A systematic DECam search for RR Lyrae in the outer halo of the Milky Way

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Abstract. The discovery of very distant stars in the halo of the Milky Way provides valuable tracers on the Milky Way mass and its formation. Beyond ∼100 kpc from the Galactic center, most of the stars are likely to be in faint dwarf galaxies or tidal debris from recently accreted dwarfs, making the outer reaches of the Galaxy important for understanding the Milky Way’s accretion history. However, distant stars in the halo are scarce. In that context, RR Lyrae are ideal probes of the distant halo as they are intrinsically bright and thus can be seen at large distances, follow well-known period-luminosity relations that enable precise distance measurements, and are easily identifiable in time-series data. Therefore, a detailed study of RR Lyrae will help us understand the accreted outskirts of the Milky Way. In this contribution, we present the current state of our systematic search for distant RR Lyrae stars in the halo using the DECam imager at the 4 m telescope on Cerro Tololo (Chile). The total surveyed area consists of more than 110 DECam fields (∼350 sq. deg) and includes two recent independent campaigns carried out in 2017 and 2018 with which we have detected >650 candidate RR Lyrae stars. Here we describe the methodology followed to analyze the two latest campaigns. Our catalog contains a considerable number of candidate RR Lyrae beyond 100 kpc, and reaches out up to ∼250 kpc. The number of distant RR Lyrae found is consistent with recent studies of the outer halo. These stars provide a set of important probes of the mass of the Milky Way, the nature of the halo, and the accretion history of the Galactic outskirts.

1. Introduction

Only a handful of Milky Way RR Lyrae stars have been identified at distances >100 kpc from the Galactic center. These stars play an important role for disentangling the accretion history of the Galaxy given that they are not expected to have formed at these remote distances, and simulations suggest that they likely originated in recently-accreted satellite galaxies (Bullock, & Johnston 2005; Sanderson et al. 2017). Other studies have
conjectured that they can also be used as potential tracers of previously unknown faint satellite systems (see, e.g., Baker & Willman 2015).

To reconstruct the outer halo accretion history one can, for instance, measure the shape of the Galactic density profile since these profiles have shown to be sensitive to properties such as the halo formation time, the accreted stellar mass, and how long ago the last merger occurred (Pillepich et al. 2014). In that regard, RR Lyrae have been particularly useful for building number density counts, due to their nature as precise distance indicators (Medina et al. 2018; Hernitschek et al. 2018). Therefore, finding them at large distances plays a key role for a correct interpretation of these profiles.

Recently, Stringer et al. (2019) identified \( \sim 6000 \) RR Lyrae using data from the Dark Energy Survey (DES) with a random forest classifier and taking advantage of the large footprint and depth of the survey (over 5000 deg\(^2\) and \( g \sim 23.5 \) mag in a single exposure). Of the RR Lyrae found by their team, \( \sim 30\% \) are considered new discoveries. In what follows, we describe the methodology we followed to detect RR Lyrae in the Galactic halo as part of the Halo Outskirts With Variable STars survey (HOWVAST), which resulted in \( \sim 20 \) new RR Lyrae candidates found beyond 100 kpc.

### 2. Survey Design

To carry out this work, we used data obtained with the Dark Energy Camera (DECam), which is mounted on the 4 m telescope at Cerro Tololo Interamerican Observatory, in the context of the HOWVAST survey. The survey consists of independent campaigns that took place in the 2017B and 2018A semesters, and the fields were selected to cover diverse Galactic latitudes of the Galactic halo that have not been mapped by other deep surveys such as the DES.

In the first run we observed 16 DECam fields during four consecutive half-nights in the \( r \)-band, with 180 s exposures and a cadence of one hour, whereas the second run consisted of 24 fields observed during four consecutive nights, the same exposure times and a shorter cadence (\( \sim 40 \) m). This resulted in a combined total area of \( \sim 120 \) sq. degrees of the halo mapped for the survey, and light curves made up of 20 to 30 datapoints per star. Figure 1 shows the footprint of the HOWVAST survey, and includes the fields from the High cadence Transient Survey (HiTS; Förster et al. 2016) in which our group searched for distant RR Lyrae in previous studies (Medina et al. 2017, 2018). Observations in the \( g \)-band were obtained as well, in order to provide \( g - r \) colors to facilitate the process of identification of RR Lyrae stars.

### 3. RR Lyrae Detection

Beginning with images that were processed through instrument signature removal by the DECam Community Pipeline (Valdes et al. 2014), source detection and photometry were carried out using the data processing pipeline currently in development for the LSST survey (Bosch et al. 2019). The LSST pipeline performs detection, aperture flux measurement, and point spread function (PSF) fitting. Throughout this work, we use PSF magnitudes, since our sources of interest are stars.

The following data analysis was performed using the computer cluster leftraru located at the Center for Mathematical Modeling of Universidad de Chile. A relative zero point was computed to determine the magnitude values for all the epochs with re-
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Spect to a selected reference epoch, and these magnitudes were corrected for extinction using the recalibrated dust maps from Schlafly, & Finkbeiner (2011). Stellar objects with less than 15 datapoints in their light curves, or lacking clear indications of variability, were filtered out. In addition, we only examined sources with $\Delta\text{mag} > 0.2$, and $g - r$ colors similar to those of typical RR Lyrae (between -0.45 and 1.0).

For period determination we used the python package P4J, which was developed for period detection on irregularly sampled and heteroscedastic time series, and the criterion chosen to be maximized by this routine was the Cauchy-Schwarz Quadratic Mutual Information (Huijse et al. 2018). We allowed the two best periods to be selected, requiring them to be longer than 0.2 d, shorter than 0.95 d, and to be considered statistically significant detections. As a final step, we performed a visual inspection of the phased light curves making sure that only RR Lyrae-like objects were selected, based on their periods, amplitudes, and light curve shapes. In the case of RR Lyrae candidates with more than two high probability periods, we considered the four most likely ones in the power spectrum before selecting their final period.

4. Early Results

Our selection process described above resulted in 408 RR Lyrae candidates detected in the $\sim 120\text{ deg}^2$ of 2017 and 2018 data (128 and 280 RR Lyrae, respectively). Of these, 70% are ab-type, 29% c-type and 1% d-type, as depicted in the Bailey diagram shown in Figure 2. These RR Lyrae have $r$ magnitudes ranging from 15 to $\sim 22.5$. Example light curves of the detected RR Lyrae in different brightness ranges are displayed in Figure 3. In terms of completeness, when comparing with larger RR Lyrae catalogs that overlap the surveyed regions, such as the one coming from the Catalina Real-time Transient Survey (Torrealba et al. 2015; Drake et al. 2017), we recover $\sim 90\%$ of the sources fainter than 17 in the V-band.

To estimate the heliocentric distance to these RR Lyrae candidates, we first used the period-luminosity-metallicity (PLZ) relations computed by Sesar et al. (2017) to determine their absolute magnitudes $M_r$, assuming $[\text{Fe/H}] = -1.5$ as a representative
metallicity value for halo stars. Since the PLZ relations of Sesar et al. (2017) are only suitable for ab-type RR Lyrae, we fundamentalized the period of the c-type candidates in order to estimate their absolute magnitudes, following the relationship provided by Catelan (2009). As a result, the distances obtained range from 10 to ~ 250 kpc, and 20 candidates were found to have heliocentric distances larger than 100 kpc.

With the estimated distances of our sample of RR Lyrae candidates, we studied the space density distribution of both ab− and c−type RR Lyrae stars in the halo, that is, the Galacticentric distance dependence of the number of RR Lyrae stars per unit volume. To do this, we adopted a spherical halo model and used the Markov Chain Monte Carlo routine emcee (Foreman-Mackey et al. 2013) to find the parameter distribution of the model. We also considered a break in the density profile as a free parameter. As an overall result, taking into account the distributions obtained in Medina et al. (2018) and the stars obtained in this work (under these assumptions, and not considering known structures or dwarf galaxies in the profiles), the inner and outer halo slope are found to be $-1.06^{+0.25}_{-0.84}$ and $-4.36^{+0.10}_{-0.11}$ respectively, with a break radius at 20 kpc.

Figure 2. Bailey diagram of the sample of RR Lyrae candidates detected in this study. Blue symbols represent RRe stars, whereas RRab are displayed in red.

Figure 3. Examples of phased light curves from our catalog. The templates used were obtained through the code gatspy (VanderPlas, & Ivezić 2015), which uses light curve templates based on SDSS Stripe 82 RR Lyrae stars (Sesar et al. 2010).
5. Final Remarks

By using data from the Dark Energy Camera, we are conducting a study to uncover the nature of the outskirts of the Galaxy, and its formation, by investigating the population of remote Milky Way RR Lyrae. As a continuation of our previous study (using HiTS data), we designed the HOWVAST survey as an effort to specifically map the outer limits of the Galaxy. Using HOWVAST data we identified ~400 RR Lyrae star candidates in ~ 120 deg$^2$, which when combined with the RR Lyrae in DECam HiTS data analyzed by our team (Medina et al. 2017, 2018) adds up to > 650 RR Lyrae stars in ~ 350 deg$^2$ of sky.

With these stars we have constructed preliminary number density profiles, and found that the results are consistent with simulations that build up the halo using accretion-only models, with which a reasonable value for the outer halo slope is -4.4 (Deason et al. 2013). Other power law indices from the literature are summarized in Table 4 from our previous work (Medina et al. 2018).

Finally, the total number of remote RR Lyrae identified in this work is in line with the results shown by Stringer et al. (2019) using DES data. It is worth noting that, even though our findings are still below the number of distant RR Lyrae expected from theoretical predictions (Sanderson et al. 2017), these programs form part of an important group of surveys that are precursors for future deep-large sky programs that will provide a more complete vision of the halo populations.

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