Serendipitous Discovery of RR Lyrae Stars in the Leo V Ultra-faint Galaxy

Gustavo E. Medina1,2, Ricardo R. Muñoz1, A. Katherina Vivas3, Francisco Förster2,4, Jeffrey L. Carlin5, Jorge Martínez1,2,4, Lluís Galbany6, Santiago González-Gaitán2,4, Mario Hamuy1,2, Thomas de Jaeger1,2,7, and Jaime San Martín4

1 Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile
2 Millennium Institute of Astrophysics, Santiago, Chile
3 Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile
4 Center for Mathematical Modelling, Universidad de Chile, Av. Blanco Encalada 2120, Piso 7, Santiago, Chile
5 LSST, 933 North Cherry Avenue, Tucson, AZ 85721, USA
6 PITT PACC, Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA
7 Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA

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Abstract

During the analysis of RR Lyrae stars (RRLs) discovered in the High Cadence Transient Survey (HiTS) taken with the Dark Energy Camera at the 4 m telescope at Cerro Tololo Inter-American Observatory, we found a group of three very distant, fundamental mode pulsator RR Lyrae (type ab). The location of these stars agrees with them belonging to the Leo V ultra-faint satellite galaxy, for which no variable stars have been reported to date. The heliocentric distance derived for Leo V based on these stars is 173 ± 5 kpc. The pulsational properties (amplitudes and periods) of these stars locate them within the locus of the Oosterhoff II group, similar to most other ultra-faint galaxies with known RRLs. This serendipitous discovery shows that distant RRLs may be used to search for unknown faint stellar systems in the outskirts of the Milky Way.

Key words: galaxies: individual (Leo V) – Galaxy: halo – Local Group – stars: variables: RR Lyrae

1. Introduction

With the advent of large, optical sky surveys like the Sloan Digital Sky Survey (SDSS; York et al. 2000), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS-1; Chambers et al. 2016), or the Dark Energy Survey (DES; Abbott et al. 2016), over the past decade and a half, a flurry of new Milky Way (MW) satellites have been discovered (e.g., Willman et al. 2005; Belokurov et al. 2006a, 2006b, 2008, 2010; Zucker et al. 2006a, 2006b; Irwin et al. 2007; Bechtol et al. 2015; Drlica-Wagner et al. 2015, 2016; Koposov et al. 2015a; Martin et al. 2015). These discoveries are of particular relevance since they allow us to probe the faint end of the galaxy luminosity function and shed new light into known discrepancies between predictions from cosmological simulations and observations. Among these stands the well-known “missing satellites problem” present in ΛCDM models (e.g., Kauffmann et al. 1993; Klypin et al. 1999; Moore et al. 1999; Simon & Geha 2007), wherein hundreds to thousands of low-mass subhalos should orbit around the MW but only a few dozen actual dwarf satellites are known. In this context, a reliable census of satellite galaxies, particularly at the faint end, is essential to make progress toward solving these inconsistencies. This has led to focused efforts to discover dwarf galaxies and extremely low-luminosity subhalos, and finding new ways to use the data available from wide- and deep-field surveys in an efficient way (e.g., Baker & Willman 2015; Bechtol et al. 2015; Koposov et al. 2015a).

The detection of variable stars in dwarf satellites has played a major role in the study of their properties and populations. The case of the pulsating RR Lyrae stars (RRLs) is particularly interesting since they are old stars (>10 Gyr) easily identifiable by the shape of their light curves. In fact, historically, the discovery of RRLs in dwarf spheroidal (dSph) galaxies was the first confirmation that these systems contained old, population II stars (e.g., Baade & Hubble 1939; Saha et al. 1986; Siegel 2006).

Additionally, this type of variable stars play an important role since they are considered well-known standard candles and therefore provide reliable distances to their host dwarf satellites. In this context, at least one RRL has been reported in every MW satellite classified as a dwarf galaxy that has been searched for them (see the compilation in Vivas et al. 2016), including systems with extremely low luminosity and surface brightness like Segue 1 (Simon et al. 2011) and Segue 2 (Boettcher et al. 2013). This fact has brought forth the idea that RRLs can actually be used to discover new stellar systems in the outer halo (Sesar et al. 2014; Baker & Willman 2015; Sanderson et al. 2017), as well as to study the properties of halo substructures (Vivas et al. 2001; Drake et al. 2013b; Sesar et al. 2013; Torrealba et al. 2015). Since distant RRLs are rare, these works suggest that they can trace the existence of faint stellar systems (as the light of the lighthouse). In particular, Baker & Willman (2015) suggested that groups of two or more RRLs at heliocentric distances >50 kpc could reveal stellar systems as faint as $M_V = -3.2$.

In this Letter, we describe the serendipitous discovery of variable stars in the Leo V ultra-faint galaxy while studying a sample of distant RRLs from the High Cadence Transient Survey (HiTS; Förster et al. 2016). Following Baker & Willman’s idea, two close groups of RRLs were recognized in these data. The locations of these groups agreed with the locations of the dwarf satellites Leo IV and Leo V. Variable stars in Leo IV have been identified before by Moretti et al. (2009), but no search so far has been reported in Leo V. Leo V was discovered in SDSS data by Belokurov et al. (2008). It is a faint system, $M_V = -4.4$ (Sand et al. 2012), composed of an old, metal-poor ([Fe/H] = −2.48; Collins et al. 2016) stellar population. Based on the observed horizontal branch (HB), the estimates of the distance to Leo V have been set between 175 and 195 kpc (Belokurov et al. 2008; de Jong et al. 2010; Sand et al. 2012). Its closeness with Leo IV
in both location in the sky and radial velocity has suggested a possible common origin for both galaxies (Belokurov et al. 2008; de Jong et al. 2010; Blaña et al. 2012). It has also been suggested that the galaxy is undergoing tidal disruption (Belokurov et al. 2008; de Jong et al. 2010; Collins et al. 2016), although Sand et al. (2012) did not find evidence for extra-tidal features in their data. In any case, the detection of RRLs in this work allows the determination of a precise distance to this galaxy, which will be useful for future dynamical works to understand the origin of this system and its possible interaction with Leo IV and/or the MW.

The structure of this article is as follows. In Section 2, the details of the HiTS observations are presented. Properties of the RRLs discovered in Leo V are presented in Section 3, and finally, a summary and final discussion are addressed in Section 4. The details of the methodology and analysis of the complete list of distant RRLs in the HiTS survey is the topic of a separate paper (G. Medina et al. 2017, in preparation).

2. Observations and Data Analysis

The data used in this article were collected between UT 2014 February 28 and UT 2014 March 4 with the Dark Energy Camera (DECam; Flaugher et al. 2015), a prime focus CCD imager installed at the Blanco 4 m telescope at the Cerro Tololo Inter-American Observatory (CTIO), as part of the HiTS (Förster et al. 2016, hereafter F16). The survey is focused on the detection of young supernovae with emphasis on the early stages of the explosions. Despite being designed for other purposes, the data can be mined for the study of optical transients in general.

HiTS observed 40 blindly selected fields in 2014 at high Galactic latitudes, covering a total of ~120 square degrees from 150° to 175° in RA and −10° to 3° in decl. (see Figure 4 in F16). These fields were observed on the g SDSS photometric system filter with exposure times varying from 160 s (83% of the total) to 174 s (14%) and a cadence of two hours. That resulted in a total of 20 epochs for most of the fields, with a limiting apparent magnitude of 23–24.5 (F16). The mean seeing of the survey was 1.5 arcsec. Details on the survey strategy can be found in F16, while the search for RRLs will be detailed in an upcoming paper (G. Medina et al. 2017, in preparation). Here, we summarize the most relevant steps.

The data processing was carried out using the DECam community pipeline (Valdes et al. 2014). Point-source photometry was done with the SExtractor photometry software (Bertin & Arnouts 1996). To generate time series, we performed an alignment in the x, y position of the SExtractor outputs. Using our second epoch as reference, we compared the instrumental magnitudes of all stars and calculated a zero-point offset (\( \Delta zp \)) on a chip-by-chip basis. Then, the reference scan was calibrated (only by zero point) using overlapping SDSS photometry from DR10 (Ahn et al. 2014). To correct for extinction, we used the re-calibrated dust maps of Schlafly & Finkbeiner (2011) and calculated the extinction values following \( A_g = 3.303 \ E( B - V) \).

For the detection of RRLs, we filtered out objects with less than five observations and also stars with a low variation in brightness compared with the typical magnitude errors. After that, we performed a period search using the Generalized Lomb–Scargle technique (GLS; Zechmeister & Kürster 2009) using an astroML python module developed by VanderPlas et al. (2012). Pre-candidates were selected based on the periods found, where objects with periods shorter than 4.8 hr and longer than 21.6 hr were rejected for being outside the typical pulsation window of RRLs. In this process, we did not consider periods within 0.1 days around 0.33 and 0.50 days to avoid spurious detection attributable to aliasing. Another filter was applied based on the level of significance of the period detection computed by the python module (statistical significance <0.08 were left out). Following these criteria, we accepted the two most significant periods (if applicable). Finally, the candidates with a difference in magnitude between the brightest and faintest observation larger than 0.2 were visually inspected to make the final catalog. The pulsation parameters of the light curves were obtained by adjusting RRLs templates from SDSS Stripe 82 (Sesar et al. 2010). For this fitting, small variations around the observed amplitude and GLS period were allowed. We selected the best fit based on a \( \chi^2 \) minimization criterion. The mean magnitudes of the RRLs were calculated by integrating the transformed fitted template, in intensity units, and transforming back to the magnitude the mean.

We examined the best two periods because aliasing can produce reasonable light curves for different periods. This was indeed the case for one RRL found in Leo V, HiTS113105, for which the second best period, 0.657 days, produced a light curve almost indistinguishable from the main period (a 1-day alias), 1.955 days. We took the 0.657 days period as the correct one as it agrees better with the expectations for RRL stars.

3. RR Lyrae Stars in Leo V

Theoretical calibrations for the absolute magnitude of RRL stars in the SDSS g-band exist in the literature (Marconi et al. 2006; Cáceres & Catelan 2008), but they require knowledge of color information that is not available from our single-band survey. For the same reason, we do not have data to calculate a Johnson V magnitude using known transformation equations like the ones derived by R. Lupton.\(^8\) Thus, we estimated preliminary \( M_g \) for our stars by comparing our complete sample of RRL with the ones in the Catalina surveys (Drake et al. 2013a, 2014). Distances were computed for the RRLs in the Catalina survey using their mean V magnitudes (corrected by extinction) and assuming [Fe/H] = −1.6 as the metallicity for the halo, which yields \( \langle M_g \rangle = 0.55 \) (Demarque et al. 2000). We found ~50 stars in common between our catalogs and from the known apparent g magnitudes of the stars in our sample, we determined an average absolute g magnitude of \( \langle M_g \rangle = 0.69 \pm 0.06 \). We validated this method by comparing the results for a sub-sample of the HiTS RRL stars that belong to the Sextans dSph galaxy. Using the \( M_g \) above, we obtained a distance of \( d_H = 83 \pm 4 \) kpc for this galaxy, which agrees well with literature values (e.g., Lee et al. 2009).

From the list of distances obtained for the RRLs detected in the HiTS data we closely analyzed stars beyond 100 kpc with special attention paid to potential close pairs or groups on the sky, i.e., stars with small angular separation as well as similar distances. A pair and a triplet were obvious in the data, in both cases with angular distances smaller than one degree and a heliocentric distance difference no larger than 10 kpc; one of these groups seemed to coincide with the position and published distance of the Leo V dSph. The stars are identified as HiTS113057+021303, HiTS113105+021319, and HiTS113107+021302 (hereafter HiTS113057, HiTS113105, and HiTS113107). Figure 1 shows

\(^8\) http://www.sdss.org/dr12/algorithms/sdssUBVRITransform/#Lupton2005
the light curves of the three RRLs. No search for variable stars in this galaxy has been reported to date, and thus these are the first RRLs detected in this ultra-faint galaxy.

**Figure 1.** Folded light curves for the three RRLs found in Leo V. The solid blue line is the best-fit template from the library of Sesar et al. (2010). The pulsational properties and distance of these variables are shown in Table 1.

**Figure 2.** Left panel: color–magnitude diagram of the inner 5 arcmin of Leo V. The blue stars mark the position of the three RRLs. Overplotted is a 13 Gyr old isochrone with [Fe/H] = −2.2, visually matched to the BHB stars at a distance of 175.4 kpc, consistent with the mean distance of 173 ± 5 kpc from the RRLs. Right panel: spatial distribution of stars near the center of Leo V. The location of the three RRLs is marked. The ellipse marks the position of Leo V’s effective radius (R. Muñoz et al. in preparation).

Figure 2 (right panel) shows that, at 0.75 arcmin from the center, only HiTS113107 lies within one half-light radius of the dwarf galaxy (with $r_h = 1$ arcmin; according to R. Muñoz et al. 2017,
in preparation). The other two stars lie at 1.26 and 3.05 arcmin (HiTS113057 and HiTS113105, respectively). Although not as centrally located, they are still close enough to be associated with Leo V. Figure 2 (left panel) shows a color–magnitude diagram (CMD) of Leo V using data from the Megacam survey by R. Muñoz et al. (2017, in preparation). The RRLs fall redward of the predominantly blue and sparsely populated blue horizontal branch (BHB), as expected. For reference, a 13 Gyr old, [Fe/H] = −2.2 Padova isochrone (Girardi et al. 2004; Bertelli et al. 2008) was visually matched to the blue horizontal branch (BHB) at a distance of 175.4 kpc. We note that in our single-epoch CMD, the three RRLs are located below the BHB, at magnitudes of $g = 22.07$, 22.24, and 22.16, respectively, consistent with their amplitudes having been observed at fainter phases in their light curves (see Figure 1). Table 1 summarizes the main properties of the triplet.

We detected another close group, this time of two RRLs, in addition to Leo V. This pair matched the position of the Leo IV dwarf galaxy. In fact, these two RRLs had been previously discovered by Moretti et al. (2009). These authors identified three RRLs in the Leo IV region. It is worth noting that in G. Medina et al. (2017, in preparation) we estimated the completeness for detecting RRL at these magnitudes to be ~60%, which is consistent with the fact that we detected only two of the three RRLs in Moretti et al. (2009).

We looked for other RRLs in our sample that lie spatially close to Leo V, but at closer distances, with the purpose of checking whether possible anomalous Cepheids had been misclassified as RRLs. We also looked in the region bridging Leo IV and Leo V considering that there is a potential association between the two ultra-faint systems (de Jong et al. 2010; Blaña et al. 2012; Jin et al. 2012). We did not find any other RRLs within a radius of 15′ from the center of Leo V, or connecting both dwarf galaxies. The closest star was HiTS113107+023025, at 17′4 but ~3 mag brighter than the HB of the galaxy and hence too bright for being an anomalous Cepheid in the galaxy. Also, it is located in the opposite direction to Leo IV, and thus not in the possible bridge. Stars lying close to the three RRLs in the CMD of Leo V shown in Figure 2 (left panel) were also inspected, resulting in no additional RRL candidates.

We estimated the distance to the Leo V RRLs in two ways. As mentioned above, using the mean metallicity of the Galactic halo ([Fe/H] = −1.6) as a representative value for our sample, we found a mean g-band absolute magnitude of $(M_g) = 0.69$. With this value we obtain a mean distance to Leo V of 163 ± 4 kpc. However, it is known that Leo V is significantly more metal-poor than this value. For this reason, a more appropriate estimation should assume a lower metallicity for the RRLs. To address this issue, we re-estimate the mean absolute magnitude of our RRLs using as reference the Leo IV stars in common with Moretti et al. (2009) and assuming their derived distance of 154 ± 5 kpc. Leo IV has a metallicity of [Fe/H] = −2.31 (Simon & Geha 2007), which is very close to the recent value of [Fe/H] = −2.48 found for Leo V by Collins et al. (2016). In this case, we derived $(M_g) = 0.57 ± 0.07$, which results in a mean heliocentric distance to Leo V of 173 ± 5 kpc. The individual values for the distances are shown in Table 1.

### 4. Discussion and Conclusions

We have used data from the HiTS in the g-band and identified the first three RRLs known to date in the Leo V ultra-faint galaxy. From the shape and properties of their light curves, we classified these three RRLs, HiTS113057+021330, HiTS113105+021319, and HiTS113107+021302, as fundamental mode pulsators (ab-type RRLs). The periods found for them are 0.6453, 0.6573, and 0.6451 days, respectively, and the amplitudes, according to fitted models, are 0.72, 1.34, and 0.99 mag.

Globular clusters in the MW separate in two groups (the Oosterhoff, Oo, groups; Oosterhoff 1939), based on both the mean period of their RRLs and the proportion between ab-type and c-type stars. dSph satellites of the MW do not show such fundamental mode pulsators (ab-type RRLs). The periods found for them are 0.6453, 0.6573, and 0.6451 days, respectively, and the amplitudes, according to fitted models, are 0.72, 1.34, and 0.99 mag.

In the context of the specific number of RRLs in dSphs as a function of magnitude (see Figure 3 from Baker & Willman 2015), we find that Leo V is broadly consistent with what has been seen in other ultra-faint dwarfs (Vivas et al. 2016). However, due to the large dispersion in this correlation, no further conclusions can be drawn just from this additional data.

To derive the distance to Leo IV, we anchored our measured g-band magnitudes to a known distance to thus calibrate $(M_g)$. In particular, we used data from the low-metallicity ultra-faint system Leo IV, similar in metallicity to Leo V. Anchoring our measurements to the RRL stars in Leo IV (Moretti et al. 2009), we obtained a mean heliocentric distance to Leo V of 173 ± 5 kpc. While consistent within the uncertainties, our value lies on the low side of previously published values. In their discovery paper, Belokurov et al. (2008) used data from the 2.5 m INT telescope and estimated a distance of 180 ± 10 kpc to Leo V. de Jong et al. (2010) obtained deep photometry of the Leo IV and V pair with the Calar Alto 3.5 m telescope and determined a heliocentric distance of 175 ± 9 kpc. Sand et al. (2012), on the other hand, based on images taken with the Clay Magellan telescope, derived

| ID            | R.A. (deg) | Decl. (deg) | $(g)$ | $A_g$ | $d_H ([\text{Fe/H}] = −1.6)$ (kpc) | $d_H ([\text{Fe/H}] = −2.31)$ (kpc) | Period (days) | Amplitude (g) | Type | N |
|---------------|------------|-------------|-------|-------|---------------------------------|---------------------------------|--------------|---------------|------|---|
| HiTS113057+021330 | 172.73946  | 2.22514     | 21.79 ± 0.08 | 0.09 | 166 ± 8                         | 176 ± 9                         | 0.6453       | 0.72          | ab   | 20 |
| HiTS113105+021319 | 172.76936  | 2.22200     | 21.79 ± 0.08 | 0.09 | 166 ± 8                         | 176 ± 9                         | 0.6573       | 1.34          | ab   | 20 |
| HiTS113107+021302 | 172.77796  | 2.21734     | 21.68 ± 0.08 | 0.09 | 158 ± 7                         | 167 ± 8                         | 0.6451       | 0.99          | ab   | 21 |
a much larger distance of 196 ± 15 kpc. The relatively large uncertainties associated with all of these measurements are understandable given the sparsely populated BHB of Leo V. These stars are commonly used as distance indicators and do not require time-series observations, but they lack precision compared to RRLs estimations when the BHB is poorly populated and not well defined, as is the case for the literature data for Leo V.

Baker & Willman (2015) argued that groups of two or more closely spaced RRLs in the halo can reveal the presence of a Galactic satellite beyond 50 kpc. The serendipitous discovery of three RRLs beyond 100 kpc coinciding with the position of the Leo V ultra-faint dwarf is a proof-of-concept for their proposal and opens up the exciting possibility of searching for distant ultra-low-luminosity, low surface brightness MW satellites. This possibility becomes even more relevant when looking ahead to projects like the Large Synoptic Survey Telescope (LSST; LSST Science Collaboration et al. 2009); the traditional method for detecting ultra-faint systems based on detecting their major CMD sequences will suffer from significant contamination at the faint end, especially arising from unresolved galaxies, a problem that progressively worsens as we explore the outer regions of the MW halo. Since RRLs lie in a region of the CMD less contaminated by foreground sources, and particularly due to their identification as pulsational sources, the use of these variables as lightposts for ultra-faint systems will be with no doubt of much valuable help in the efforts to obtain a complete census of Galactic satellites up to distances of ~400 kpc (Ivezic et al. 2008; Oluseyi et al. 2012).

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**ORCID iDs**

A. Katherina Vivas https://orcid.org/0000-0003-4341-6172
Francisco Förster https://orcid.org/0000-0003-3459-2270
Jeffrey L. Carlin https://orcid.org/0000-0002-3936-9628
Lluís Galbany https://orcid.org/0000-0002-1296-6887
Santiago González-Gaitán https://orcid.org/0000-0001-9541-0317
Thomas de Jaeger https://orcid.org/0000-0001-6069-1139
Juan Carlos Maureira https://orcid.org/0000-0002-7458-6142

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