Discovery of Distant RR Lyrae Stars in the Milky Way Using DECam

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Abstract

We report the discovery of distant RR Lyrae stars, including the most distant known in the Milky Way, using data taken in the g-band with the Dark Energy Camera as part of the High cadence Transient Survey (HiTS; 2014 campaign). We detect a total of 173 RR Lyrae stars over a ~120 deg^2 area, including both known RR Lyrae and new detections. The heliocentric distances \( d_{\text{HI}} \) of the full sample range from 9 to >200 kpc, with 18 of them beyond 90 kpc. We identify three sub-groups of RR Lyrae as members of known systems: the Sextans dwarf spheroidal galaxy, for which we report 46 new discoveries, and the ultra-faint dwarf galaxies Leo IV and Leo V. Following an MCMC methodology, we fit spherical and ellipsoidal profiles of the form \( \rho(R) \sim R^n \) to the radial density distribution of RR Lyrae in the Galactic halo. The best fit corresponds to the spherical case, for which we obtain a simple power-law index of \( n = -4.17^{+0.18}_{-0.20} \), consistent with recent studies made with samples covering shorter distances. The pulsational properties of the outermost RR Lyrae in the sample (\( d_{\text{HI}} > 90 \) kpc) differ from the ones in the halo population at closer distances. The distribution of the stars in a period-amplitude diagram suggest they belong to Oosterhoff-intermediate or Oosterhoff II groups, similar to what is found in the ultra-faint dwarf satellites around the Milky Way. The new distant stars discovered represent an important addition to the few existing tracers of the Milky Way potential in the outer halo.

Key words: Galaxy: halo – Galaxy: stellar content – Galaxy: structure – stars: variables: RR Lyrae

Supporting material: machine-readable tables

1. Introduction

The outermost regions of the Milky Way (MW) halo are key probes of the recent assembly history of our Galaxy. Models suggest that stars in the outer halo (beyond Galactocentric radii of \( R_{\text{GC}} \approx 100 \) kpc) likely originated in relatively recently accreted satellite galaxies (e.g., Bullock & Johnston 2005; Zolotov et al. 2009). While current models of galaxy formation generate specific predictions of the amount of stellar substructure in the outermost part of the halo, these have been hard to explore because of the lack of deep, large-area surveys of tracers with reliable distance estimates. Because RR Lyrae pulsational variable stars (RRLs) are easily identified in time-series data, are intrinsically bright, and follow well-known period–luminosity relations, they provide a means of mapping the distant halo at distances beyond \( d \gtrsim 100 \) kpc. Sanderson et al. (2017) predicted that different accretion histories of 12 synthetic halos (from Bullock & Johnston 2005) yield populations of 2000–10,000 RRLs at 100 < \( d < 300 \) kpc in the MW halo, with roughly half of these in intact dwarf galaxies, and half unbound from their parent satellite.

The accreted dwarfs that are expected to have contributed their stellar populations to the MW halo imprint evidence of the MW’s accretion history in the radial stellar density profile. Studies of the halo density profile with various tracers (e.g., Saha 1985; Vivas & Zinn 2006; Watkins et al. 2009; Deason et al. 2011; Sesar et al. 2011; Akhter et al. 2012, summarized later in Table 4) have found widely varying stellar density slopes at large radii, making it difficult to place the MW in a broader context. The discrepancies may be due in part to small samples, especially at large distances from the Galactic center. The addition of outer halo stars is vital to anchor density profile fits in regions of the Galaxy where recent accretion should dominate, and where long dynamical times preserve a record of the accretion events. Simulations also suggest that there is a clear difference in the behavior of the inner and outer halo number density profiles, probably driven by different formation processes (see, e.g., Bullock & Johnston 2005). The inner halo is thought to contain both accreted and formed in situ populations, while the stellar component of the outer halo seems to be formed mainly by accretion events (Zinn 1993; Bullock & Johnston 2005; Carollo et al. 2007; Abadi et al. 2006; Zolotov et al. 2009). There is possible evidence for the different formation pathways of the inner/outer halo in the form of a break in the radial number density profile of MW stars near 25 kpc from the Galactic center (see, e.g., Saha 1985; Watkins et al. 2009; Deason et al. 2011; Sesar et al. 2011). However, the behavior of the MW’s radial density profile at Galactocentric distances (\( R_{\text{GC}} \)) beyond 80 kpc is a subject that has not been covered with similar depth, mainly due to incompleteness in current surveys at large distances.

Furthermore, the most distant stars are vital tracers for the estimation of the total mass of the MW. Detailed predictions
(e.g., the number and luminosity function of satellites) for MW-like galaxies extracted from cosmological models for comparison with observations are highly sensitive to the total mass of the host halo (e.g., Geha et al. 2017); thus determining a reliable total mass for our Galaxy becomes essential if one wishes to use it as a cosmological laboratory. Unfortunately, the total mass of the MW within 150 kpc is known only within a factor of two (e.g., Eadie & Harris 2016; Abilmit & Zhao 2017). Mass modeling of the MW halo is most strongly constrained by tracers in the outermost regions; RRLs are thus valuable probes of the Galactic potential because they can be found at large distances, and their distances can be determined to better than ~10% with ground-based data. Regarding remote Milky Way stars, only a small number have been detected at heliocentric distances \((d_H)\) larger than 100 kpc. A summary can be found in Bochanski et al. (2014). In that study, the authors reported the discovery of the two most distant MW stars known to date, with estimated distances larger than 200 kpc and classified as M giants. These stars are intrinsically bright, which makes them good tracers of halo structure at large distances, but the distance estimations suffer from significant uncertainties (Bochanski et al. 2014 adopted a 25% of uncertainty in their distance estimations).

Other distance tracers such as pulsational variables have been commonly used to map the Galactic halo over a wide range of distances. RR Lyrae stars, for example, have been identified from a few parsecs to beyond 100 kpc (e.g., Watkins et al. 2009; Drake et al. 2013b; Sesar et al. 2017a, reaching \(d_H \sim 115\) kpc). RRLs are old, metal-poor pulsating variables that are considered standard candles in the same way as Cepheids, though they are not as luminous. The light curves of these RRL variables have very characteristic shapes, and they are usually classified into two main groups: \(ab\) and \(c\)-type RRLs. The first class (R Rab) are fundamental mode pulsators, with saw-tooth-shaped light curves and a negative correlation between their amplitudes and periods, which are known to be of the order of 0.6 days. RRc, on the other hand, pulsate on the first overtone and display more sinusoidal light curves. The latter have in general shorter periods (~0.35 days) and smaller amplitudes compared to RRab.

The discovery of groups of RRLs at medium to large distances has become particularly important for the physical description of substructures in the inner and outer halo. Some examples are the discovery and characterization of the Sagittarius stellar tidal stream (Vivas et al. 2001; Vivas & Zinn 2006; Prior et al. 2009; Watkins et al. 2009; Sesar et al. 2010, 2017a; Drake et al. 2013a; Zinn et al. 2014), the Virgo stellar stream (Duffau et al. 2006; Vivas et al. 2016; Sesar et al. 2017a), the Pisces overdensity (Sesar et al. 2010), or the Gemini stream that extends beyond 100 kpc (Drake et al. 2013b), among others. However, the discovery of very distant, isolated stars in the halo brings out questions related to the understanding of their origin. Since they are not expected to have formed in the outskirts of the halo, the origin of distant stars is generally thought to be either the gravitational interaction between the Milky Way and its satellites or the ejection from the center (or disk) of the Galaxy (Brown et al. 2005; Bullock & Johnston 2005; Zolotov et al. 2009). Simulations suggest that it is possible to reproduce important stellar halo properties (the break in the density profiles for instance), taking only accretion events into consideration (Deason et al. 2013). In this context, an interesting suggestion regarding the origin of distant RRL comes from evidence that all known Milky Way dwarf galaxies have at least one RRL (Boettcher et al. 2013; Vivas et al. 2016). This would make RRL potential tracers of faint satellite systems in the outer halo. Indeed, based on the data presented in this work, Medina et al. (2017) recognized the presence of the ultra-faint dwarf galaxies Leo IV and Leo V based on compact groups of distant RRLs.

To date, large RRLs catalogs have been constructed using data from different variability surveys that map different parts of the halo. Among them, the Quasar Equatorial Survey Team (QUEST) RRL catalog (Vivas et al. 2004) contains 457 objects with \(V < 19.5\), and subsequently with La Silla QUEST Southern Hemisphere Variability Survey (LSQ) came the discovery of 1013 RRab and 359 RRc distributed across \(\sim 840\) deg\(^2\) of the sky in the range \(150^\circ < \text{R.A.} < 210^\circ\) and \(-10^\circ < \text{decl.} < 10^\circ\) (Zinn et al. 2014). The latter contains stars with \(d_H\) between 5 and 80 kpc. More recently, the Catalina Surveys identified \(~ 43,500\) RRLs over \(~ 30,000\) sq degrees of the sky up to heliocentric distances of \(\sim 60-110\) kpc (Drake et al. 2017). The Pan-STARRS1 (PS1) \(3\pi\) survey also has proven to be an excellent source for RRLs, despite its poor temporal sampling, by identifying a sample of \(~ 45,000\) RRLs up to \(~ 130\) kpc from the Sun with a 90% purity (Sesar et al. 2017b). All these surveys have found several distant RRLs, but the surveys’ low completenesses at faint magnitudes limit the depth of the findings.

In this contribution, we use data from the High Cadence Transient Survey (HiTS; Förster et al. 2016) to search for distant RRL (beyond 100 kpc). HiTS is a survey designed for the detection of young supernovae events with a total sky coverage of \(\sim 350\) square degrees and a limiting \(g\) magnitude that varies between 23 and 24.5 (Förster et al. 2016). Since the cadence and observing strategy of the survey are well matched for RRL detection, it should allow us to find distant RRL in the observed region, if present. Here we discuss results from \(\sim 120\) deg\(^2\) of HiTS survey data, corresponding to the second campaign, which was held during semester 2014A.

The structure of this paper is organized as follows. In Section 2 an overview of the observation context of this work is given, including details of HiTS. In Section 3 the candidates selection and characterization process is described, as well as the distance determination. The analysis of the sample, including the presence of substructures in our data like the Sextans dwarf spheroidal galaxy and the description of the most distant candidates is presented in Sections 4 and 5, respectively. In Section 6 we use our sample to construct radial density profiles of the halo and compare them with previous studies. Finally, in Section 7 our main results are summarized.

2. Observations

HiTS is a deep optical campaign carried out with the Dark Energy Camera (DECam; Flaugher et al. 2015) mounted at the prime focus of the Blanco 4 m telescope at Cerro Tololo Inter-American Observatory (CTIO). The camera contains 62 CCDs with 520 megapixels and generates three square degree images. It is currently the largest etendue camera in operation in the Southern Hemisphere, and it will remain so until the Large Synoptic Survey Telescope (LSST) begins operations in 2022.

One of the main goals of HiTS is the detection of optical transient objects, in particular young supernovae events mainly in the \(g\) SDSS photometric system filter (~4000–5500 Å), in the search for empirical evidence of the shock breakout
Figure 1. Color-coded plot of the distribution of our 173 RRL stars in the sky, with the colors representing their heliocentric distances. An approximation of the HiTS footprint is shown in gray in the background as a reference.

phenomena. The fact that the survey can detect transient objects with characteristic timescales of hours make HiTS suitable for RRLs studies as well.

The observations used for the current work took place between UT 2014 February 28 and March 4 (five consecutive nights). Forty fields were observed with a cadence of 2 hours, 4 times per night in the g-band, and the exposure times varied from 160 s (83% of the observations) to 173 and 174 s (3% and 14%, respectively). This translates into 20 epochs per field, with the exception of one field (centered in 151.5 R.A., −2° decl.), which has 37 (see Förster et al. 2016 for detailed field positions). The sky was clear during all nights, with typical seeing values around 1.5 arcsec.

The fields observed by HiTS were selected almost entirely blindly, covering ∼120 square degrees in the sky region from 150° < R.A. < 175° and −10° < decl. < 3° (see Figure 1). The only requirement for the fields was the observing availability during the entire night. Six of the fields were chosen for being known cluster fields and two for being SuperCOSMOS fields (Hambly et al. 2001). The data obtained were stored on the National Laboratory for High Performance Computing (NLHPC) cluster at the Center for Mathematical Modeling (CMM) of Universidad de Chile and then analyzed using the HiTS pipeline.

The HiTS pipeline is based on basic calibrations, image subtraction, candidate filtering, and visualization (Förster et al. 2016). The instrumental signature removal steps were performed using the DECam community pipeline (Valdes et al. 2014). For this work, we generated catalogs using the SExtractor photometry software (Bertin & Arnouts 1996), with a limiting apparent magnitude of 23–24.5 (Förster et al. 2016).

3. Search and Characterization of RRLs

3.1. Photometric Calibration

In order to select periodic variables, we need to define a common x, y pixel coordinate system using the output catalogs generated by SExtractor, a process we call “alignment.” We select the second epoch observation as the reference frame for having the best observing conditions. The scaling constants needed to do the alignment were found by the HiTS pipeline (Förster et al. 2016). Subsequently, we performed a cross-match between the aligned catalogs and rejected as possible candidates sources with fewer than five detections. Sources whose mean flux uncertainties are larger than two times the flux standard deviation were also filtered out. Pixel coordinates were transformed into equatorial coordinates following the procedure described in Förster et al. (2016).

To account for the effects of the atmospheric conditions over the different epochs, we calculated a relative zero-point associated with the reference. This was performed comparing the instrumental magnitudes given by

\[ g_{\text{inst}} = -2.5 \log \left( \frac{\text{counts}}{s} \right) - a_g - k_g A, \]  

where A is the airmass, \( a_g \) is the photometric zero-point in the g-band (one for each CCD), and \( k_g \) is the first-order extinction in g. Then, the g magnitude was calculated as follows:

\[ g_{\text{ref}} = g_{\text{inst}} + \Delta_{\text{rel}} \]
\[ g = g_{\text{ref}} + \Delta_{\text{PS}}. \]

In the previous equation, \( \Delta_{\text{rel}} \) refers to the relative zero-point between the different epochs and the reference, which was calculated on a chip-by-chip basis, and \( \Delta_{\text{PS}} \) is a calibration zero-point with respect to the PS1 DR1 public catalog. To obtain the PS1 zero-points, we compared the instrumental magnitudes for all the stars in a given chip (corrected by \( \Delta_{\text{rel}} \)) with the corresponding magnitudes listed in the PS1 database. This yields 60 different zero-points for a given field. We repeated this procedure for all fields in the PS1 footprint.

To estimate the photometric uncertainties, we assume that the uncertainties for each star magnitude can be obtained using a non-parametric model of the standard deviation and mean magnitude relation for all the stars in their respective fields, as can be seen in Figure 2. We do not use the flux errors given by SExtractor, since they are, in general, underestimated (Gawiser et al. 2006; Martínez et al. 2018) and therefore are not reliable when accounting for the photometric uncertainties. The photometric uncertainties reach ∼0.10 mag at \( g \sim 22 \) and ∼0.15 mag at \( g \sim 23 \).

The final magnitudes include extinction corrections for which the re-calibrated dust maps of Schlafly & Finkbeiner

\[^9\] http://www.ctio.noao.edu/noao/content/Mean-Photometric-Standard-Star-Module-PSM-Solutions-mean-zeropoints-color-terms-extinctions
(2011) were used. The extinction values for the $g$-band were calculated using the relation $A_g = 3.303 \cdot E(B-V)$ from the mentioned work. Following this, the average $A_g$ of the RRLs in the HiTS fields is $\sim0.14$ mag, with a standard deviation of 0.03 mag.

### 3.2. Selection of RRLs

For period determination, we ran the generalized version of the Lomb–Scargle periodogram (GLS; Zechmeister & Kurster 2009), which provides more accurate frequencies and is less susceptible to aliasing than the Standard Lomb–Scargle (LS; Lomb 1976; Scargle 1982) periodogram analysis. We selected as pre-candidates objects with periods greater than 4.8 hr (0.2 days) and less than 21.6 hr (0.9 days), and with a GLS statistical level detection of $<0.08$. The statistics were computed by using the GLS tool from the astroML python module (Vandenberg et al. 2012). In spite of the reduction in the aliasing by the GLS near certain problematic periods (0.33 and 0.50 days) compared with the standard LS, we considered it reasonable to filter out objects with periods between 0.32 and 0.34 days, and within 0.49 and 0.51 days, to reduce the number of spurious variables. This resulted in the rejection of $\sim3\%$ of non-variable sources that were spuriously identified as variables due to period aliasing. In the case where two or more significant periods met the requirements discussed above, we allowed the two most significant to be selected. This results in the selection of 2434 objects.

Finally, objects with $\Delta$ mag $<0.2$ were filtered out, and we use visual inspection of the phased light curves (looking for periods, amplitudes, and light curve shapes typical of RRLs) to obtain our final list of RRLs composed of only 173 objects ($\sim7\%$). A small number of stars look clearly periodic, but they do not have the correct amplitude, period, or shape for being considered RRLs, and they are not further discussed here. An additional visual inspection of the reference images for each of the RRLs was performed to reject possible extended objects.

Color information provides additional constraints at the moment of selecting/confirming RRLs (see, e.g., Ivezić et al. 2005). Unfortunately, HiTS observations were done only in the $g$-band. Not all our stars have a counterpart in SDSS because some of our fields are outside the footprint of that survey, and our limiting magnitude is significantly fainter than SDSS. However, 139 of our RRLs have a counterpart in SDSS DR12, and the ones with small photometric errors in SDSS are constrained within $0.9 < u - g < 1.8$ and $-0.1 < g - r < 0.3$, as expected for RRLs. We also look at the colors in PS1, which completely covers our region, although again does not go as deep as HiTS. In this case we found a match for 161 RRLs, and all of them have colors $g - r$, $r - i$, and $i - z$, consistent with RRLs, and confirming our selection criteria based on the $g$ light curves is good enough to isolate RRLs.

To have a more robust method for the estimation of the light curve parameters, we adjusted templates of RRLs from the work by Sesar et al. (2010), which was based on SDSS Stripe 82 RRLs. In that study, a list of 23 templates is provided for the $g$-band, two of which are for RRc. The selection of the best fit for each candidate was based on $\chi^2$ minimization. For the fitting we allowed small variations around the observed amplitude and maximum magnitude ($0.2$ mag for each), as well as for the period and initial phase obtained through GLS ($0.01$ days and 0.2, respectively).

The 173 RRLs (131 RRab and 42 RRc) have mean magnitudes between 15.5 and 22.7. Figure 3 shows the distribution of the mean $g$ magnitude for the full sample. The strong peak seen at $g \sim 20.5$ corresponds to stars associated with the Sextans dSph galaxy and are further discussed in Section 4. Surprisingly, there is a non-negligible number of RRLs with $g > 21$, which correspond to very distant halo objects. Folded light curves and tables with the properties of the RRLs are shown in Section 5 (for the very distant stars) and in the Appendix material (for the rest of the stars).

Figure 4 shows the location of the RRLs in the Period-Amplitude diagram. As expected, the sequences of the Oosterhoff (Oo) groups I and II (Oosterhoff 1939; Catelan & Smith 2015) are clearly visible in this plot, especially for the halo RRab at distances $<90$ kpc (red symbols in Figure 4). This is reassuring that our methodology is correctly recovering properties of RRLs. We discuss implications of the location in this diagram of the newly found RRLs later in the article.
3.3. Detection Efficiency

To estimate the detection efficiency of our survey, we generated 5000 artificial light curves of RRLs, mimicking our real cadence and photometric errors. Specifically, the number of observations per object was set equal to the number of randomly selected stars in our survey. Thus the number of epochs in the artificial light curves vary from 16 to 37. Each light curve was modeled using the parameters (amplitude in g, period, template) from the list of SDSS RRLs in Sesar et al. (2010), which includes stars with periods within the ranges rejected by our selection criteria. A random initial phase was added to the template magnitudes according to the values of the main locus of stars seen in Figure 2. The artificial light curves were then processed by our software, and stars that pass all our criteria and have a period within 10% of the real one were flagged as recovered.

Figure 5 shows the results of the process represented as a histogram where 0.25 mag bins were used. In the bright end, our method is able to recover ~86% of the full sample, and the rate ranges between 81% and 92% down to g = 21.5. The detection efficiency drops to less than 70% for RRL fainter than g = 22. The estimation of the RRLs detection efficiency does not take the photometric completeness of the survey into account. A detailed analysis of the photometric completeness of HiTS can be found in Förster et al. (2016).

3.4. Comparison with Previous Surveys

Another way to investigate how many RRLs we are missing in our survey is to compare our results with recent large-area surveys that covered the same portion of the sky as HiTS. In this work we compare with data from the Catalina Real-Time Transient Survey (CRTS) data release 1 (Drake et al. 2013a, 2014), from the La Silla-QUEST (LSQ) survey (Zinn et al. 2014; both have a large number of observations in the V-band) and from PS1 (grizy filters, but only a few epochs in each band). The overlap in sky coverage is complete in the case of the CRTS and PS1, and partial for LSQ.

When compared with Drake et al. (2014), 93 RRL (76 RRab and 17 RRc) fall into the fields observed by HiTS with magnitudes fainter than 16 (near our saturation limit) that we should have been able to detect. Of these 93, 69 matched up with our list within 2 arcsec (74%), and 74 within 2.5 arcsec (80%). In terms of percentages, 74% (79% for 2.5 arcsecs) of the ab types and 76% (82%) of the RRCs were recovered. There are no differences among the classifications they give to the RRLs and what we find in this work. The periods obtained for our sample are in agreement with the periods for the stars in common, with a mean discrepancy of 2 × 10^{-3} ± 2 × 10^{-2} days. We considered the position of the 24 (19) missing RRLs in the CCFs, and found that at least 7 of them fell near the edges for the reference frame and therefore were not clearly detected by our procedure. Removing these 7 stars from the list of potential matches with Drake et al. (2014) increases the rate of recovery to 80% (84%), which is closer to the numbers obtained for the theoretical recovery rate computation. In general, the missed RRLs are relatively bright sources (V < 19, dA < 40 kpc), with (V) ~ 17 and enough phase coverage to perform a good characterization in the CRTS (N > 180). In our sample we classified as RRLs 103 sources that were not present neither in Drake et al. (2013a) nor in Drake et al. (2014), 74 of them are RRab, and the remaining 29 are RRC. These stars may have been missed by these surveys for different reasons, but the most likely is attributable to the different depths of our surveys. Both studies by Drake et al. (2013a, 2014) have shallower limiting magnitudes, and have high completeness levels until V_{CSS} ~ 19.5. More than a half of the new RRLs (~60%) are grouped together and seem to be part of the Sextans dwarf spheroidal galaxy (as described in Section 5), while from the remaining objects, 22 have magnitudes g > 20, mostly beyond the detection limits of the CRTS.

In the case of LSQ, which has 43 RRab and 7 RRC fainter than g = 16, the comparison yielded 44 stars recovered (88%; 5 RRC and 39 RRab). In general, the periods seem to coincide with an absolute mean difference of 4.7 × 10^{-2} days. However, there is one star with a significantly different period (HiTS101413-004502). If we do not include HiTS101413-004502 in the comparison, the period discrepancy turns out to be |ΔP| ~ 5 × 10^{-4}. For that star we found a period of 0.386 days as the most likely period, while LSQ gives 0.628 days. However, the latter corresponds to the second most probable period according to our procedure. Since LSQ has 87 observations for that star and we only have 21, their period is likely more reliable. This discrepant period

Figure 4. Period-amplitude diagram of the complete sample of RRLs. The blue stars symbols represent RRc stars, while the RRab are plotted with red pentagons. Black filled circles represent RRLs with dA > 90 kpc (top) and RRLs members of the Sextans dSph galaxy (bottom).

Figure 5. Recovery rates as a function of mean g magnitude of synthetic RRLs.
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Table 1
Most Distant RR Lyrae Stars ($d_H > 90$ kpc)

| ID          | R.A. (degree) | Decl. (degree) | $\langle g \rangle$ | $d_H$ (kpc) | Type | $N$ |
|-------------|---------------|----------------|---------------------|-------------|------|-----|
| HITS105754-002603 | 164.47577    | −0.43403       | 20.5                | 92.5 ± 6.8  | c    | 20  |
| HITS110739-012813 | 166.91383    | 1.7037         | 20.4                | 92.6 ± 6.6  | c    | 20  |
| HITS104009-063304 | 160.03895    | −6.55105       | 20.8                | 100.5 ± 4.0 | ab   | 21  |
| HITS103943-021726 | 159.93119    | −2.29061       | 20.9                | 107.8 ± 4.5 | ab   | 21  |
| HITS111106-041718 | 167.77512    | −4.28834       | 21.2                | 113.4 ± 8.8 | c    | 22  |
| HITS105209-043942 | 163.03718    | −4.66174       | 21.5                | 136.0 ± 5.7 | ab   | 20  |
| HITS113259-003404 | 173.24674    | −0.56770       | 21.5                | 147.0 ± 6.9 | ab   | 18  |
| HITS113256-003329 | 173.23270    | −0.55818       | 21.5                | 155.8 ± 7.5 | ab   | 19  |
| HITS102414-095518 | 156.05905    | −9.92180       | 21.7                | 161.0 ± 8.0 | ab   | 21  |
| HITS103601-015451 | 159.00456    | −1.91422       | 21.7                | 161.3 ± 12.9| c    | 21  |
| HITS113107+021302 | 172.77796    | 2.21734        | 21.7                | 162.8 ± 8.6 | ab   | 21  |
| HITS113057+021331 | 172.73946    | 2.22514        | 21.8                | 171.7 ± 9.4 | ab   | 20  |
| HITS113105+021319 | 172.76936    | 2.22200        | 21.8                | 172.4 ± 9.4 | ab   | 20  |
| HITS101222-001624 | 165.59251    | −0.27337       | 22.1                | 179.8 ± 10.3| ab   | 19  |
| HITS104054-042827 | 160.22661    | −4.47424       | 21.9                | 183.2 ± 14.8| c    | 20  |
| HITS110510-022710 | 166.28982    | −2.45282       | 22.4                | 218.6 ± 14.6| ab   | 19  |
| HITS102014-042354 | 155.05789    | −4.39843       | 22.5                | 232.9 ± 21.9| c    | 19  |
| HITS104738-020627 | 161.90718    | 2.10746        | 22.8                | 262.2 ± 24.3| c    | 19  |

Notes. This table includes the main properties of the sample, such as their distances, types, and number of observations ($N$).

(This table is available in machine-readable form.)

...determination led us to a misclassification of that RRL (from a RRab to a RRc). In Table 5, the period obtained with our methodology is presented. Of the RRLs we missed, four are RRab and two are RRc. Nevertheless, one RRab (LSQ250) fell relatively close to the edges of its CCD, following the criteria applied in the comparison with the CRTS. Rejecting LSQ250, the recovery rate rises up to ~90%. As in the case of the comparison with CRTS, we report numerous RRLs that do not appear in the LSQ catalog. We found 93 new variables in the common regions (70 ab’s and 23 c’s), most of which seem to be related, again, to the Sextans dSph RRLs overdensity (65%).

The PS1 public catalog has 24,000 RRLs and was built based on machine learning techniques (Sesar et al. 2017b). From this sample, 298 fall into the HiTS fields. Based on their calculations, an RRab/RRc score in their selection higher than 0.90 gives a purity of 0.97/0.94 and a completeness of 0.88/0.57 for $r < 18.5$. If only RRLs with scores higher than 0.90 are considered, the number of PS1 RRLs in the HiTS fields with mean magnitudes in $g$ fainter than 16 is 110. A comparison of this group with HiTS RRLs yields 87 matches within 2 arcsec (75 ab’s, 12 c’s)—that is, we recover 80% of the intersecting PS1 sample. The mean period difference is 0.001 days, with 0.07 days as the most significant discrepancy, and the mean magnitude difference is 0.09. The faintest common RRL, HiTS101243+022118, has $g = 20.61$ (87 kpc) in the HiTS catalog, and $g = 20.79$ in PS1. The classifications of all the stars in this subsample of the PS1 catalog are in agreement with the classifications presented in this work.

It is worth noticing that five of the RRLs in PS1 that were not detected by us fall near the edges of the CCDs for the reference frame. If we do not take into account these RRLs, our recovery rates go as high as 83%, in agreement with our estimations. The rest of the undetected RRL correspond to relatively bright sources, with a mean value of $g$ of 18.3.

Of the 86 RRLs that are not clearly detected by PS1, 28 have $g < 20$ (18 ab’s, 10 c’s), which corresponds to $d_H \lesssim 70$ kpc. The rest of the stars not present in the PS1 catalog are mostly ab-type (65%), and include the entire sample of faint RRLs described in Section 5.

3.5. Heliocentric Distance Determination

RR Lyrae stars are known to follow a period–luminosity-metallicity (PLZ) relationship that makes them useful as distance indicators. We used Sesar et al. (2017b) PLZ relations to compute individual values of $M_r$, and subsequently heliocentric distances through distance modulus. For deriving the absolute magnitudes, we used the values from Table 1 in Sesar et al. (2017b) and assumed $[\text{Fe/H}] = −1.5$ as a representative value of the metallicity of the Galactic halo, given our lack of individual metallicities. It is worth noticing that the PLZ relationship is valid for RRc only when their period is “fundamentalized.” For the RRc in our sample, we used the periods given by

$$\log(P_F) = \log(P) + 0.128,$$

where $P_F$ is the fundamentalized period and $P$ is the pulsational period of the RRc stars (Catelan 2009). However, due to a discrepancy between the distances of RRab and RRc in one of the dwarf galaxies we study in this work, we applied an additional correction to the entire sample of RRLs in our catalog (see Section 4).

The dependence of the absolute magnitude on metallicity is weak. Considering a mean metallicity offset of ±0.5 dex from $[\text{Fe/H}] = −1.5$ dex for the entire sample would lead to a fractional difference in heliocentric distances of 1.8%, being these differences as high as 4 kpc (for the faintest RRL). If the metallicity offset is ±1.0 dex instead, these values vary ~3.6% and with distances up to 8 kpc. Hence the lack of individual metallicities should not introduce large discrepancies in our distance estimates. In Table 1 the distances obtained by this method are shown for the faintest (and hence farthest) candidates. Distances obtained for the remaining sample are...
reported in Tables 5 and 6 in the Appendix section. The uncertainties in the distance estimates include the propagation of the errors associated with not only the photometric errors but uncertainties in the distance estimates include the propagation of the errors associated with

![Figure 6. Radial plot of heliocentric distances as a function of right ascension (R.A.). The overdensity located at ~80 kpc corresponds to the Sextans dSph galaxy. Sixteen RRLs have distances >100 kpc.](image6)

![Figure 7. Positions in the sky of RRLs found by this work near the Sextans dSph galaxy (black dots). These RRLs cover a range of magnitudes from 20.03 to 20.57 in the g-band. Known RRLs from Amigo et al. (2012) and Zinn et al. (2014) are shown as red and green dots, respectively. In addition, variable star candidates at the level of the Horizontal Branch (19.0 < V < 21.6) from Lee et al. (2003) are plotted with blue dots. The HiTS footprint is plotted in gray in the background. An ellipse centered in (R.A., decl.) = (153°2512, -1°6147) (Irwin et al. 1990) is shown as a reference of the tidal radius (rt = 83”/2), orientation (θ = 56°/7), and ellipticity (ε = 0.29) of the dSph as determined by Roderick et al. (2016).](image7)

4. Sextans dSph RRL Population

Figures 1 and 6 show an overdensity of stars centered at R.A. ≈ 153°3, decl. ≈ -1°7, and dh ≈ 80 kpc. The position of these stars, both in equatorial coordinates and distance, matches the location of the Sextans dwarf spheroidal galaxy (R.A. = 153°2512, decl. = -1°6147, dh = 86 ± 4 kpc, McConnachie 2012). Sextans is a Milky Way satellite discovered by Irwin et al. (1990), with an absolute magnitude of MV = -9.3. The system is characterized by a relatively old and metal-poor population (age = 12 Gyr; [Fe/H] = -1.9), as described by Mateo et al. (1991) and Kirby et al. (2011), respectively. The Sextans dwarf is a relatively extended satellite with a half-light radius rL of 695 pc (Irwin & Hatzidimitriou 1995; Roderick et al. 2016) and a surface brightness of ~28 mag arcsec^-2, typical of Local Group dSph galaxies. A recent study of Sextans carried out by Roderick et al. (2016) analyzed its structural parameters using wide-field photometric data in order to investigate its kinematics and stellar structures. According to their results, the dSph has a halo-like substructure extended up to 82° from its center, with several overdensities detected at statistically high significance levels.

From our sample, 65 of the RRL candidates are located within 1°75 of Sextans, and between heliocentric distances of 76 and 90 kpc (48 ab’s, 17 c’s). Their distribution, as well as the position of the HiTS fields are shown in Figures 1 and 7, in different scales. Figure 7 also shows an ellipse marking the tidal radius from a King profile of the galaxy (Roderick et al. 2016) and known RRLs in the galaxy from the literature. As can be seen in the figure, the HiTS fields do not cover the center of Sextans but only the outskirts of the dwarf. However, none of the previous surveys of RRLs in this galaxy were able to cover the full extension of Sextans. Thus HiTS is providing for the first time information on the outermost RRLs in Sextans. The distribution of the RRLs along the fields does not show any particular kind of structure or shape, and all are contained within the galaxy’s known King limiting radius.

The distances for the Sextans dSph RRLs were re-calculated, since values for the metallicity of the galaxy are available in the literature, and they are not necessarily close to our assumption for the Halo ([Fe/H] = -1.5). For the Sextans RRLs, we adopted [Fe/H] = -1.93 ± 0.01 from Kirby et al. (2011).

Based on our subsample of RRLs associated to Sextans (both ab and c-types), in principle we estimated a mean heliocentric distance to the satellite of 81.4 ± 5.7 kpc. We noted, however, a clear offset between the mean distance obtained with only RRab and only RRc (84.2 and 74.5 kpc, respectively). This discrepancy (13%) may be due to the different behavior of the period–luminosity relations for these stars (see, e.g., Vivas et al. 2017), and we are using PLZ relations that are exclusive for RRab (Sesar et al. 2017b). As we do not expect the different populations to be located at different distances, we corrected the the distances of the RRc from our entire sample by this number, including all type c stars outside Sextans. By doing this, the re-derived mean
heliocentric distance of the dSph is 84.2 ± 3.3 kpc, which is in agreement with the distance of 86 ± 4 kpc obtained by Mateo et al. (1995), also based on RRLs.

Knowing the distance, we can estimate the physical distances of our Sextans RRLs to the dwarf’s center. We find stars out to 1.9 kpc (12.30), which is in agreement with the results of Roderick et al. (2016), who found Sextans halo overdensities to be as far as 2 kpc from the center.

RRLs have been used as a mean to detect extra-tidal material around satellite galaxies and globular clusters (e.g., Fernández-Trincado et al. 2015; Garling et al. 2018). From Figure 7 it is possible to claim that there is no clear evidence of extra-tidal RRLs based on our sample. Extending the search for RRLs in Sextans to the contiguous HiTS fields does not change this statement, even if a significantly larger radius is considered (e.g., \( r_1 = 90' \); Irwin et al. 1990). One of the RRLs from the LSQ survey lies outside Roderick et al.’s (2016) tidal radius (see Figure 7), but inside the estimate by Irwin et al. (1990). Thus it is not strong evidence of extra-tidal material. Regarding hypothetical internal substructures in the galaxy, it is not possible to measure any, given the mean uncertainty of the distance of our sample of Sextans’s RRLs (4.1 kpc), the standard deviation of the distribution (3.3 kpc), and its size (∼700 pc; Irwin & Hatzidimitriou 1995; Roderick et al. 2016).

In Amigo et al. (2012), a list of 114 RRLs covering the inner regions of Sextans is presented, including 37 identified earlier by Mateo et al. (1995). This catalog contains a large number of new discoveries (ranging from \( V = 20.06 \) to \( V = 20.50 \)), and recovers as RRLs most of the variable star candidates presented in Lee et al. (2003). Since Amigo et al. (2012) covers the central region of the dwarf, the overlap with HiTS’s fields is not significant. However, there are 16 stars in common between HiTS and that work, with highly similar periods (∆\( \Delta P \) ∼ 2 × 10^{-4}) and the same classifications. In addition, Zinn et al. (2014) recognized seven RRLs in the galaxy, four of which are not contained in the catalog of Amigo et al. (2012). Thus there are 46 new RRLs discovered by HiTS in Sextans, seven of which are not flagged as RRLs by Lee et al. (2003). This brings the total number of RRLs in this galaxy to 165.

Folded light curves for the HiTS Sextans RRLs sample are shown in the Appendix section (Figures 12–14). Table 5 contains the information of these stars. The mean period of the RRab is 0.63 days, which is close to the nominal Oo II group. However, the distribution of the 65 RRLs in Sextans in the Period-Amplitude diagram (Figure 4) clearly shows that the stars do not follow a single sequence of Oo groups. Thus HiTS confirms the Oo-intermediate nature of this dSph, which was already established by Mateo et al. (1995) based in 34 stars in the inner part of the galaxy. Following the Milky Way satellites (except the massive galaxies of Sagittarius and the Magellanic Clouds), our extended sample confirms that Sextans do not contain High Amplitude Short Period (HASP) stars, which have been interpreted by Fiorentino et al. (2015) as coming from populations more metal-rich than [Fe/H] ∼ −1.5.

5. RR Lyrae Stars beyond 90 kpc

We find 18 distant RRLs within our list of candidates that are located at \( d_H > 90 \) kpc; this corresponds to mean magnitudes \( (g) > 20.5 \). Two recent works, Drake et al. (2013b) and Sesar et al. (2017a), have reported some of the most distant Galactic RRLs known to date, located at ∼120 kpc and ∼130 kpc, respectively. Among our distant RRLs sample there are 13 with \( d_H > 130 \) kpc; that is, beyond the most distant previously known MW RRLs. The distant RRLs group span a range from \( ∼92 \) kpc \((g) ∼ 20.5\) to beyond 200 kpc \((g) ∼ 22.8\). In Table 1 the main properties of these distant stars are presented (full info is presented in Table 6 in the Appendix section), and Figure 8 shows the folded light curves for this group.

Regarding their classification, 11 RRLs (61%) from this faint subsample correspond to RRab, while seven were classified as RRC (Table 1), roughly consistent with the observed ratio in the rest of the sample. We note that three of the four most distant RRLs are c-type. Given their lower intrinsic amplitude and the large photometric uncertainties of the individual observations near the detection limit of our survey, we regard their classification as tentative; the most distant RRab, which has a secure classification, is at \( d_H = 219 ± 15 \) kpc. In the period-amplitude diagram (Figure 4, top panel), these stars are mostly located toward the locus of the Oo II group, although a large dispersion is observed. However, the distribution looks significantly different compared with the one from nearby stars \((d_H < 90 \) kpc\). The mean period of the sample of 11 distant RRab stars is 0.668 ± 0.05 days, which is significantly different to the mean period of the RRab with \( d_H < 90 \) kpc, 0.600 ± 0.09 days. The mean period of the distant RRLs is remarkably similar to the mean period of the ensemble of RRLs in the UFD satellites of the Milky Way, 0.667 days (Vivas et al. 2016), suggesting that these galaxies may be the main contributors of the outermost regions of the halo. As Sextans, the distant RRLs sample does not contain HASP stars.

In Figure 1 we showed the spatial distribution of the distant RRLs, color-coded by their heliocentric distance. The distant RRLs look randomly distributed in the sky except for two compact groups, with two and three RRLs respectively, whose stars are very close together in the sky. We discuss those groups in the next sub-section.

5.1. Leo IV and Leo V

Among the sample of distant RRLs, we found two distant groups of closely spaced RRLs, both in angular separation and heliocentric distances. In these cases, they coincide with the position on the sky and distance of the ultra-faint galaxies Leo IV and Leo V. In Medina et al. (2017) we reported the discovery of the RRLs in Leo V, since that galaxy was not explored before for variability. Medina et al. (2017) also argues the importance of groups of distant RRLs as a means to discover previously unknown satellites or substructure in the halo. Since the properties of the RRLs in Leo IV and Leo V were already discussed in Medina et al. (2017), here we only present a summary and update the distance estimates.

Out of the three known RRLs in Leo IV (Moretti et al. 2009), we detected two stars, HiTS113256-003329 and HiTS113259-003404, both RRab. The non-detection of the third RRLs (called V3 by Moretti et al. 2009) is consistent with the detection efficiency expected for RRLs of these magnitudes, according to our results (Section 3). Three RRLs were identified as members of Leo V, HiTS113057+021331, HiTS113105+021319, and HiTS113107+021302, all being new discoveries.

In Medina et al. (2017), the distances of the Leo IV and Leo V RRLs were anchored to the known distance to Leo IV (Moretti et al. 2009). Here we obtain revised distances for those RRLs, since metallicities for both systems are available in the literature and we can use them in the PLZ relation given by...
Sesar et al. (2017b), which was not available at the time of writing Medina et al. (2017). Using $\text{[Fe/H]} = -2.31$ for Leo IV (Simon & Geha 2007), we get a mean heliocentric distance of $151.4 \pm 4.4$ kpc. This number is in agreement with the estimation made by Moretti et al. (2009) ($154 \pm 5$ kpc). For Leo V, assuming $\text{[Fe/H]} = -2.48$ (Collins et al. 2017) gives

Figure 8. Folded light curves of the distant RR Lyrae stars listed in Table 1.
us a mean distance of $169.0 \pm 4.4$ kpc, which is still consistent with our earlier results.

6. Space Density Distribution

The density profile of halo tracers contains important clues about the accretion history of the Milky Way (Bullock & Johnston 2005; Cooper et al. 2013). Since RRLs are excellent distance indicators, they are particularly useful for the construction of number density profiles $\rho(R)$—that is, the variation in the number of RRLs per unit volume ($\#/kpc^3$), where $R$ is the distance to the center of the Galaxy. Recent studies have worked with catalogs of RRLs sufficiently large to allow them to study the variation of the number density with direction in the sky (see, e.g., Zinn et al. 2014). In our case, the sample is made up of only ~100 RRLs (excluding stars from known dSph galaxies) spread over an area of ~120 deg$^2$. Therefore working with sub-samples located in different directions would not be statistically meaningful. For this reason, we use the data from all 40 fields to build a single number density profile. Since HiTS’s fields span from $39^\circ$ to $60^\circ$ in Galactic latitude, and from $236^\circ$ to $269^\circ$ in longitude, this can be considered a single line of sight in the Galaxy. For the selection of the distance bins and the number density calculation, the distance from the Galactic center $R_{GC}$ was calculated for each star in our sample. $R_{GC}$ can be obtained from

$$R^2_{GC} = (R_\odot - d_H \cos b \cos l)^2 + d_H^2 \sin^2 b + d_H^2 \cos^2 b \sin^2 l,$$

(4)

where $d_H$ is the heliocentric distance; $b$ and $l$ are the Galactic latitude and longitude of each star, respectively; and $R_\odot$ is the distance from the Sun to the Galactic center. For this work we assumed $R_\odot$ to be 8 kpc. The bins were created evenly spaced on a log scale.

We are interested in placing the Milky Way into context with external galaxies and model stellar halos. Given that in typical data sets, small overdensities of 2–3 stars, such as what we found in Leo IV and Leo V, may not have been identified with known galaxies, we first performed density profile fits including the RRLs in the UFD, but leaving out the RRLs from the larger Sextans dSph. We repeated the fits with the Leo IV/V stars removed, in order to test the effect of these ultra-faint dwarfs on the profile; the fits are virtually unchanged by the inclusion/exclusion of the Leo IV/V RRLs.

Two halo models were used to fit the data—a spherical (sp) halo model and an ellipsoidal (ell) one with a flattening parameter $q = 0.7$ adopted from Sesar et al. (2011). The adopted model was $\rho(R) = \rho_\odot (R/R_\odot)^m$, where $\rho_\odot$ is the local (solar circle) number density of RRLs. The fit was done using the logarithmic form of the previous equation:

$$\log(\rho(R)) = A + n \log(R/R_\odot),$$

(5)

where $A = \log(\rho_\odot)$. We used the Markov Chain Monte Carlo routine emcee (Foreman-Mackey et al. 2013) to find distributions for the parameters of this model of a simple power law (SPL), $A$ and $n$.

Although our main interest is to study the behavior of the density profile at large distances from the Sun, we also explored a model with a broken power law that has been observed in multiple works (Saha 1985; Watkins et al. 2009; Deason et al. 2011; Sesar et al. 2011) at $\sim 25$ kpc. For the broken power-law model (BPL), the break radius was considered a free parameter, as well as the inner and outer slopes. In the case of the BPL profile, the equations used are

$$\log(\rho(R)) = A + n_1 \log(R/R_\odot),$$

$$\log(\rho(R)) = A + n_2 \log(R/R_\odot),$$

$$A + n_1 \log(R_{break}/R_\odot) = A + n_2 \log(R_{break}/R_\odot).$$

(6)

The values of $A$ were constrained to within 0.20 and 1.75, and $-5$ and 5 for $A_2$ (after the break). The slope was constrained to be between $-7$ and $-1$ for the SPL. For the BPL, the constraining values were set to between $-10$ and 5, and $-14$ and 15 for the inner and outer slopes, respectively. The break radius was constrained to within 15 and 70 kpc. An initial guess for the value of each parameter was given, based on the result of following a nonlinear least squares methodology (using the Levenberg–Marquardt algorithm from scipy).

The left/right panels of Figures 9 and 10 show the fitted models to the data, with sp and ell halos, respectively, under different considerations. In the left panels we fit the model to the RRLs within 145 kpc, which corresponds to the upper limit based on completeness considerations (we are $\sim 85\%$ complete down to $g = 21.5$). In this case, the more distant ($R > 145$ kpc) bins are shown for comparison with extrapolations of the fits to large radii. In the right panels, we show fits to the entire sample, after correcting for detection efficiency, as calculated in Figure 5.

In both cases the first bin, which includes the closest RRL, was removed from the plots and the analysis because these bins suffer incompleteness due to the saturation of bright stars, which was not considered in our detection efficiency calculations. The corner plot with the resulting posterior distributions from our fits is shown in Figure 11. Tables 2 and 3 show the results of the fitting for the different models assumed and with the samples with/without the RRLs in Leo IV and V, respectively.

It is important to notice that according to Equation (4), the Galactic latitude and longitude are required to determine $R_{GC}$ from $d_H$. Given the wide area covered by the survey, it is not possible to transform the detection efficiency per apparent magnitude bin to a unique Galectocentric distance, and subsequently to a unique ellipsoidal distance. If the mean latitude and longitude of the area observed by the survey is used ($b \sim 46^\circ$, $l \sim 250^\circ$), the difference in distance, between heliocentric and Galectocentric, is of up to 5 kpc. We consider the detection efficiency correction still valid in this case, since the size of the bins is in general $>5$ kpc. In the case of the ellipsoidal distances, this distance difference reaches up to 70 kpc, which makes the correction less accurate for the more distant bins. The left/right panel of the plots in Figures 9/10 are provided only to show the approximate effect to the density profile if the detection efficiency is or is not considered. For this reason, the best-fit parameters in Tables 2 and 3 and the posterior analysis are only given for the corrected/uncorrected data for the spheroidal/ellipsoidal model.

6.1. Spherical Halo

In this case $R^2 = R^2_{GC} = X^2 + Y^2 + Z^2$, where $X$ and $Y$ are the Cartesian coordinates in the Galactic plane, and $Z$ is the axis
perpendicular to it. These values are given by

\[ x = R_\odot - d_H \cos b \cos l \]
\[ y = d_H \cos b \sin l \]
\[ z = d_H \sin b. \]

Figure 9 shows the density profiles as described above. Table 2 summarizes the parameters found for the spherical halo SPL and BPL, when the data is corrected and not corrected by detection efficiency, respectively. Based on these results, the best fit for the data corresponds to the SPL model. From Figure 9 one can infer that the presence of the break at \( \sim 20 \) kpc is mostly due to the relatively high density of the point at \( R_{GC} \sim 26 \) kpc. The larger uncertainties in the determination of

6.2. Ellipsoidal Halo

For an oblate halo with \( q = 0.7 \), the semimajor axis of the ellipsoid is \( R_\odot^2 = X^2 + Y^2 + (Z/0.7)^2 \), which replaces \( R \) in Equation (5). The results of the fit are shown in Table 2 and Figure 10. As in the previous case, the best fit corresponds to the SPL model (based on \( \chi^2 \)), but again, this may be due to the scarce bins at short distances in our data set. As in the case of the spherical halo model, the distant bins make the difference when looking for a change in the slope. The fits give \( R_\odot \sim 22 \) kpc as the most likely value for the break radius for the BPL, while for the DBPL these are \( \sim 25 \) kpc and \( \sim 80 \) kpc, with large uncertainties. For the latter, overfitting is much more likely to have happened than in the spherical halo model.

Overall, the spherical halo model provides a better fit to the halo than the ellipsoidal model with \( q = 0.7 \). The results of using samples that include/exclude the RRLs in the UFD Leo IV and Leo V are the same, within the errors, indicating that small galaxies do not affect the general behavior of the density profile of the halo.
6.3. Contribution from Known Substructures in the HiTS Field of View

The approach we have taken here best facilitates comparisons to model and external galaxy halos, where individual stellar streams and substructures may not be distinguished from the halo as a whole. However, we acknowledge that there are known MW substructures in the vicinity of the HiTS field of view. Here we briefly assess these substructures’ contributions to the halo density profiles shown in Figures 9 and 10.

The Orphan tidal stream (Grillmair et al. 2006; Belokurov et al. 2007) is a wide stellar stream that spans more than 100 degrees (Grillmair et al. 2015), tracing a roughly north–south path across (and extending southward beyond) the SDSS footprint. The distance to the stream ranges from ~55 kpc at its northernmost point, decreasing to ~20 kpc as the Orphan extends below the southern edge of the SDSS footprint (Sesar et al. 2013). We select Orphan RRLs candidates using the coordinate system defined by Newberg et al. (2010) to align with the stream and at distances between 20 < d_H < 32 kpc (consistent with the stream distances found in the region of the HiTS footprint by Hendel et al. 2017). We find 12(7) RRLs within 5°(3°) of the stream center and satisfying this distance cut. Newberg et al. (2010) showed that the Orphan stream is a ~10% excess of MSTO stars relative to the nearby field density; thus we estimate that ~1–2 of the stars selected as Orphan candidates are actual members of the stream. Indeed, one of them (HiTS104924-023635) corresponds to “RR49” from Hendel et al. (2017), who measured a distance with Spitzer Space Telescope time-series data of 23.05 ± 0.58 kpc. This compares favorably to our estimate of d_H = 20.92 ± 0.75 kpc for the same star, especially given that if we instead adopted its metallicity of [Fe/H] = −2.02 as measured by Sesar et al. (2013), we would derive a slightly larger distance (by ~2%).

Another possible contributor to the halo stellar populations in the HiTS field of view is the Sagittarius (Sgr) tidal stream. Sgr is a prominent stellar overdensity over much of the sky (see review in Law & Majewski 2016). Using the N-body model of Law & Majewski (2010), we select model Sgr stars within the footprint of our HiTS RRLs search that were stripped from the progenitor within the last ~5 Gyr (i.e., are part of the most recent leading debris tail). The model predicts that only the northeastern corner of the HiTS footprint should contain any Sgr debris. The mean distance of these model debris points is ⟨d⟩ = 42 kpc, with a spread of σ_d ~ 6 kpc. There are nine HiTS RRLs between 31 < d_H < 49 kpc, of which four are in the region occupied by Sgr model debris (i.e., 170° < RA < 175°, −3° < decl. < 3°). Interestingly, these four stars are tightly clumped in distance, with a mean of ⟨d_H⟩ = 40.0 kpc and standard deviation of σ_d ~ 0.7 kpc. Nonetheless, given that these four stars are ~16°±20° from the center of the Sgr stream (using the Sgr-aligned coordinate system of Majewski et al. 2003), we consider their association with Sgr tentative at best.

In conclusion, while there are likely stars from previously identified substructures in our sample of HiTS RRLs, it is unlikely that they have significantly biased our density profile fits, as each of the substructures would contribute only a small number of stars in our field of view.

### 7. Discussion and Summary

We present the detection of 173 RRLs using observations from the 2014 campaign of the HiTS survey. The data cover ~120 square degrees of the sky and include from 20 to 37 epochs in the g-band. The photometric depth of the HiTS data enables us to build a catalog that includes a significant number of stars that do not appear in previous public surveys overlapping the same sky region (such as the CRTS). Most of the additional RRLs we contribute have ⟨g⟩ > 20, corresponding to d_H > 60 kpc.

The surveyed region overlaps with the position of currently known satellite galaxies of the Milky Way. We detect 65 RRLs members of the Sextans dSph, 46 of them being new discoveries. This number includes seven stars that were not classified as RRLs by other works, but were already considered as members of the dwarf. Two additional dwarf galaxies, Leo IV and Leo V, were found within our RRLs catalog. A more detailed analysis of the RRLs in Leo V has been presented in a companion paper (Medina et al. 2017).

Regarding distant RRLs in our sample, we find 18 candidates with d_H > 90 kpc, 11 of which are classified as ab-type, while seven are c-type. To understand the connection of this subsample with previously known/unknown systems, the period-amplitudes of the individual stars could play a major role. RRLs that are members of globular clusters are separated in the distinguished Oosterhoff groups (Oo I and Oo II; Oosterhoff 1939). On the other hand, RRLs in ultra-faint dwarf galaxies are mostly Oo II (Clementini 2014), while the halo general population (within a radius of ~80 kpc) presents stars in both locius, but the majority of them follow the locus of the Oo I group. This has been shown multiple times in the literature (e.g., Zinn et al. 2014; Catelan & Smith 2015), and it is also clearly seen in Figure 4. The distant sample of RRLs, however, does not follow the main trend of nearby field RRLs, suggesting that the main contributor to the outer halo may come from UFD galaxies.

We build number density radial profiles with our RRLs catalog (Section 5), and then fit models of the form ρ(R) = ρ_0(⟨R⟩/R_0)^q for a spherical halo and an ellipsoidal one with a flattening parameter q = 0.7. The fits described in the previous section do not support the presence of a clear break in the profiles. However, due to the saturation limit of our photometry, we only have ~1–2 bins within the radius where a break is typically identified, so that our data may not be sensitive to the presence of a break. In fact, the data are well
represented by a SPL, with a slope of $-4.17^{+0.18}_{-0.20}$ for the spherical halo, and $n = -4.16^{+0.23}_{-0.25}$ for the elliptical case. If a broken power law is considered, the profile for a spherical halo exhibits a break at $R_b = 19.52^{+3.27}_{-3.23}$ kpc, with inner and outer slopes of $n_1 = -3.50^{+1.98}_{-1.46}$ and $n_2 = -4.22^{+0.27}_{-0.26}$, respectively. The position of the break and the values of the power-law indices are broadly consistent with previous studies. We summarize values from the literature for these parameters in Table 4. This agreement might represent a possible real feature of the Galactic halo, even when the samples used for those studies are located at different positions. However, it is not clear that the data favor a certain model over the other. We tried a less likely double broken power law (a power law with two breaks) profile as well, but it was not considered for further analysis due to the lack of a strong physical meaning, big uncertainties, and possible overfitting.

Our sample of HiTS RR Lyrae is an unprecedented probe of the outer Galactic halo; all but three of our stellar density bins are at distances beyond 30 kpc. As illustrated in Table 4, the power-law slope of the outer MW halo is typically found to be rather steep, whether it is measured by fitting a single power-law to the outer halo ($R_{GC} \gtrsim 50$ kpc) or a broken power-law with separate slopes for the inner/outer halo. The existence of a break in the halo density profile at $R_{GC} \sim 20$–30 kpc is typically argued to represent a transition between predominantly in situ halo stars in the inner halo and an accretion-dominated outer halo (e.g., Bullock & Johnston 2005; Abadi et al. 2006). Deason et al. (2013) fit broken power laws to the density profiles of synthetic, accretion-only models from Bullock & Johnston (2005), and found a mean from the 11 outer halo slopes of $(n) = -4.4$, with values in the range of $-2.5 < n < -6.5$, and median break radius of 26 kpc. Because all but two of our radial profile bins are beyond this typical break, these predictions provide a valid comparison to even our single power-law fits. Cooper et al. (2010) also predicts slightly steeper (on average) slopes (all with $n < -4.4$) for the outer halos of Aquarius model galaxies formed by the tidal disruption of dwarf satellites. The rough agreement of our power-law fits (both the SPL with $n = -4.17$, and the BPL with $n_2 = -4.22$, $R_b = 19$ kpc) with these predictions from halos made entirely of accreted satellites suggests that the outer MW halo may be made up completely of accreted stars.

We can perhaps learn even more about our Galaxy’s accretion history based on the density profile. Pillepich et al. (2014) fit the power-law stellar density profiles of $\sim 5000$ MW
analogs from the Illustris simulation suite between radii of the stellar half-mass radius ($r_{1/2}$; $\sim 10$ kpc for a $10^{12} M_\odot$ galaxy) out to the virial radius. These slopes are in the range of $3.5 < n < 5.5$, with more massive halos exhibiting shallower stellar density profiles. More recently formed halos, those that had a recent minor-major merger, or those that accreted a larger fraction of their stellar mass from satellites, typically have shallower slopes; thus the fact that the MW’s outer slope is often found to be steep suggests a relatively quiescent recent accretion history. Our measured slope of $n = -4.17$ is remarkably consistent with Illustris model predictions for MW-mass galaxies (see Figure 6 of Pillepich et al. 2014).

With the addition of radial velocities for our outer halo RRLs, we can assess whether groups of stars that share similar radial velocities and 3D positions are part of physically associated, recently accreted tidal debris (e.g., Baker & Willman 2015; Vivas et al. 2016). If tidal debris structures in the outer halo can be linked to related structures at smaller Galactocentric radii, they provide a means of tracing the halo potential over the intervening distances (e.g., Johnston et al. 2012). Furthermore, the 13 RRLs we have discovered beyond 130 kpc in the Galaxy, more than double the number of known stars at such distances in the MW. With spectroscopically derived radial velocities, these stars will be vital tracers of the MW mass (e.g., Watkins et al. 2010; Sanderson 2016), which is currently known only to roughly a factor of two (e.g., Eadie & Harris 2016; Ablimit & Zhao 2017).

The data presented here cover only a small field of view in the Galactic halo, making interpretation within a global galaxy-formation context limited. Fully understanding our Galaxy’s accretion history thus requires samples of tracers at $R_{GC} > 100$ kpc over many sky areas. Even with a handful of $\sim 100$ deg$^2$ fields such as that presented in this work, we could examine the fraction of stars in substructures as a function of position, and the variation of density profiles with line of sight, while also combining data sets to average over local variations. The deep, $\sim 20,000$ deg$^2$, time-domain LSST survey (e.g., LSST Science Collaboration et al. 2009) will recover a nearly complete sample of RRLs out to $\gtrsim 350$ kpc by the completion of the 10-year survey (Ivezić et al. 2008; Oluseyi et al. 2012; VanderPlas & Ivezić 2015, see also Figure 2 of Baker & Willman 2015). The HiTS results presented here are part of a larger ongoing LSST precursor observing program we are conducting, with which we will continue to map the outer limits of the Galactic halo with RR Lyrae variables, and develop tools for interpretation that lay the groundwork for exploiting the huge samples of RRLs in the LSST era.

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Appendix

Tables and Light Curves

In this section, we include tables with the main properties of the sample of RRLs found by HiTS, as well as phased light curves for the stars that are not shown in Figure 8. Table 5 displays information about the RRLs in the Sextans dSph, while Table 6 shows the information of the rest of the sample.

Figures 12–14 display the phased light curves of the RR Lyrae stars in the Sextans dwarf spheroidal galaxy. On the other hand, Figures 15–18 show the light curves of the field RR Lyrae stars closer than 90 kpc.
Figure 12. Phased light curves of RR Lyrae stars in the Sextans dwarf spheroidal galaxy (1/3).
Figure 13. Phased light curves of RR Lyrae stars in the Sextans dwarf spheroidal galaxy (2/3).
Figure 14. Phased light curves of RR Lyrae stars in the Sextans dwarf spheroidal galaxy (3/3).

Table 5
RR Lyrae Stars Found in the Sextans dSph by HiTS

| ID             | R.A. (degree) | Decl. (degree) | $g$   | Period (days) | Amplitude | $d_H$ (kpc) | Type | N  | Previous ID |
|----------------|--------------|----------------|-------|---------------|-----------|-------------|------|---|-------------|
| HiTS100815-021625 | 152.06402    | −2.27369       | 20.3  | 0.6973        | 0.85      | 84          | ab   | 30 | ...         |
| HiTS100936-015356 | 152.40198    | −1.89876       | 20.4  | 0.346         | 0.65      | 84          | e    | 38 | ...         |
| HiTS100958-015954 | 152.49002    | −1.99832       | 20.4  | 0.6497        | 0.97      | 84          | ab   | 36 | ...         |
| HiTS101010-021303 | 152.54151    | −2.21761       | 20.4  | 0.6775        | 0.67      | 87          | ab   | 38 | ...         |
| HiTS101011-012028 | 152.54492    | −1.34107       | 20.4  | 0.675         | 0.67      | 86          | ab   | 38 | ...         |

Note. In the column previous ID, stars with prefixes V and C are taken from Amigo et al. (2012), with the former corresponding to detections made by Mateo et al. (1995). The RRLs with prefixes LSQ are stars from LSQ (Zinn et al. 2014), and the ones labeled as VV, VI, and MV are from Lee et al. (2003). Stars with MV come from Mateo et al. (1995) as well. Note that only four of our RRLs are classified as RRLs in Lee et al. (2003).

(This table is available in its entirety in machine-readable form.)
Figure 15. Phased light curves of nearby (<90 kpc) RR Lyrae stars in the field (1/4).
Figure 16. Phased light curves of nearby (<90 kpc) RR Lyrae stars in the field (2/4).
Figure 17. Phased light curves of nearby (<90 kpc) RR Lyrae stars in the field (3/4).
Figure 18. Phased light curves of nearby (<90 kpc) RR Lyrae stars in the field (4/4).

Table 6
Full List of the RRLs Presented in this Work, Excluding the Candidates in the Sextans dSph Galaxy

| ID            | R.A. (degree) | Decl. (degree) | $<g>$ | Period (days) | Amplitude | $d_R$ (kpc) | Type | $N$ |
|---------------|---------------|----------------|-------|---------------|-----------|-------------|------|-----|
| HiTS095845   | 149.68616     | 2.52172        | 17.9  | 0.6453        | 0.36      | 28          | ab   | 18  |
| HiTS100129   | 150.37090     | 0.18338        | 16.4  | 0.6098        | 1.30      | 13          | ab   | 21  |
| HiTS100207   | 150.52751     | 1.37554        | 16.5  | 0.7208        | 0.91      | 15          | ab   | 16  |
| HiTS100236   | 150.64878     | 3.00649        | 16.1  | 0.6079        | 1.02      | 12          | ab   | 20  |
| HiTS100838   | 152.15703     | −2.05345       | 17.4  | 0.5799        | 1.28      | 20          | ab   | 38  |

(This table is available in its entirety in machine-readable form.)
