that Liller & Tokarz were incorrect. On the contrary, all proper motion studies agree in classifying V168 as a non cluster member, which also agrees with our photometric classification as a field star: Figure 1 clearly shows that this RRL star is a background interloper.

V68 and V84: These two stars have controversial mode classification in the literature. First thought as RRLs by Bailey (1902), they were later suggested to belong to the Acep group by Nemec et al. (1994), because of its brighter optical magnitudes compared with the other RRLs of the cluster. Acep stars are Population II stars with periods between 0.4 and 2.4 days, that do not follow either the RRL or the type II Cepheid PL relations. Most of them are found in dwarf spheroidal galaxies (Nemec et al. 1994) and the Large Magellanic Cloud (Soszynski et al. 2008), a few Acep stars are known in Galactic globular clusters (see Zinn & Dahn 1976; Sollima et al. 2010; Osborn et al. 2012; Arreliano Ferro et al. 2013) and only one in the Galactic field (XZ Ceti; Teays & Simon 1985; Sazabados et al. 2007). V68 appears as an RRC cluster member star according to its radial motions and its position in the CMD (see Table 1 and the bottom panel of Fig. 1). Although it has the longest period among the RRC stars of the cluster (0.56 days), which is longer than...
than even the short-period end of the RRab stars’ period distribution, the amplitude of its light curve is small enough to place it within the RRc stars group (see Fig. 2). V68 also follows the PL relations for RRc stars in J and Ks (Navarrete et al. 2014b, in preparation). This star, on the other hand, also appears to follow the optical (B, V) PL relations for ACEP stars, as derived by Nemec et al. (1994).

On the other hand, V84 was discarded as a cluster member by vl.00, with a membership probability \( P_\mu = 0 \). Unfortunately, we were unable to confirm this result using proper motions from B09, since V84 is outside their FoV. Our NIR CMD shows that V84 is well located in the RRL instability strip, opening the possibility that it is a cluster member. However, as Dei Principe et al. (2006) pointed out, V84 does not follow the NIR PL relation for RRab stars. This result is confirmed using our PL relations (Navarrete et al. 2014b, in preparation), with V84 appearing brighter than other stars with the same period. Conversely, Nemec et al. (1994) found that V84 was placed slightly below the B- and V-band PL relations for ACEPs, which could be explained if the star was not an ACEP but instead an RRL star leaving the HB.

Using our NIR observations, we cannot adopt a definitive classification for either of these stars. If they are RRLs, the most probable scenario is that V68 is an RRc member and V84 is an RRab star from the field. However, the ACEP classification cannot be completely discarded. Indeed, V68 and V84 follow the \( K_s \)-band PL relation for ACEPs in the Large Magellanic Cloud derived by Rippe et al. (2014), assuming a distance modulus for \( \omega \) Cen of \( (m-M)_0 = 13.63 \pm 0.1 \) mag – which is in good agreement with the one derived by Matsunaga et al. (2006) using type II Cepheids. If these two stars are indeed ACEPs, they should be members of the cluster.

**V80:** This star was detected in the first variability study on \( \omega \) Cen carried out by Bailey (1902). In that work, V80 was reported as difficult to measure because it is distant from companion stars, and accordingly only sparse measurements of differential magnitudes were published, without an accompanying light curve. Bailey suggested a period of 0.45 or 0.51 days for this star, wherewith it was tentatively classified as an RRL-type star. Based on our wide-field VISTA observations, we determined its period, \( P = 0.37718 \) d (Table 1), and derived its complete, phase-folded light curve (Fig. A1).

According to its coordinates, ID-53, \( P = 0.377 \) d, from Weltdrake et al. (2007), appears as the nearest star to V80 among the list of new variables discovered by those authors. However, Weltdrake et al. did not associated ID-53 to V80; probably because a period value had never previously been published for V80 – and accordingly, they claimed that their ID-53 was a newly discovered variable star. Instead, our independently derived period and coordinates alike indicate that V80 and ID-53 are one and the same star.

V80 is not present in any proper motion study. Its derived period and position in the CMD indicates that V80 is an RRc star that is also a member of the cluster.

**V118, V135, and V139:** These three stars appear well located within the RRab region in the IS (see Fig. 1). Based on the vl.00 and B09 proper motion studies, V118 has a membership probability of \( P_\mu = (100\%, 96\%) \), respectively, whereas V139 has \( P_\mu = (100\%, 90\%) \), V135 is only present in B09, with a membership probability of 97%. However, all appear brighter than the other RRab stars with similar periods in the J and Ks PL relations (Navarrete et al. 2014b, in prep.).

V118 is located in a very crowded region. According to the HST catalogue of Anderson & van der Marel (2010), there are more than 10 stars inside a 1′′ radius around its coordinates. A similar situation occurs with V139, having a neighbor located at only 0.432″, according to the Anderson & van der Marel catalogue – which is a difference of less than 2 pixels, given the VIRCAM pixel scale. Hence, this star is almost certainly brighter in our photometry than it would be, in case it were isolated.

V135 is suffering the influence of a disturbing neighbor, located 2.5″ away, which is saturated. This situation was previously reported by Samus et al. (2009), with both stars being labeled in that study as a visual binary.

**V143:** It is certainly a member of the cluster according to vl.00, with 99% membership probability. B09 give instead \( P_\mu = 90\% \) for this star. However, it appears a few tenths of a magnitude brighter than other RRab stars with the same color. A visual inspection of this star in some of our images suggested to us that its anomalous position in the CMD is not due to a blend effect of an unresolved system, but rather to a saturated companion located close by (i.e., at a distance of \( \approx 3.4″ \)) that is somehow disturbing the photometric quality in its neighborhood. Indeed, this situation was explicitly reported by Shokin & Samus (1996), where the presence of a bright star located southwest from the position of V143 is remarked upon. Therefore, despite its anomalous position in the CMD, we suggest that V143 is indeed a cluster member.

**V151:** Listed as an RRab star by Kaluzny et al. (2004) with a period of 0.4078 days, this star would appear to be the shortest-period fundamental-mode RRL in \( \omega \) Cen. However, despite the fact that our estimated period (\( P = 0.407756 \) d) is in excellent agreement with the one derived by Martin (1938), we notice that its light curve shows a very small amplitude, which is among the lowest for RRab stars in our study. Small amplitudes are unusual for short-period RRab stars. Figure 2 shows the position of V151 in the Bailey (period-amplitude) diagram, as compared to other \( \omega \) Cen RRab stars. This plot clearly shows that V151 is well located among the RRc-type variables. In addition, its position in the PL relation (Navarrete et al. 2014b, in preparation) is also consistent with first-overtone pulsation. Thus, we conclude that this star should be classified as an RRc. We note that Martin (1938) also classified V151 as an RRc star, hence the erroneous RRab type adopted by Kaluzny et al. is likely a typo, which was later inadvertently reproduced in the C13 online catalogue. V151 was not included in the proper motion studies of vl.00 and B09; however, our NIR CMD suggests that this variable likely belongs to the cluster.

**V172, V173, V175, V177, and V180:** Wilkens (1965) announced the discovery of V171-V180. Of these 10 stars, V176 was subsequently discarded as a non-variable star, V174 classified as an EB, and the remaining stars classified as RRab’s, except for V180, which was classified as an RRc instead. To the best of our knowledge, no further variability studies of these stars have been carried out, except for V172 and V177 which were included in the observations by Weltdrake et al. (2007) as ID-18 and ID-49, respectively. None of them has had a period assigned in the C13 catalogue.

Four of Wilkens’s stars, namely, V171, V175 (without a previous type assigned), V178, and V179 are all very far from the cluster center, and thus were not observed by us, despite VIRCAM’s large FoV. Consequently, only light curves for V172, V173, V177, and V180 were derived, and they are shown in Figure A2. Only V180 has membership probability derived based on proper motions studies, being considered a non-member of the cluster with a null membership probability by vl.00. According to their positions in the CMD (bottom panel of Fig. 1), we suggest that V172, V173, and V177 are cluster members. We

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Fig. A.1. VISTA NIR light curves for all the RRLs that lacked a derived light curve or period in the literature. For each star, the upper panel shows the $J$-band curve, whereas the lower one displays the $K_S$ band instead. Our derived period for each star is provided in each panel. Note that the V180 light curve is consistent with a W UMa classification. Variables ID-91 and (especially) ID-99, from Weldrake et al. (2007), have light curve shapes that are different from all the other RRab in ω Cen, and are suspected field stars.
confirm the ab-type classification for V172, but at odds with Wilkens, we did not find an RRab behavior for either V173 or V177, and we suggest instead an RRc classification for both these stars. This is consistent with their positions in the Bailey diagram, as can be seen from Figure 2. V175, according to A. K. Vivas (2014, priv. comm.; see also Fernández Trincado et al., 2013) is a foreground c-type RRL. As can be seen in Figure 1, V180 is located in the RRab region, redder than any other RRc stars. Moreover, it has a large amplitude compared to other RRc stars (Fig. 2). Our estimated period produces a light curve clearly showing 2 different minima. Accordingly, we propose to classify V180 as a contact EB of the W Ursae Majoris type, rather than as an RRc, which is consistent with its fairly red color and the fact that this star is not a cluster member.

**V181 and V183**: V181, V182, and V183 were discovered by Wesselink (1969, unpublished, priv. comm. to H. Sawyer-Hogg), who indicated the stars’ coordinates and periods, but without providing light curves or variability types for these stars. Clement et al. (2001), based on Wesselink’s periods, classified V181 and V182 as RRab’s, and V183 as an RRc. These stars were outside the FoV in subsequent investigations by other authors. Unfortunately, V182, at 59.7 arcmin from the center of the cluster, is also outside the FoV of VISTA.

Figure A.1 shows the first complete light curves for V181 and V183. They are ab- and c-type RRL stars, respectively, in agreement with the periods originally derived by Wesselink. These two stars are very distant from the cluster center (though still inside its tidal radius), and thus they are absent from proper motion studies of the cluster. However, based on their positions in the CMD (see the top panel of Fig. 1), they both appear to be field RRL stars.

**V268**: vL00 claimed that V268 is a field star with a membership probability of 0%. However, we found some inconsistencies in this membership status using our coordinates and those from the literature: in fact, the nearest star to V268 in vL00’s catalogue has a membership probability of 70%. Moreover, according to B09, this star has a 99% membership probability. Using the NIR CMD to figure out the membership status of this star, it is found that V268 is located well inside the RRL instability strip, as the other RRab members of the cluster (Fig. 1, bottom panel). We thus conclude that V268 is indeed a cluster member.

**V283**: This star was studied by neither vL00 nor B09. Based on its faint visible magnitude, Kaluzny et al. (1997) claimed that it is a background halo RRL. This field status is confirmed by our photometry, which locates the star a few magnitudes below its NIR magnitudes of \( V \approx 17.1 \) and \( 17.45 \) mag for these two stars, respectively, which is consistent with their being field interlopers. Unfortunately, neither star appears in the proper motion catalogues of vL00 and B09. As far as their variability status is concerned, Weldrake et al. (2007) suggested that ID-99 could be either a long-period RRc with a 0.671-d period or an EB with a period twice as long. For ID-91, in turn, they assigned an RRab type. Both stars’ light curves are shown in Figure A.1, according to which the RRab status of ID-91 seems reasonable, whereas the RRL nature of ID-99 remains a possibility. However, if indeed an RRl, ID-99’s long period might more naturally suggest an RRc classification, as opposed to the RRc type suggested by Weldrake et al. To further check their classification, ID-91 and ID-99 were plotted in the Bailey diagram (see Fig. 2). Their location suggest that both stars are either extreme examples of OoI RRab stars, and/or show a modulation in their light curves (e.g., the Blazhko effect), and/or are unresolved blends. The latter possibility receives some support from the positions of the stars in the CMD (Fig. 1), which show that both stars are slightly redder than expected for RRl stars. However, these stars are also quite far away (~ 25’) from the cluster center, and inspection of our images reveals that they are in relatively unpopulated areas, thus making the possibility of blends seem unlikely. Unfortunately, HST images of these fields are not available, and thus we cannot conclusively establish that unresolved companions to these stars are indeed absent. In like vein, the presence of the Blazhko effect is not supported by either our photometry (Fig. A.1) or the Weldrake et al. (2007) photometry.

Based on the astrometry that is provided along with the VISTA images (which is tied to the 2MASS system), we found some erroneous matches between some of the known variables in the catalogues of Weldrake et al. (2007) and Kaluzny et al. (2004). ID-115 = V264 (instead of V48) and ID-135 = V266 (not V356). Moreover, Weldrake et al. erroneously claimed that ID-133 was the same star as V144 from the Clement & Rowell (2000) catalogue for several other RRL stars in \( \omega \) Cen. Using the coordinates and periods provided by Kaluzny et al. (2004), these two variables were not found neither in our ALLFRAME nor in our DoPhot photometry. The matching radius used was 1 arcsec. Increasing the matching radius until 10 arcsec still did not return any variable stars. The last check step was to consider all the stars within 30 arcsec around the listed coordinates, and check for the presence of periodicity in this enlarged sample using the Analysis of Variance statistic (ANOVA; Schwarzenberg-Czerny, 1989). Again, no periodic variables were detected in this way.

Therefore, V349 and V351 could not be recovered using PSF photometry in our VISTA images.

### Appendix B: RR Lyrae stars from Weldrake et al. (2007)

Weldrake et al. (2007) reported the discovery of five new RRL stars in \( \omega \) Cen: ID-53, ID-91, ID-99, ID-144, and ID-145. By carefully checking these stars’ positions and periods, we have been able to establish that three out of these five variables were not really new discoveries. More specifically, according to our analysis, we were able to establish that ID-53 = V80, ID-144 = V272, and ID-145 = V15.

ID-91 and ID-99, on the other hand, do appear to be bona-fide new variables. Weldrake et al. (2007) listed optical magnitudes of \( V \approx 17.1 \) and \( 17.45 \) mag for these two stars, respectively, which is consistent with their being field interlopers. Unfortunately, neither star appears in the proper motion catalogues of vL00 and B09. As far as their variability status is concerned, Weldrake et al. suggested that ID-99 could be either a long-period RRc with a 0.671-d period or an EB with a period twice as long. For ID-91, in turn, they assigned an RRab type. Both stars’ light curves are shown in Figure A.1, according to which the RRab status of ID-91 seems reasonable, whereas the RRL nature of ID-99 remains a possibility. However, if indeed an RRl, ID-99’s long period might more naturally suggest an RRc classification, as opposed to the RRc type suggested by Weldrake et al. To further check their classification, ID-91 and ID-99 were plotted in the Bailey diagram (see Fig. 2). Their location suggest that both stars are either extreme examples of OoI RRab stars, and/or show a modulation in their light curves (e.g., the Blazhko effect), and/or are unresolved blends. The latter possibility receives some support from the positions of the stars in the CMD (Fig. 1), which show that both stars are slightly redder than expected for RRl stars. However, these stars are also quite far away (~ 25’) from the cluster center, and inspection of our images reveals that they are in relatively unpopulated areas, thus making the possibility of blends seem unlikely. Unfortunately, HST images of these fields are not available, and thus we cannot conclusively establish that unresolved companions to these stars are indeed absent. In like vein, the presence of the Blazhko effect is not supported by either our photometry (Fig. A.1) or the Weldrake et al. (2007) photometry.

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C13 has included ID-74 of Weldrake et al. (2007), a possible RRl based on its period of \( (0.667 \pm 0.004) \) d, and an amplitude that is
likely not higher than 0.05 mag in $K_S$, again preventing us from classifying it as an RRL. The star’s red color is unlikely to be caused by a blend with a red star, since it is $\sim 30'$ away from the cluster center, and without any obvious close companions in our images. According to Da Costa & Coleman (2008), the star is a radial velocity non-member. In conclusion, we follow Weldrake et al. (2007), and consider V433 as a variable star with an uncertain variability type.