The QUEST RR Lyrae Survey:
III. The Low Galactic Latitude Catalogue

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ABSTRACT
We present results for the QUEST RR Lyrae Survey at low galactic latitude, conducted entirely with observations obtained with the QUEST mosaic camera and the 10/1.5m Jürgen Stock Schmidt telescope at the National Observatory of Venezuela. The survey spans an area of 476 deg² on the sky, with multi-epoch observations in the V, R, and I photometric bands for 6.5 × 10⁶ stars in the galactic latitude range −30° ≤ b ≤ +25°, in a direction close to the Galactic Anticenter 190° ≤ l ≤ 230°. The variability survey has a typical number of 30 observations per object in V and I and ~25 in R, with up to ~120 – 150 epochs in V and I and up to ~100 in R in the best sampled regions. The completeness magnitudes of the survey are V ∼ R = 18.5 mag, and I = 18.0 mag. We identified 211 RR Lyrae stars, 160 bona fide stars of type ab and 51 candidates of type c, ours being the first deep RR Lyrae survey conducted at low galactic latitude. The completeness of the RR Lyrae survey was estimated in ≥95 per cent and ~85 per cent for RRab and RRc stars respectively. Photometric metallicities were computed based on the light curves and individual extinctions calculated from minimum light colours for each RRab star. Distances were obtained with typical errors ~7 per cent. The RR Lyrae survey simultaneously spans a large range of heliocentric distances 0.5 ≤ Rhel(kpc) ≤ 40 and heights above the plane −15 ≤ z(kpc) ≤ +20, with well known completeness across the survey area, making it an ideal set for studying the structure of the Galactic thick disk.

Key words: stars: variables: other, Galaxy: stellar content, Galaxy: structure, Astronomical Data bases: surveys

1 INTRODUCTION

In the Milky Way (MW), the thick disk hosts a very old (>10 Gyr) and relatively metal-poor ([Fe/H] ∼ −0.7) stellar populations (Wyse 2009; Reddy & Lambert 2008), comprising ~10 per cent or even up to ~20 of the thin disk mass (e.g. Juric et al. 2008). The Galactic thick disk therefore constitutes an important fossil record of the earliest stages of the formation of the Galactic disk, which could help understand the relevant mechanisms contributing to the formation of our Galaxy. From the perspective of galaxy formation, thick disks are remarkably relevant since these have proven to be an ubiquitous component of disk galaxies, as external galaxy surveys have shown that approximately 95 per cent of disk galaxies contain thick disks (Yoachim & Dalcanton 2006).

On the other hand, despite many advances in the last few years, there is no consensus about the formation mechanism of the Galactic thick disk, or even on some fundamental properties of its structure, mainly due to observational difficulties. Scale length measurements for the MW thick disk range from hp ∼ 2 to 4.7 kpc (Carollo et al. 2010; Larsen & Humphreys 2003; Cabrera-Lavers et al. 2005; Chiba & Beers 2000), which makes it unclear whether the thick disk is more radially extended than the thin disk or not, or how the density profile behaves at large radii. Another example are metal abundances, the iron abundance of thick disk stars seems to be fairly homogeneous in the vertical direction (e.g. Katz et al. 2011; Soubiran et al. 2005), although Chen et al. (2011) recently report an appreciable metallicity gradient. Radial metallicity gradients have not been probed yet and there is also ongoing debate regarding the reach in [Fe/H] at both the low and high metallicity tails of the thick disk (Bensby et al. 2007; Reddy & Lambert 2008; Reddy et al. 2005). In a recent paper, Bovy et al. (2011) argue against the need of a thin/thick disk decomposition, proposing that the Galactic disk can be described as a series of simple stellar populations having scale lengths and
Like populations (Smith 1995; Demarque et al. 2000), the expected contamination from the thin disk is negligible (Martin & Morrison 1998). Finally, RRLSs are pulsating stars with relatively short periods (0.3 – 1.0 d) and large light curve amplitudes (V ∼ 0.3 – 1.2 mag), which makes them easily identifiable by a photometric multi-epoch survey (see e.g. V04, Kinemuchi et al. 2006).

RRLSs have been extensively used as tracers of the Galactic halo by numerous surveys which have studied their spatial distribution in a wide range of distances, from very near the Galactic centre up to large distances Rgal ≳ 100 kpc. This is illustrated in Figure 1 which shows, in an Aitoff projection map in galactic coordinates, the footprint of recent large-scale RRLS surveys including the present one. Table 1 summarizes the characteristics of each survey.

Unlike in the Galactic halo, the distribution of RRLSs in the thick disk has been less thoroughly studied, in particular due to the lack of deep RRLS surveys at low/intermediate galactic latitudes. As illustrated in Figure 1 the Galactic Plane area |b| < 20° has only been covered by the large-scale yet shallow (V < 14 or Rgal ≤ 5 kpc) ASAS-3 (Pojmanski 2002) and NSVS (Kinemuchi et al. 2006) surveys, as well as the compilations of nearby RRLS (V < 13) from Layden (1994, 1995) and Mainz (2005); having been avoided by deep surveys (16 < V < 20). This makes ours, the first deep large-scale RRLS survey conducted at low Galactic latitudes. Furthermore, our survey probes the outer regions of the thick disk, outside the solar circle. In particular, Layden (1995), Mainz & de Boer (2005) and Kinemuchi et al. (2006, NSVS) have studied the distribution of thick disk RRLSs in the vertical direction, but the limited coverage at low galactic latitude prevented the determination of the scale length as well as the exploration of deviations from an exponential profile such as the warp and flare, which have been observed in the Galactic thin and thick disks with other tracers (e.g. López-Corredoira et al. 2002, Momany et al. 2006, Hammersley & López-Corredoira 2011). For these reasons it was essential to conduct a deep RRLS survey at low galactic latitude, which provided an ample spatial coverage both in the radial and vertical directions.

In this paper we will present the catalogue of the QUEST survey, which spans a total area of 476

Figure 1. Aitoff projection map showing the footprints of recent large-scale RRLS surveys in Galactic coordinates. Left: Deep surveys (V > 16), (blue) Present survey, (cyan) QUEST halo RRLS survey, (orange) SDSS Stripe 82, (green) LONEOS (red) SEKBO, (purple) MACHO, (dark yellow) OGLE. Right: Shallow surveys (V < 16), (magenta) NSVS, (yellow) ASAS-3 and (light green) HATNET. The solid black line corresponds to the Celestial Equator. Survey characteristics are summarized in Table 1.

1 Acronym for the ‘QUasar Equatorial Survey Team’
Table 1. Characteristics of recent large-scale RRLS surveys

| Survey      | Filters | Area (deg$^2$) | Completeness | Telescope | Observatory | Reference          |
|-------------|---------|----------------|--------------|-----------|-------------|--------------------|
| QUEST       | VRI     | 476            | $V < 19$     | 1.0 m Schmidt | NOV         | This Work          |
| QUEST (V04) | V       | 380            | $V < 19$     | 1.0 m Schmidt | NOV         | V04                |
| NSVS ROTSE-NT | ~31000   | $V < 14$      | $4 \times 200$ mm ROTSE-I | Los Alamos | Kinemuchi et al. (2006) |
| ASAS-3 V    | ~31000   | $V < 14$      | $2 \times 200$ mm ASAS | Las Campanas | Pojmanski (2002)   |
| LONEOS LONEOS-NT | 1430     | $V < 18$      | 0.6 m Schmidt | Lowell     | Miceli et al. (2008) |
| SEKBO $B_M R_M$ | 1675     | $V < 19.5$    | 1.27 m MACHO | Mount Stromlo | Keller et al. (2008) |
| HATNET I    | 67       | $V < 15$      | 11 cm HATNET | Fred L. Whipple | Hartman et al. (2004) |
| OGLE I      | 0.87     | $V < 20.5$    | 1.3 m Warsaw | Las Campanas | Udalski et al. (1998) |
| SDSS Str82  | ugriz    | 249            | $V < 22$     | 2.5 m SDSS | Watkins et al. (2009) |
|             |          |                |              | Apache Point | Sesar et al. (2010) |
| MACHO $B_M R_M$ | ~75      | $V < 20$      | 1.27 m MACHO | Mount Stromlo | Kunder & Chaboyer (2008), |
|             |          |                |              |            | Alcock et al. (2003) |

deg$^2$ at $-30^\circ < b < +25^\circ$, with multi-epoch $V, R, I$ observations obtained with the 1.0/1.5 m Jürgen Stock Schmidt telescope and the QUEST mosaic camera, at the National Astronomical Observatory of Venezuela (NOV). In Section 2 we describe the observations and spatial and time coverage of the survey, as well as the photometric processing, error estimation and calibration. In Section 3 we describe the procedures used in the identification of RRLSs, we estimate the completeness and possible contamination of the survey and we describe the computation of periods, amplitudes, reden- ders, photometric metallicities and distance for the identified RRLS. In Section 4 we summarize the characteristics of our survey. The computation and analysis of RRLS density profiles for the Galactic thick disk and halo will be presented in an upcoming paper of the series.

2 THE SURVEY

2.1 The Data

The present survey spans a total area of 476 deg$^2$ and makes use of archive observations obtained between late 1998 and mid-2008 with the QUEST camera and the 1.0/1.5 m Jürgen Stock Schmidt telescope at the NOV in Llano del Hato, Venezuela. The camera is a 16 CCD mosaic, with 2048 $\times$ 2048 pixel CCDs layed out in a 4 $\times$ 4 array, having a field of view of $2.3 \times 2.3$ and a scale of 1"02 pixel$^{-1}$. The QUEST camera was designed to operate optimally in drift-scanning mode and can be fitted with up to four different filters at a time. For a more detailed description of the camera and the drift-scanning technique see Baltay et al. (2002) and V04.

For the present survey we used archive drift-scan observations at low Galactic latitudes ($|b| \leq 30^\circ$) approximately in the direction towards the Galactic anticentre. These observations were obtained by different observational projects with very different goals, but since the equipment and method of observations are the same as the original QUEST RR Lyrae survey (V04), we have decided to keep that name for the present survey. Many of the observations come indeed from the QUEST (quasar) survey (Baltay et al. 2002; Rengstorf et al. 2004, V04), and there is also an important number of scans from the CIDA Equatorial Variability Survey (Briceno et al. 2003). The latest spans the equatorial region in the full range of right ascension and has thoroughly surveyed the Orion star forming region, resulting in a large number of observations in this area (Briceno et al. 2005; Downes et al. 2013). Our sample is restricted to observations in the range $60^\circ \leq l \leq 230^\circ$ in Galactic longitude), where the Galactic Plane crosses the celestial equator and drift-scan observations in the declination range $|\delta| \leq 6.5^\circ$ are available.

The observations were obtained using different filter combinations and have different spatial coverage and cadence, all of which changed over time, resulting in a highly inhomogeneous sample. The survey is composed by 452 drift-scans corresponding to 19,238 hours of observation and 6.3 Tb of data in the $V, R$ and $I$ photometric bands, obtained in a total of 427 nights between December 1998 and June 2008. Although ideally an RRLS survey would use a blue filter, since the amplitudes of variation of RRLS would be larger, we did not include these observations in our sample since these were very few due to the low sensitivity of QUEST CCDs in this band.

The present survey includes the low galactic latitude observations from the RRLS surveys of V04, which consisted of QUEST drift-scans at $\delta = -1^\circ$ obtained between December 1998 and April 2001. This results in an overlap area of 90 deg$^2$ at both ends of the present survey (see Figure 1) in the right ascension ranges $60^\circ \leq \alpha \leq 90^\circ$ and $120^\circ \leq \alpha \leq 135^\circ$ and the declination range $-2^\circ \leq \delta \leq 0^\circ$. New observations (post-2001) were added in this area and the existing ones from V04 were reprocessed using the procedures described in the following section, which were devised to make an optimal use of data in the three available filters $V, R, I$. Finally, data in the range $60^\circ \leq \alpha \leq 90^\circ$ are also part of the CIDA Deep Survey of Orion (Downes et al. 2012, in preparation).

2.2 Data Reduction and Photometry

In the following sections we will describe the procedures used in the object detection, astrometric reduction, aperture and PSF photometry.

2.2.1 Object Detection, Astrometry and Aperture Photometry

Each individual drift-scan observation was reduced using Offline, the standard pipeline developed by the QUEST collaboration (Baltay et al. 2002). The Offline pipeline automatically performs basic reductions, object detection, aperture photometry and astrometric reductions for each image frame in a drift-scan observation. This processing was conducted independently for the images obtained by each of the camera’s CCDs, resulting in 16 independent
catalogues having position in celestial equatorial coordinates, photometric magnitude and error for each point-source, as well as photometric parameters such as FWHM, ellipticity, sky background flux and error, etc.

Image reduction consists in standard bias, dark and flat-fielding corrections. Object detection is made at the 3-$\sigma$ level and aperture photometry is performed over all detected point-sources with an aperture radius of one FWHM. The astrometric matrices are computed using the USNO-A2 (Monet 1998) astrometric catalogue as a reference. The astrometric solutions computed by Offline have a typical accuracy of $\sim 0''15$, which is sufficient for the cross-identification of an object in the different catalogues.

2.2.2 PSF Photometry

Since our drift-scan observations include very crowded regions at low Galactic latitude, the use of PSF photometry was necessary. Figure 2 shows a plot of the typical number of stars per image in the $V, R$ and $I$ bands, as a function of right ascension $\alpha$ for a drift-scan at $\delta = -3^\circ$ which spans the entire right ascension range covered by this survey. The right-hand vertical axis shows the scale in terms of $N_C$ the number of stars in a circle with a 16 $''$ radius (which is twice the aperture diameter in an observation with a bad seeing of 4$''$). The plot illustrates how the number of objects per image increases when approaching the Galactic Plane. In particular $N_C > 1$ in the range $95^\circ < \alpha < 115^\circ$, meaning that the typical separation between two objects in an image is less than twice the aperture diameter and, therefore, aperture photometry for most stars will be contaminated by neighbours. Therefore, the computation of PSF photometry was restricted to the right ascension range $90^\circ \leq \alpha \leq 120^\circ$, in which $N_C \gtrsim 0.8$ (indicated in Figure 2 with dashed black lines). In low density areas, consistency was checked by computing both aperture and PSF photometry.

PSF photometry was obtained using the standard DAOPHOT routines implemented in IRAF tied together in an automated pipeline called OfflinePSF, which is customized for QUEST drift-scan observations.

OfflinePSF includes as a first step, prior to the computation of PSF photometry, the recentering and recomputation of aperture photometry for all point-sources previously detected with Offline. This is necessary since initial Offline detections have centering errors of $\sim 1$ pixel, which are reduced to $\sim 0.1$ pixel by using PHOT’s recentering options. Using the recalculated centroids and aperture photometry magnitudes, PSF photometry is obtained according to an iterative scheme where, for each individual image, input parameters such as the fit radius $r_{fit} = 1 \times FWHM$ and the model PSF radius $r_{psf} = 3 \times r_{fit}$ are computed independently. Then, from 90 to 120 PSF stars are selected, uniformly distributed across the image, without neighbours within a radius $r_{psf}$ and, for distances less than $2r_{psf}$ requiring neighbours be at least one magnitude fainter and there are no bad pixel columns near. An initial PSF model is made with the DAOPHOT PSF task, with a second order spatial variation across the image. The PSF model is fit around PSF stars with the NSTAR and SUBSTAR tasks, PSF stars with newly detected neighbours are discarded and the PSF model recomputed. The PSF model is then fit to all point-sources in the en-

Figure 2. Number of stars per image as a function of $\alpha$, for a drift-scan centered at $\delta = -3^\circ$, with filters $V, R e I$ (+, ×, + respectively). The right-hand vertical axis indicates the typical number of stars $N_C$ inside a circle of radius 16 $''$ ($C(16'')$). Dotted grey lines indicate the regions corresponding to galactic latitudes $b = \pm 20^\circ, \pm 40^\circ$. The black dashed lines delimit the region were PSF photometry was computed.

2.2.3 Photometric Calibration

The photometric calibration was done in two stages: the calibration of a master catalogue by means of second order photometric standards and the normalization of individual drift-scan observations to this master photometric catalogue.

The master catalogue is composed of 3 to 4 individual scans per declination stripe, observed with good and constant seeing and sky background throughout the whole duration of the scan. The combination of these scans allowed for a much more homogeneous master catalogue, than would have been obtained if only one scan had been used, due to empty regions caused by bad columns and defective regions of the CCDs. The master catalogue obtained contains 6,513,705 objects and its coverage is illustrated in the density map shown in Figure 3.

The instrumental magnitudes for each object in the master catalogue were calibrated using second order photometric standards. A total of 4526 photometric standards were used, spanning the magnitude range $10 < V < 17$ with colours $-0.2 < V - R < 1.2$ and identified as non-variable stars in any one of the VRI bands, with a spatial distribution illustrated in Figure 3. Photometric standard stars indicated by black dots (2621 in total) were set up by Downes et al. (2012) using observations obtained with the 1.2 m telescope and the KeplerCam camera, at the Fred L. Whipple Observatory, Mt. Hopkins, US. The asterisks indicate the 28 standards having $\delta = -1^\circ$ and $\alpha < 175^\circ$, established by V04 with observations from the 1.0m YALE telescope at the Cerro Tololo Interamerican Observatory (CTIO), Chile. Finally, as part of this work, we established 1877 second order standards in the range $15 < R < 20$.

3 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy Inc., under cooperative agreement with the National Science Foundation.

4 Acronym for “Yale Aura Lisbon Ohio”
\( -4^\circ \leq \delta \leq -2^\circ \) (denoted in Figure 3 with dark gray dots), using observations obtained during December 2004, with the 0.9 m SMARTS telescope at CTIO. Data for these 1877 second order standards is summarized in Table 2. The photometric calibration was performed independently in declination stripes having the width of a QUEST CCD and in 1-hour-long intervals in right ascension where the distribution of standards allowed it. The catalogue regions centered around \( \delta = -1^\circ \) with \( 110^\circ \leq \alpha \leq 135^\circ \) and \( \delta < -5^\circ \) with \( \alpha > 130^\circ \) lacked photometric standard stars, so these were calibrated using long reference scans which extended as far as the area covered by the \( \text{V04} \) standards (asterisks) and \cite{Downes2012} (black dots) respectively.

The photometric solutions for each scan were obtained using zero-point and \( V-R \) or \( V-I \) colour terms, depending on the filters available for each observation. A mean photometric precision of \( \sim 0.021 \) mag was achieved for the \( V, R \) and \( I \) bands.

2.2.4 Normalization

The master photometric catalogue, described in the previous subsection, provides the calibrated reference photometry for all survey objects. The individual observations, used to construct time series for each object (see Sec. 3.2) used in the RRLS search, were calibrated by normalizing each scan to the master reference catalogue.

The normalization process, taken from \( \text{V04} \), consists in identifying all objects of a particular scan in the reference master catalogue and computing the mean magnitude residuals in both, throughout the whole scan in 0.25 bins in right ascension. Since most stars (\( \geq 95 \) per cent) are non-variable and the number of stars in each bin is sufficiently large (\( \sim 1500 \sim 3000 \)), the average residuals obtained result in a precise estimation of the zero point needed to calibrate each bin of the scan. This normalization process allows for the correction of systematic trends in the magnitude residuals caused by changes in the atmospheric conditions during each observation, which in our case is critical given that a single drift-scan can be up to 7 to 8 hours long (see Figure 3 in \cite{V04} for an example of the normalization process). The typical resulting standard deviation of the residuals in each bin was \( \sim 0.015 \) mag, giving zero point errors \( \sim 0.002 \) mag.

2.2.5 Photometric Errors

Taking advantage of the fact that each star in our survey has multiple observations in each filter, it is suitable to use the standard deviation \( \sigma \) of magnitudes of non-variable stars as the representative photometric error in the given filter. Since the majority of stars in any given field are non-variable, these give rise to the main trend in a plot of \( \sigma \) versus mean magnitude, as seen in Figure 4.

In the figure the crosses show the average standard deviation computed as a function of mean magnitude in 0.5 mag bins using an iterative 3\( \sigma \) clipping. The sharp increase in \( \sigma \) for objects brighter than \( V \sim 14.5 \) mag is due to objects saturated in most observations. This behaviour provided us with a means to empirically determine the saturation magnitude and, for each object, remove the individual observations brighter than this limit. The solid line indicates a polynomial fit of the average \( \sigma \) versus magnitude (crosses) and the error bars correspond to the standard deviation around this average. The polynomial fit consequently provides the typical magnitude standard deviation due to photometric uncertainties only, as a function of an object’s mean magnitude, which we assumed as its photometric error.

For each survey star we computed the corresponding photometric error as the typical magnitude standard deviation given by the polynomial fit, for the corresponding mean magnitude. This error analysis was conducted independently for observations in each of the \( V, R \) and \( I \) filters and dividing the entire survey in separate regions of \( \Delta \delta = 0.5^\circ \) times \( \Delta \alpha = 15^\circ \).

2.3 The Photometric Catalogue

The final photometric catalogue spans a total area of 476 sq. deg. having 6,513,705 objects with multi-epoch observations in the \( V \),
Table 2. Magnitudes for second order photometric standards.

| ID  | α      | δ      | V      | R      | I      |
|-----|--------|--------|--------|--------|--------|
|     | (°)    | (°)    | (mag)  | (mag)  | (mag)  |
| ss4000 | 82.401749 | -2.04192 | 13.446 ± 0.003 | 12.238 ± 0.003 | 12.822 ± 0.003 |
| ss4001 | 82.420319 | -2.10225 | 14.386 ± 0.005 | 13.201 ± 0.005 | 13.800 ± 0.004 |
| ss4002 | 82.431961 | -2.04361 | 16.905 ± 0.020 | 14.526 ± 0.009 | 15.849 ± 0.012 |
| ss4003 | 82.436493 | -2.11058 | 16.630 ± 0.018 | 15.197 ± 0.014 | 15.912 ± 0.012 |
| ss4004 | 82.437607 | -2.03612 | 16.784 ± 0.019 | 15.329 ± 0.015 | 16.046 ± 0.013 |

Note: Table 2 is published in its entirety in the electronic edition of the journal. A portion is shown here for guidance regarding its form and content.

Figure 5. Spatial coverage of the survey in the V (top), R (middle) e I (bottom) bands. The colourbars indicate the mean number of epochs per object in each filter.

3 THE RR LYRAE SEARCH

3.1 Light Curve Simulations

The present survey has very inhomogenous time sampling and number of epochs in the different filters, which in turn change in R, and I bands. Table 3 summarizes the saturation ($m_s$), completeness ($m_c$) and limiting ($m_l$) magnitudes in the three photometric bands, as well as the typical errors corresponding to these magnitudes.

The spatial coverage of the survey as well as the typical number of epochs per object, in each of the photometric bands, are illustrated in Figure 5 in equatorial coordinates. As can be seen in the figure, the number of observations per object goes from ~10 up to ~150 in the V and I bands and up to ~60 in the R band. The number of epochs per star per filter is quite inhomogeneous throughout the survey, as illustrated by Figure 5; nevertheless most objects have at least 10 observations in two photometric bands; while objects in the thoroughly sampled Orion region have more than ~30 observations in each of the V, R and I bands.

| Filter | $m_s$ (mag) | $\Delta m_s$ (mag) | $m_c$ (mag) | $\Delta m_c$ (mag) | $m_l$ (mag) | $\Delta m_l$ (mag) |
|--------|-------------|--------------------|-------------|--------------------|-------------|--------------------|
| V      | 14.0        | 0.018              | 18.5        | 0.064              | 19.70       | 0.15               |
| R      | 14.0        | 0.018              | 18.5        | 0.072              | 19.75       | 0.15               |
| I      | 13.5        | 0.020              | 18.0        | 0.078              | 18.80       | 0.15               |

Table 3. Saturation, completeness and limiting magnitudes of the survey.

A total of 425,000 synthetic light curves were generated for RRLS of each type, ab and c, and the same number for non-variable stars. The time sampling and photometric errors as a func-
tion of magnitude (see Sec. 2.3) were taken from actual objects uniformly distributed throughout the entire survey area. This ensures a truly representative realization of the time spacing, the number of observations per filter and the number of quasi-simultaneous observations in different filters, for each synthetic object. This point is of particular importance given the differences both in the cadence and spatial coverage in the different photometric bands as a function of position, as illustrated in Figure 5.

The parameters used to create synthetic light curves for RRab and RRe stars are summarized in Table 4. We generated synthetic stars with random mean V magnitudes (V) uniformly distributed in the range [13.0, 20.0]. For each object, the corresponding mean magnitudes (R) and (I) were computed from the mean V – R and V – I colours, randomly drawn from gaussian distributions with means and standard deviations taken from Alcock et al. (2003), indicated in Table 4. The pulsation period P of each object was randomly drawn from a gaussian distribution and the V-band amplitude computed from the (Oosterhoff I) Period-Amplitude relation from Cacciari et al. (2005), with random gaussian noise with sigma 0.12 mag, for RRab stars. For RRe stars, since the Period-Amplitude relation is weak, the V-band amplitude was randomly drawn from a gaussian distribution assuming a mean and standard deviation taken from Dorfi & Feuchtiger (1999), see Table 4. This way our simulated population of RRLS shows the period-amplitude trend for Oosterhoff I RRab stars (which represent ~ 80% of all RRab stars in the Galactic halo, e.g. Sesar et al. 2010), albeit not the Oosterhoff dichotomy. Note that although we do not simulate the Oosterhoff dichotomy, nor the Blazhko effect (an amplitude modulation known to occur in some RRLS, e.g. Kovacs 2009), we do not expect they will affect our completeness estimates for the survey. For a given period, Oosterhoff II stars would have even larger amplitudes than Oosterhoff I ones making them even easier to identify. On the other hand, the amplitude of RRLS is large enough such that the (relatively small) variations due to Blazhko effect will only translate in the light curves appearing slightly more noisy.

Table 4. Parameters used in the simulation of RRab and RRe light curves.

| Parameter | RRab | RRe | Reference |
|-----------|------|-----|-----------|
| P         | 0.35 d | 0.33 d | V04 |
| σP        | 0.09 d | 0.07 d | V04 |
| ⟨AmpV⟩   | 1.04 mag | 0.536 mag | V04 |
| σAmpV    | 0.24 mag | 0.13 mag | V04 |
| AmpR     | 0.74064 × AmpV + 0.0361 | Alcock et al. (2003) |
| AmpI     | 0.66800 × AmpV + 0.0501 | Dorfi & Feuchtiger (1999) |
| (V)       | 13.0 – 20.0 | … | |
| ⟨(V – R), σV–R⟩ | (0.30;0.26) | Alcock et al. (2003) |
| ⟨(V – I), σV–I⟩ | (0.42;0.20) | Alcock et al. (2003) |

3.2 Variable star identification

The first step in the search for RRLS consisted in identifying variable stars, by means of the variability indices defined by Stetson (1996).

The J and K variability indices were initially defined by Welch & Stetson (1993) and later modified and combined by Stetson (1996) in the definition of the L index, specifically designed for the automated identification of pulsating variables and the reduction of contamination due to spurious variables caused by de-viant photometric observations. The definition of the L index uses the fact that, for pulsating stars, quasi-simultaneous observations in two photometric bands must experience deviations (with respect to the corresponding means) which show a positive correlation, as opposed to non-variable stars for which this deviations would be uncorrelated.

The QUEST drift-scans comprising this survey have data in up to four different filters (see Sec. 2.3) obtained almost simultaneously, since the mean separation between observations in two different filters is Δt ~ 2 – 6 min (given by the time it takes an object to cross the different CCD rows of the camera), which compared to the typical period of an RRLS star (P ~ 0.55 d) can be considered negligible (Δt/P ~ 7 × 10⁻³). This makes it an ideal set of observations to use Stetson’s variability indices.

Candidate variable stars were identified based on the three Stetson L indices that can be computed with our observations, i.e. LVR, LV1 and LR1. Given that the survey coverage and sampling are very inhomogeneous in the different filters (see Figure 5), the criteria used in identifying variable stars needed to be sufficiently flexible in order to consider e.g. objects which have observations in any two bands and not the third, yet without seriously reducing the completeness in the process. Therefore, we selected as candidate variable stars, those objects having at least one of the three possible L indices respectively, in order to obtain the magnitudes corresponding to each epoch of observation (in each filter). A random gaussian photometric uncertainty was added to each of the synthetically produced magnitudes, using the error vs magnitude curves for each filter derived for the survey (see Sec. 2.3).
indices greater than a threshold value of 1, slightly higher than the threshold value 0.9 used by Stetson (1996) in the identification of Cepheid variables. This threshold value was chosen based on results from light curve simulations of RRab, RRc and non-variable stars with the survey’s time sampling.

A plot of $L_{LR}$ as a function of $V$ is shown in Figure 6 (left). As expected, the larger amplitude RRab stars (blue dots) have on average large $L$ values than the lower amplitude RRc stars (green dots), while non-variable (black dots) stars have $L$ values around 0. The criteria used to select variable star candidates (at least one $L$ index higher than 1, see Sec. 3.2) ensures there will be negligible contamination from non-variable and low-amplitude (≲ 0.2 mag) variable stars, while still recovering most variable stars, regardless of whether these have a small number of observations (≲ 10 – 12) in some filters. The completeness of the variable candidate sample achieved using this criteria is illustrated as a function of mean magnitude in Fig 6 (right). Within the saturation and completeness magnitude limits (dashed lines), the completeness in the variable star identification was estimated in 99.1 per cent for RRab and 98.3 per cent for RRc stars.

Using this criteria we obtained a sample of 486,766 candidate variable stars, corresponding to 7 per cent of the total number of stars in the survey.

3.3 RR Lyrae identification

3.3.1 Period Search

The search for RRLS was conducted using a version of the Løffler & Kinman (1965) method for the identification of periods of variable stars, modified by Stetson (1996) and extended in the present work in order to incorporate the information of multi-filter time series data.

The method consists in computing, for a series of trial periods, the parameter

$$S(M) = \frac{\sum_{i}^{N} \omega(i, i + 1) |m_{i} - m_{i+1}|}{\sum_{i}^{N} \omega(i, i + 1)}$$

where $m_{i}$ and $m_{i+1}$ are consecutive magnitudes in the $M$ filter, in the light curve folded with the trial period, $N_{ob}$ is the number of observations and $\omega(i, i + 1)$ are weights proportional to the magnitude errors $\sigma_{i}$, given by

$$\omega(i, i + 1) = \frac{1}{\sigma_{i}^{2} + \sigma_{i+1}^{2}}$$

The true period corresponds to the minimum $S(M)$, since the light curve is smooth when folded with the correct period and therefore the sum of differences between consecutive magnitudes is minimal. Since $S(M)$ considers only the data in the $M$ filter, in order to incorporate the information available for each object in all three $V, R$ and $I$ filters we used the composite index $S_{VRRI}$ as the average of the $S(M)$ for each filter (see e.g. Watkins et al. 2009), weighted by the corresponding number of observations, as given by

$$S_{VRRI} = \frac{N_{V}S(V) + N_{R}S(R) + N_{I}S(I)}{N_{V} + N_{R} + N_{I}}$$

where $N_{V}, N_{R}, N_{I}$ correspond to the number of observations in each of the $V, R, I$ filters respectively. By minimizing the $S_{VRRI}$ parameter given by Equation 3 we are using the data in all the available filters, requiring that the best period be the one that smooths the period-folded light curves in the three photometric bands.

RRLS are known to exhibit a narrow range in temperatures, and therefore colour, which is why the use of colour cuts is frequent in RRLS searches (e.g. Ivčić et al. 2008, V04). However, in low galactic latitude surveys, stars are severely affected by strong and highly variable extinction, and the use of colour cuts is better avoided in order to ensure the survey’s completeness, albeit increasing the computational cost of conducting the period search over a much larger sample. Therefore, the period search was conducted over the full sample of 486,766 variable candidates selected without imposing any sort of colour cuts. The search spanned the period range from 0.2 – 1.2 d with a $10^{-4}$ d period step and for each star, and a second order search was performed with increased period resolution around the 5 best periods initially found, using a period step of $10^{-5}$ d. The best 3 periods found after the refined search were reported for each object characterized by a statistical significance parameter $\Lambda$ defined as

![Figure 6. Left: $L_{LR}$ versus $V$ magnitude, for synthetic non-variable (black), RRab (+) and RRc (triangle) stars. The dashed line indicates the threshold chosen for the selection of variable stars. Right: Completeness of the variable star identification, estimated from synthetic light curves of RRab (blue) and RRc (green) stars. The dotted lines indicate the survey’s saturation and completeness magnitudes in the V-band (see Table 3).](image-url)
where \( \langle S_{VRI} \rangle \) and \( \sigma(S_{VRI}) \) are the mean and standard deviation of the distribution of \( S_{VRI} \) values for all trial periods.

3.3.2 Period Aliases

The emergence of alias or spurious periods is a common problem when trying to identify the period of a signal from time samplings which may or may not be uniform. In general, these can simply be harmonics of the true period or they can come up as a consequence of an underlying periodicity in the time sampling, being therefore external to the signal itself. Following Lafler & Kinman (1965) we can express the relationship between the true period \( P \) and spurious periods \( \Pi \) as

\[
\frac{1}{\Pi} = \frac{k}{P} + \frac{1}{p}
\]

where \( k \) is a rational number, which produces the true period harmonics; and \( p \) is the external period of the sampling. As noted by Lafler & Kinman (1965) the external periods \( p \) of interest are those which produce period aliases in the expected range of the signal, in this case in the period range of RRLSs, since the rest can be ruled out on physical grounds.

In the present case of the RRLS search, the typical one day periodicity between the drift-scan observations composing our survey, leads to the emergence of spurious periods in the range \( 0.2 \lesssim P(d) \lesssim 1 \) expected for RRLSs. This spurious periods, commonly termed one-day aliases, are obtained from Equation (5) with \( p = \pm 1 \) and \( k = 1 \). Other period aliases can arise due to underlying periodicities in the time sampling, as a consequence of the inhomogeneity in the time sampling of our survey.

In order to empirically identify the most frequent alias periods in our sample, we conducted the period search described in the previous section, over the synthetic time series data for \( \sim 130,000 \) of our simulated RRab and RRc stars (see Sec. 3.3.1) Figure 7 shows the recovered period as a function of the true period for synthetic RRab (left) and RRc (right) stars. The most populated sequence in the plot is the identity, indicated by the red shaded area. Different alias periods given by Equation (5) match the other sequences observed in Figure 7. The most prominent loci defined by the alias periods identified in the sample are shaded in different colours, as detailed in Table 5. The widths of the shaded loci in Figure 7 indicates a separation smaller than 2 per cent from the corresponding main locus.

Figure 7 shows that the majority of the periods lie in the identity locus. If the recovered period differs in less than 10 per cent from the true period, we consider it correctly recovered, with this definition we find that for RRab 80 per cent of the times the period is recovered, while for RRc stars it is only \( \sim 46 \) per cent. For the majority of the remaining stars the recovered period is an alias of the true period. This indicates, as can be seen in the figure, that the fraction of RRc stars affected by spurious periods is much larger than that for RRab stars. The frequency of occurrence of the alias periods indicated in Figure 7 is summarized in Table 5 for both types of RRLSs, computed from \( \sim 130,000 \) simulated RRab and RRc light curves. As can be seen both in the table and in Figure 7 one-day aliases are the most frequent as noted by Lafler & Kinman (1965). Nevertheless, other spurious periods can arise, albeit less frequently, such as the 1/3-day and 1/4-day aliases for RRab stars and the 1/2-day alias and first harmonic of the true period for RRc stars.

This empirical overview of the most frequent spurious periods, obtained by means of the simulated light curves, enabled us to quantify the relative importance of the different possible aliases present in our RRLS survey. Based on these results, an inspection of the identified period aliases was included in the period search, described in the previous subsection, during the visual inspection of the period-folded light curves. This allowed increasing the completeness in the RRLS identification, which is described in the following section.

3.3.3 Final Selection of RRLS

We visually inspected the light curves for the 66,086 stars for which a statistically significant (\( \Lambda > 3.0 \)) minimum of \( S_{VRI} \) was found. The visual inspection and classification of light curves was done using the plotting tool *InspectLC.py*, developed as part of this work, whose graphical user interface is shown in Figure 8. The *InspectLC.py* program allows visualizing, for each star, light curves in three different filters (in this case \( VRI \)) period-folded with each of the three most significant periods found. These light curves are shown in Fig. 5 under the labels P1, P2 and P3. The text box to the left of the window summarizes each star’s parameters: identification number, \( \alpha, \delta \), amplitude and number of observations in each of the three filters, the three best periods (\( P_i \) with \( i = 1, 2, 3 \)) and their corresponding values of \( \Lambda \). The ‘TRY ALIAS’ button displays, for a given period \( P_i \), the period-folded light curves using 5 of the most common alias periods (see Table 5) plus one user-defined alias, computed from the values inserted in the ‘k’ and ‘1/p’ textboxes (see Section 3.3.2 and Equation 5). These light curves are displayed in Figure 8 under the labels P4 to P8 and P9 respectively. The program does not display the light curves for alias periods outside the period range of RRLS. The ‘PLOT P-A’ button plots each period with its corresponding aliases in a period-amplitude plot, as shown in the upper right corner of the window in Figure 8. This plot also shows data for RRLS in the globular cluster M3 from Corwin & Carney (2001) as a reference to illustrate the loci occupied by RRab and RRc stars in this diagram. This plot is useful for deciding between different periods that produce similarly good period-folded light curves. In the above example P1 was selected as the correct period. Additionally, the ‘DSS’ button allows downloading and plotting a DSS thumbnail image centered on the coordinates of the star, in order to facilitate the identification of contaminants like spurious extended objects, artifacts on very bright stars or double stars. Finally, the ‘SAVE’ button allows sav-
Figure 7. Top: Recovered versus true period for synthetic stars: (Left) RR\textsubscript{ab} (Right) RR\textsubscript{c}. Bottom: Loci defined by the period aliases visible in the top panels. The shaded red area indicates the identity locus. The remaining indicate the loci of the most common alias periods: (Green) one-day aliases, (Blue) $2 \times P_{\text{real}}$ and $0.5 \times P_{\text{real}}$, (Magenta) $2 \times$ one-day alias, (Cyan) $1/2$ day aliases, (Orange) $1/3$ day aliases, (Grey) $1/4$ day aliases, (Yellow) $2 \times 1/2$-day alias. The shaded areas have a width equal to 2 per cent separation from the corresponding locus. Note that, in the top panels, the points lying within the identity locus correspond to 80 per cent and 46 per cent of the total synthetic RR\textsubscript{ab} and RR\textsubscript{c} samples respectively.

3.3.4 Comparison with Variable Star Catalogues

The present survey partially overlaps with the RRLS catalogue from V04 (see Figure I), also conducted with QUEST observations but focused on high latitude regions. All 21 RR\textsubscript{ab} stars and 31 ($\sim$ 78 per cent) of the RR\textsubscript{c} stars from V04, expected in our survey’s area were successfully recovered. The remaining 22 per cent of RR\textsubscript{c} stars were re-classified as contaminants based on their improved light curves which include a larger number of observations, in particular in the $R$ and $I$ bands, with respect to V04. The 52 RRLS recovered from V04 keep their original identification numbers, which correspond to numbers $\leq$ 999 in Tables 6 and 7. The 27 RRLS with identification numbers in the range 500-600 are from Vivas et al. (2012, in preparation). The 132 RR\textsubscript{ab} and RR\textsubscript{c} stars identified in the present survey have identifiers from 1000 onwards.

We also cross-matched our RRLS catalogue with the ASAS-3 (Pojmanski 2002) and NSVS (Kinemuchi et al. 2006), with a tolerance of 7". Out of the 132 RRLS not present in V04 or Vivas et al. (2012), 131 are new discoveries: one match is found in NSVS and none in ASAS-3. Our RRLS 1012 corresponds to star 722 of the NSVS. The period reported for this star on the NSVS is $P_{\text{NSVS}} = 0.53495$ d which coincides within the errors with our period $P_{\text{QUEST}} = 0.53497$ d and in both catalogues, the star was classified as RR\textsubscript{ab}.

3.3.5 Completeness

The completeness achieved in the RRLS identification was estimated from the catalogue of synthetic light curves for RR\textsubscript{ab} and RR\textsubscript{c} stars described in Sec. 3.1. The completeness was computed,
independently for each RRLS type, as the percentage of synthetic stars recovered after the period search described in Sec. 3.3.1 was performed on a sample of \( \sim 65,000 \) synthetic RRLS of each type. A synthetic star was considered successfully recovered if one of the 3 best periods found were within 10 per cent of the true light curve period or one of the period aliases described in Sec. 3.3.2. The average completeness was computed for synthetic stars in the magnitude range \( V < 18.5 \) as a function of position in the survey area, since it strongly depends on the time sampling and number of observations in each filter.

The resulting completeness maps for RRLS of types \( \text{ab} \) (left) and \( \text{c} \) (right) are shown in Figure 9 in equatorial coordinates. As illustrated by the figure, for RRLS stars the average completeness is \( \sim 95 \) per cent for most of the survey area, except in the declination stripe \( -6^\circ \leq \delta \leq -4^\circ \), where the number of observations per object is typically less than 15 in all three photometric bands (see Figure 5). For RRC stars the estimated completeness is \( \sim 80 - 85 \) per cent, significantly lower than for RRab stars, as expected since RRC light curves have smaller amplitudes.

### 3.3.6 Possible Contaminants

The main source of contamination in an RRLS survey are eclipsing binaries (mostly of the WUMa type), \( \delta \) Scuti and SX Phoenicis stars. Eclipsing contact binaries or WUMa stars, consist of a system in which both stars have filled their Roche lobes and are undergoing mass transfer (Sterken & Jaschek 2005) and have light curves showing two eclipses of very similar depths. \( \delta \) Scuti stars are pulsating main sequence dwarfs and blue stragglers, while SX Phoenicis stars are their metal-poor counterparts; both types are also called Dwarf Cepheids (Nemec & Mateo 1990; Sandage & Tammann 2006) and have asymmetric light curves, similar to those of RRLSs, though with smaller periods \( (P < 0.2 \text{ d}) \) and amplitudes \( (V < 0.2 \text{ mag}) \) (Sterken & Jaschek 2005).

A plot of \( V \) amplitude versus period is shown in Figure 10 for RRab, RRc, Algol, \( \beta \) Lyrae, WUMa and \( \delta \) Scuti stars from the ASAS-3 survey (Pojmanski 2002). As illustrated by the figure, the period and amplitude ranges for most of these stars largely overlap, making the light curve shape an important criteria in distinguishing between the different types of variables. Most of the contamination problems affect the RRc rather than the RRab stars.

Eclipsing binary light curves, of any type, are unlikely to be mistaken for RRLSs of type \( \text{ab} \), while dwarf cepheids, though having similar light curves, have periods and amplitudes which are...
Table 7. Light curve parameters for RRc stars.

| ID   | α    | δ     | (Nv, Nr, NI) | Period (d) | AmpV (mag) | AmpR (mag) | AmpI (mag) | HJDmaxl (d) | ⟨V⟩ (mag) | ⟨R⟩ (mag) | ⟨I⟩ (mag) |
|------|------|-------|--------------|------------|------------|------------|------------|-------------|-----------|-----------|-----------|
| 1013 | 74.15 | -3.74  | (21, 17, 31) | 0.3319     | 0.40       | 0.23       | 1824.12     | 17.91      | ±0.05     | 17.67     | ±0.04     |
| 1015 | 74.72 | 3.88   | (44, 39, 33) | 0.4002     | 0.36       | 0.53       | 1870.98     | 15.22      | ±0.01     | 14.83     | ±0.01     |
| 1019 | 75.68 | 5.07   | (19, 12, 19) | 0.3847     | 0.38       | 0.38       | 1871.10     | 15.90      | ±0.01     | 15.77     | ±0.01     |
| 1022 | 76.73 | 0.80   | (33, 20, 9)  | 0.4125     | 0.44       | 0.37       | 1539.59     | 18.80      | ±0.07     | 18.63     | ±0.06     |
| 1028 | 77.48 | 0.07   | (82, 21, 34) | 0.3708     | 0.30       | 0.22       | 1539.62     | 17.51      | ±0.04     | 17.40     | ±0.05     |

Note: Table 7 is published in its entirety in the electronic edition of the journal. A portion is shown here for guidance regarding its form and content.

Figure 9. Map of average completeness in the identification of RRab (left) and RRc (right) stars, computed from synthetic RRLS within the photometric completeness limits of the survey (14.0 ≤ V ≤ 18.5).

too small for RRab stars. A few dwarf cepheids could have alias periods in the range of RRLS, however in this case the contaminants are unlikely to follow the well known Period-Amplitude relationship for RRab stars (e.g. Smith [1995], Cacciari et al. [2005]), which can in turn be used as a criterion to discard them. This criterion is also helpful to avoid other possible contaminants of the RRab sample, such as Anomalous Cepheids and short period Type-II Cepheids (Sandage & Tammann [2005]), also known as BL Her and W Vir stars, which have light curve shapes similar to RRab stars with periods in the range from 1 – 50 d (W Vir) and 1 – 7 d (BL Her), partially overlapping the range for RRab stars in the long-period end. Therefore, the contamination expected in the RRab sample can be considered negligible.

The RRc sample is, on the contrary, more prone to contamination. The light curves of eclipsing binaries of the WUMa and β Lyrae type can resemble those of RRc stars if period-folded with half the true period of the binary. However, as noted by Kinman & Brown [2010], an important difference between RRc stars and eclipsing binaries is that pulsating stars have larger amplitudes in bluer bands compared to red bands; while eclipsing binaries have similar amplitudes in different photometric bands (Kinman & Brown [2010], Sterken & Jaschek [2003]). This is a useful criterion for differentiating both types of variables, except for variable stars with poorly sampled light curves or very small amplitudes (< 0.2 – 0.3 mag), in which case the distinction is more difficult. On the other hand, since this behaviour of the amplitude in different photometric bands is common to pulsating stars, it is not useful for distinguishing RRc stars from the larger amplitude δ Scuti or SX Phoenicis stars, making these likely contaminants of the sample.

Therefore, the contamination expected in the RRc sample could be significant. In particular, among the RRc, a large number of WUMa and δ Scuti stars belonging to the thin disk is expected given the low latitudes being surveyed and the fact that we are not imposing any colour cuts which would sizeably have reduced the contamination (Ivezić et al. [2000], V04). This added to the relatively low completeness of the RRc sample (~ 80 per cent), makes it inappropriate to use the RRc stars in the computation of the thick disk structural parameters, which is why we have restricted the following analysis to the RRab sample.

3.4 Physical Parameters of RRL stars

3.4.1 Extinctions

The present survey spans areas at very low galactic latitudes (|b| < 15°), where the extinction can be very high and spatially variable. The Schlegel, Finkbeiner & Davis [1998] dust maps, although covering the whole sky, are unreliable at galactic latitudes lower than ~ 10°. On the other hand, a correct estimate of the extinction is
A computed from the previous two colours. The observed minimum-light colour indices we computed the corresponding templates in the two bands used. Comparing these with the ascriptions of Kunder, Chaboyer & Layden (2010); obtaining smaller standard deviations of Kunder, Chaboyer & Layden (2010); obtaining smaller standard deviations of the Orion Molecular Cloud (at $|b| \geq 20^\circ$), while the latter are integrated along the entire line of sight. Figure 11 also shows larger residuals around latitudes $b \sim 20^\circ$ and $b \sim +10^\circ$, which are presumably due to abrupt variations in the extinction on relatively small scales, mainly due to the presence of the Orion Molecular Cloud (at $b \sim 20^\circ$). The points showing the larger residuals in Figure 11 coincide with regions where the extinction change abruptly and the colour excesses computed from the $V - R$ and $V - I$ intrinsic colours and the corresponding errors were computed by standard error propagation.

Residuals between these colour excesses and those obtained from interpolations in the Schlegel et al. (1998) dust maps are shown in Figure 11. The plot shows the residuals are nearly zero for moderately high galactic latitudes ($|b| \geq 20^\circ$), while as the latitude decreases the colour excesses computed from RRab intrinsic colours are systematically smaller than those from Schlegel et al. (1998). This behaviour is expected since the former correspond to the colour excesses integrated up to the distance of each RRLS, while the latter are integrated along the entire line of sight. Figure 11 also shows larger residuals around latitudes $b \sim 20^\circ$ and $b \sim +10^\circ$, which are presumably due to abrupt variations in the extinction on relatively small scales, mainly due to the presence of the Orion Molecular Cloud (at $b \sim 20^\circ$). The points showing the larger residuals in Figure 11 coincide with regions where the extinction change abruptly and the colour excesses computed from RRab stars are systematically smaller than those reported by Schlegel et al. (1998), which is to be expected since the Schlegel et al. maps have relatively large pixels with $6.1' \times 6.1'$ and abrupt variations on smaller scales will be averaged out, while RRab stars probe the extinction exactly on the line of sight towards each star.

### 3.4.2 Photometric metallicities

RRLSs of type $ab$ exhibit a well known relationship between metallicity [Fe/H], pulsation period $P$ and the $\phi_{11}$ phase of a Fourier light curve decomposition, discovered by Jurcsik & Kovacs (1996). Also, Sandage (2004) finds that $\phi_{11}$ is correlated with the light curve amplitude and finds an expression analogous to that of Jurcsik & Kovacs (1996) relating [Fe/H] with the light curve amplitude and period for RRab stars.

![Figure 10. Bottom: $V$ amplitude versus period for variable stars of type RRab, RRC, β Scuti, Algol, β Lyrae and WUMa from the ASAS-3 catalogue (Pojmanski 2002). Top: Period histogram for the different variable star types illustrated in the bottom panel.](image-url)

![Figure 11. Residuals between colour excesses $E(B-V)$ from Schlegel et al. (1998) dust maps and those computed from RRab intrinsic colours, as a function of galactic latitude $b$.](image-url)
3.4.2.1 Jurcsik & Kovacs Metallicities

Jurcsik & Kovacs (1996) found an empirical relationship between the metallicity $[\text{Fe}/\text{H}]$, period $P$ and $\phi_{31}$ phase of a Fourier decomposition of RRab light curves, expressed in their Equation 3 as

$$[\text{Fe}/\text{H}] = -5.038 - 5.394P + 1.345\phi_{31}$$

(6)

The dispersion in this relationship was estimated by Jurcsik & Kovacs (1996) to be 0.11 dex from a comparison with spectroscopically determined metallicities.

The Fourier fitting process is very sensitive to the light curve sampling. For relatively well sampled curves, but with a moderate number of observations ($N \sim 30$), the fits usually have excessive ripples which translate into undesirable uncertainties in the determination of $\phi_{31}$. In order to circumvent this problem, we used the method proposed by Kovacs & Kupi (2007) which consists in fitting an observed light curve with one of their 248 light curve templates, representative of RRab stars, and determining $\phi_{31}$ from the Fourier decomposition of the best-fitting template. This allows for robust Fourier decompositions of light curves with a moderate number of observations ($N \gtrsim 20$). In order to have an estimate of the quality of the fit, we use the $D_F$ index defined by Jurcsik & Kovacs (1996), which tests for consistency of the Fourier decomposition parameters using the fact that different Fourier phases $\phi_i$ are correlated (see their Table 6). The restriction $D_F < 3$ was applied in order to ensure the reliability of the Fourier fits used in the computation of metallicities, as suggested by Jurcsik & Kovacs (1996).

3.4.2.2 Sandage Metallicities

Using a sample of RRab stars having spectroscopically derived metallicities, Sandage (2004) finds the following empirical relationship between $[\text{Fe}/\text{H}]$ and the light curve period, amplitude

$$[\text{Fe}/\text{H}]_V = (-1.45 \pm 0.04)\text{Amp}_V - (7.99 \pm 0.09)\log P - (2.145 \pm 0.025)$$

(7)

Sandage argues this relationship reflects the same behaviour found by Jurcsik & Kovacs (1996), since $\phi_{31}$ correlates directly with the light curve amplitude. In practice, Sandage's relation can be used in many more RRLS catalogues since it only requires an accurate knowledge of period and amplitude, while in order to perform the Fourier fits of Jurcsik & Kovacs (1996) the full time series data are required and the light curves must have an appropriate time sampling.

The relationship expressed in Equation 7 is calibrated for the $V$ band, found in the majority of RRLS observations in the literature. In our catalogue of 160 RRab stars, 25 per cent of the stars have observations only in the $R$ and/or $I$ bands and not in $V$, which

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6. We used the tff software from Kovacs & Kupi (2007) in the template fitting and Fourier decomposition processes.
made it necessary to extend Sandage’s relation for these photometric bands. Using the photometric metallicities computed from Equation 7 for 49 of our stars which are well-observed in metric bands. Using the photometric metallicities computed from Equation 8 and 9, respectively. Adding these dispersions in quadrature with the intrinsic dispersion of photometric metallicities computed from Equation 7, in comparison with spectroscopic metallicities, was estimated to be 0.04 dex.

An additional test on these methods was performed by comparing the spectroscopic metallicities for 27 RRab stars from the Vivas et al. (2008) catalogue, with the corresponding photometric metallicities computed from Equation 7. Figure 14 shows the resulting distribution of residuals [Fe/H]_{phot} - [Fe/H]_{spec}. The mean and standard deviation of these residuals are −0.01 dex and 0.34 dex respectively, in agreement with the intrinsic dispersions for Equation 7, 8, and 9.

### 3.4.2.3 Metallicity Distribution

The photometric metallicities adopted for RRab stars were calculated from a weighted average of the metallicities computed using the Jurcsik & Kovacs (1996) (Equation 6) and Sandage (2004) (Equation 7) methods. For those stars for which the Fourier decomposition obtained was unreliable (i.e. $D_P > 3$), the metallicity computed from Sandage’s method was adopted. The metallicities reported here are on the Zinn & West (1984) scale, and for all stars lie inside the metallicity range ($-2.5 \leq [\text{Fe/H}] \leq +0.07$) of the stars used in the calibration of the Jurcsik & Kovacs (1996) and Sandage (2004) methods.

The distribution of metallicities obtained is shown in Figure 15 for the full RRab sample (black) and for the stars close to the Galactic Plane with $|z| < 2.5$ kpc. The total metallicity distribution extends from $[\text{Fe/H}] \sim -2.5$ up to $[\text{Fe/H}] \sim +0.5$ with a mode at $[\text{Fe/H}] \sim -1.48$ as can be seen in the figure. The main peak coincides with the expected peak of the halo metallicity distribution, which has an observed metallicity $[\text{Fe/H}] = -1.5$ according to Carney et al. (1994) and Layden (1995), for F and G field halo dwarfs and RRLs respectively. The metallicity distribution near the Galactic Plane shows a hint of an excess for $[\text{Fe/H}] > -0.5$ around the metallicity expected for thick disk stars around $[\text{Fe/H}] \sim -0.8$ Gilmore et al. (1995) and Layden (1995).

### 3.4.3 Distances

The computation of heliocentric distances for the RRab stars was done using absolute magnitudes $M_V^{\text{RRab}}$ and $M_R^{\text{RRab}}$ derived from the Period-Luminosity-Metallicity relations in Catelan, Pritzl & Smith (2004), their Equation 8 and 3 respectively. According to Catelan et al. (2004) the use of Period-Luminosity-Metallicity relations is preferable over $M_V - [\text{Fe/H}]$ relations, since the former...
allow accounting for evolution off the Zero-Age Horizontal Branch (ZAHB). The total metal abundance $Z$ was computed from $[\text{Fe}/\text{H}]$ using Equation 10 in Catelan et al. (2004), assuming an $\alpha$ to Fe abundance of $[\alpha/\text{Fe}] = 0.2$ dex typical of halo and thick disk stars (e.g. Venn et al. 2004; Reddy et al. 2003). For the 9 RRab stars which only have $R$ band photometry, we computed $M_{\text{RR}}$ by interpolating the corresponding coefficients in Table 4 of Catelan et al. (2004).

Finally, the heliocentric distances were computed from Pogson’s equation $R_{\text{hel}} = (m_i - A_i - M_i + 5)/5$, where $A_i$, $M_i$, and $m_i$ correspond to the extinction, observed and absolute magnitudes in the $i$ filter. The corresponding errors were computed via error propagation in this equation, resulting in typical distance errors of $\sim 7$ per cent. The resulting heliocentric distance distribution is shown in Figure 16 and spans the range $0.2 \leq R_{\text{hel}}(\text{kpc}) \leq 80$. In Table 8 we summarize the colour excesses, metallicities, heliocentric distances $R_{\text{hel}}$, as well as height above the Plane $z$ and radial distance $R$ projected on the Galactic Plane, obtained for all RRab stars.

4 SUMMARY

We have presented the QUEST RR Lyrae survey at low galactic latitude, which spans an area of 476 deg$^2$ on the sky, with multi-epoch observations in the $V$, $R$, and $I$ photometric bands for $6.5 \times 10^5$ stars in the galactic latitude range $-30^\circ \leq b \leq +25^\circ$. The survey has a mean number of 30 observations per object in each of the $V$ and $I$ bands and $\sim 25$ in the $R$ band, while in the best sampled areas each object can have up to $\sim 120 - 150$ epochs in $V$ and $I$ and up to $\sim 100$ in $R$. The completeness magnitudes of the survey are $V = 18.5$ mag, $R = 18.5$ mag and $I = 18.0$ mag with saturations of $V = R = 14.0$ mag and $I = 13.5$ mag.

The survey has identified 211 RRLSs, 160 bona fide stars of type $ab$ and 51 strong candidates of type $c$. The RRLS catalogue presented here contains the positions, mean magnitudes in $VRI$, periods, amplitudes, photometric metallicities, distances and individual extinctions computed from minimum light colours for each star, as well as the period-folded light curves for RRab stars (Tables 6, 7 and Figure A). The typical distance errors obtained were $\sim 7$ per cent. The completeness of the RRLS survey was estimated in $\geq 95$ per cent for RRab and $\sim 85$ per cent for RRc stars, and was computed from light curve simulations reproducing the time sampling and other observing characteristics of our survey, as well as the variable identification and period searching techniques used.

Our RRLS survey spans simultaneously a large range of heliocentric distances $0.5 \leq R_{\text{hel}}(\text{kpc}) \leq 40$ and heights above the plane $-15 \leq z(\text{kpc}) \leq +20$, with well characterized completeness across the survey area. Combining ours with a bright RRLS survey (such as those from Layden 1995; Mantz 2005, see Sec. 1) to increase the distance coverage even further, will result in a very good tool for studying the Galactic thick disk’s structure, in particular for the determination of the density profile’s scale length, scale height as well as their dependence with radial distance in order to explore the flare and the truncation profile of the thick disk. This way, the QUEST RRLS from this work will help put constraints on the structure of the more external parts of the thick disk toward the Anticenter, as well as the mechanisms that could have contributed to the formation of the Galactic thick disk. These issues will be addressed in detail in an upcoming paper of the series.

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Table 8. Distance, colour excess and metallicities for RRab stars.

| ID  | \(E(B-V)\) (mag) | [Fe/H] (dex) | \(R_{hel}\) (kpc) | \(z\) (kpc) | \(R\) (kpc) |
|-----|------------------|-------------|------------------|--------|--------|
| 1000| 0.02             | -1.0 ± 0.3  | 17.1 ± 1.3       | -10.4 ± 0.8 | 21.5 ± 1.0 |
| 1001| 0.13             | -0.9 ± 0.3  | 46.4 ± 2.5       | -28.0 ± 1.5 | 44.8 ± 1.9 |
| 1002| 0.41             | -1.4 ± 0.5  | 13.0 ± 1.7       | -7.9 ± 1.0  | 18.1 ± 1.3 |
| 1003| 0.01             | -1.6 ± 0.1  | 11.5 ± 0.8       | -6.5 ± 0.5  | 17.3 ± 0.6 |
| 563 | 0.01             | -2.1 ± 0.1  | 5.0 ± 0.2        | -2.8 ± 0.1  | 12.0 ± 0.2 |

Note: Table 8 is published in its entirety in the electronic edition of the journal. A portion is shown here for guidance regarding its form and content.
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APPENDIX A: RRLS LIGHT CURVES

The catalogue of V, R and I period-folded light curves for all RRab and RRc stars found by the survey, is shown in Figure A.1.
Figure A1 – continued Light curves of survey RRab and RRc stars.
Figure A1 – continued Light curves of survey RRab and RRc stars.
Figure A1 – continued Light curves of survey RR\textit{ab} and RR\textit{c} stars.
Figure A1 – continued Light curves of survey RR\textsubscript{ab} and RR\textsubscript{c} stars.
Figure A1 – continued Light curves of survey RRab and RRc stars.
Figure A1 – continued Light curves of survey RRab and RRc stars.