DISENTANGLING THE VIRGO OVERDENSITY WITH RR LYRAE STARS

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Received 2016 July 18; revised 2016 August 26; accepted 2016 August 31; published 2016 November 4

ABSTRACT

We use a combination of spatial distribution and radial velocity to search for halo substructures in a sample of 412 RR Lyrae stars (RRLSs) that covers a region of ~525 square degrees of the Virgo overdensity (VOD) and spans distances from the Sun from 4 to 75 kpc. With a friends-of-friends algorithm we identified six high-significance groups of RRLSs in phase space, which we associate mainly with the VOD and with the Sagittarius stream. Four other groups were also flagged as less significant overdensities. Three high-significance and three lower-significance groups have distances between ~10 and 20 kpc, which places them in the distance range attributed by others to the VOD. The largest of these is the Virgo stellar stream at 19 kpc, which has 18 RRLSs, a factor of two increase over the number known previously. While these VOD groups are distinct according to our selection criteria, their overlap in position and distance and, in a few cases, similarity in radial velocity are suggestive that they may not all stem from separate accretion events. Even so, the VOD appears to be caused by more than one overdensity. The Sagittarius (Sgr) stream is a very obvious feature in the background of the VOD at a mean distance of 44 kpc. Two additional high-significance groups were detected at distances >40 kpc. Their radial velocities and locations differ from the expected path of the Sgr debris in this part of the sky, and they are likely to be remnants of other accretion events.

Key words: stars: variables: RR Lyrae – Galaxy: halo – stars: kinematics and dynamics – Galaxy: structure

Supporting material: machine-readable tables

1. INTRODUCTION

With the advent of large-scale surveys in the last two decades, several low-surface-brightness, large-scale structures, extending from hundreds to a few thousand square degrees in the sky, have been discovered in the halo of the Milky Way (Newberg 2016, and references therein). Contrary to the case of the Sagittarius (Sgr) dwarf spheroidal (dSph) galaxy, whose debris has been found in well-defined tidal streams wrapping around the full sky (Majewski et al. 2003), these structures have more of a cloud morphology, and their progenitors are still unknown (Grillmair & Carlin 2016). They are nonetheless interpreted as remnants of galaxies that were disrupted while merging with the Milky Way (see for example Helmi et al. 2011).

At low galactic latitudes, two such cloud-like structures have been found: the Monoceros ring (Newberg et al. 2002) and the Triangulum–Andromeda overdensity (Rocha-Pinto et al. 2004). In both cases, the interpretation of an extragalactic origin for these features is not clear, and their possible relationship with the galactic disk is still under investigation (see Price-Whelan et al. 2015; Xu et al. 2015). At high galactic latitudes and far from the disk, there are several other structures: the Virgo overdensity (VOD, Vivas et al. 2001; Newberg et al. 2002; Duffau et al. 2006; Jurić et al. 2008; Bonaca et al. 2012; Duffau et al. 2014), the Hercules–Aquila cloud (Belokurov et al. 2007; Watkins et al. 2009; Simion et al. 2014), the Pisces overdensity (Sesar et al. 2007; Kollmeier et al. 2009; Watkins et al. 2009; Sesar et al. 2010), and the Eridanus–Phoenix overdensity (Li et al. 2016). Although their interpretation as a merger event, or events, is less ambiguous, the specific merging history is still unknown. The existence of more than one kinematic substructure in some of these clouds (Newberg et al. 2007; Vivas et al. 2008; Sesar et al. 2010; Duffau et al. 2014) hints that they may contain either separate merger events or different wraps of debris material from the same event. Currently available data cannot answer this issue. In addition, no progenitors have been associated with any of these cloud-like structures. One possible explanation is that these clouds are formed from the debris of satellites in highly eccentric orbits whose stars pile up near the apocenter of their orbit because they spend a longer time near that location (Johnston 2016). The true extensions of the clouds are also uncertain. A connection between several cloud-like substructures, which are located far from each other, has also been proposed. Li et al. (2016) suggest, for example, that the VOD, the Hercules–Aquila cloud, and the Eridanus–Phoenix overdensity, all located at a distance of roughly ~20 kpc from the Sun, may share a common polar-type orbit around the Milky Way and, hence, may be related. Clearly, more investigation is needed in order to understand the origin of these structures, their relationship with each other, and their role in the formation of galaxies like our own Milky Way. A connection between different substructures in the halo is not a new idea, and “streams of galaxies” have been proposed before (e.g., the Fornax stream, Lynden-Bell & Lynden-Bell 1995), although proving their real connection has not been an easy task (Piatek et al. 2007).

Detailed studies in the VOD have proven to be very difficult mainly because of its very large expanse on the sky (up to 3000 sq. deg., Bonaca et al. 2012) and extension along the line of sight (~5–20 kpc, Jurić et al. 2008). These investigations often provide conflicting results. For example, using deep
photometry, Jerjen et al. (2013) identified a main-sequence population at 23 kpc near the center of the VOD. They did not find clear evidence of a population at 19 kpc, which is where the main overdensity of RR Lyrae stars (RRLSs) is located (Vivas & Zinn 2006; Duffau et al. 2014). Similarly, Brink et al. (2010) found a peak in the velocity distribution of main-sequence stars that is not coincident with the main peaks found by Newberg et al. (2007) using F-turnoff stars and by Duffau et al. (2006, 2014) using RRLSs. The works of both Brink et al. (2010) and Jerjen et al. (2013) were based on detailed studies of very small regions (of the order of arcmin) in an overdensity that covers a few thousand square degrees. Thus, rather than conflicting results, each study may be providing pieces for what seems to be a complex and large puzzle.

Here we present an expanded kinematic study in the VOD region covering ~525 sq. deg., using RRLSs as tracers, building on the earlier investigation by Duffau et al. (2014) of the area of the sky covered by the QUEST survey, which is about five times smaller than our present study. RRLSs are abundant in the VOD, and, indeed, this type of star provided the first indication of an overdensity (Vivas et al. 2001). The main advantage of using RRLSs as tracers of the old population of halo substructures is that they are excellent standard candles. RRLSs are pulsating variable stars located on the horizontal branch in the Hertzsprung–Russell diagram; consequently, their luminosities span only a small range, allowing the precise determination of their distances. Period–luminosity relationships have been found for RRLSs in all bands from optical to infrared bands (e.g., Cacciari & Clementini 2003, pp. 105–22, Cáceres & Catelan 2008; Neeley et al. 2015). Thus, a combination of good three-dimensional (3D) positioning of RRLSs (coordinates and distance) with radial velocities provide a powerful way to disentangle the kinematical groups within the region of the VOD. Catalogs of RRLSs covering large portions of the sky (Drake et al. 2013a, 2013b; Sesar et al. 2013a; Zinn et al. 2014; Torrealba et al. 2015) have been made available in the last few years, providing the targets for this type of investigation.

2. DATA

2.1. Catalogs of RRLSs

Our primary source of RRLSs comes from the La Silla-QUEST survey (LSQ, Zinn et al. 2014), a 840 sq. deg. survey covering a large portion of the VOD. This survey provides a catalog of 1372 RRLSs with well-sampled light curves (the mean number of epochs per star is ~70) and covering a range of distances between 5 and 80 kpc from the Sun. An overdensity of RRLSs in the Virgo region, between 5 and 20 kpc, is easily distinguished in this survey (see Figure 14 in Zinn et al. 2014). Here, we concentrate on the region where the VOD seems to be present according to the density maps shown in Zinn et al. (2014), specifically 175° < α < 210° and −10° < δ < +10°. In this region, there are 1054 RRLSs in the catalog.

The LSQ survey has a partial overlap in the Virgo region with other large-scale surveys of RRLSs, including QUEST (Vivas et al. 2004), the Catalina Real-Time Transient Survey (CRTS, Drake et al. 2013a, 2013b, 2014), and the Lincoln Near-Earth Asteroid Research program (LINEAR, Sesar et al. 2013a). The QUEST survey covers a relatively narrow band of declination, between −4° and 0°; it has a lower number of epochs (<40) than LSQ, which is sufficient for obtaining good parameters of the light curves. Our previous study on kinematical groups in the VOD was based on this survey (Duffau et al. 2014). The CRTS catalogs of Drake et al. provide ~14,000 RRLSs in all of the sky between decl. −20° and +60° with a large number of epochs (a few hundred). The catalog contains RRLSs up to ~60 kpc (Drake et al. 2013a). Finally, LINEAR covers ~8000 sq. deg. of the sky. Although this is a shallower survey (reaching only to 30 kpc), it covers the range of distance of the VOD. Since none of those surveys is complete by itself, we cross-matched all catalogs and obtained a list of 1410 unique RRLSs in the VOD region. For stars in common between different catalogs, we adopted preferentially the light curve properties measured by LSQ because it is the deepest of these catalogs. Both the amplitude of the light curve and the time at maximum light are necessary to calculate the systemic radial velocity of the stars, as explained later. The catalogs of Drake et al. (2013b) and Drake et al. (2014) do not provide the time at maximum light for the cataloged RRLSs. For those stars, we downloaded the light curve data from the CRTS DR2 webpage6 and fit a template to the light curve in order to obtain the HJD0 (see Vivas et al. 2008).

2.2. Spectroscopy

The Sloan Digital Sky Survey (SDSS) contains a large number of stellar spectra from the SDSS-I, SDSS-II, SEGUE, and BOSS surveys, which include RRLSs. Presumably they were targeted as blue horizontal branch (BHB) stars in SDSS or quasar candidates, which may overlap in color with RRLSs. These spectra have a wavelength coverage of 3800–9200 Å (3650–10400 Å for BOSS spectra), which for RRLSs means that many Balmer lines and several metallic lines (including Ca II H and K) are present. A potential problem with using spectra of RRLSs from SDSS is that there is the possibility that the final spectrum of a star is made of stacks of spectra taken nonconsecutively, or even on different nights. Because the radial velocity of an RRLS changes by up to ~100 km s⁻¹ during the pulsation cycle, and the effective temperature and luminosity change by significant amounts as well, the composite of spectra taken at very different phases may yield a radial velocity that is far from the star’s systemic radial velocity by an amount that is very hard to determine. To avoid this problem, the SDSS DR12 database7 was queried with the following restrictions: (1) all observations were done on a unique date (in practice, only one date listed in the keyword mjdList in table PlateX), (2) there were no flags associated with the radial velocity (zwarning = 0), and (3) the total exposure time had to be less than 2 hr. After these constraints, we found 423 usable spectra in DR12, several of which were multiple observations of the same star (Table 1).

The first constraint ensures that several exposures over multiple nights were not combined into a single spectrum. The constraint on the total exposure times avoids excessive blurring due to the changing radial velocity. A 2 hr exposure is equivalent to 15% of the pulsation cycle of a typical ab-type RRLS (0.55d). The corresponding phase span for the shorter periods of c-type stars is much longer. However, the change in radial velocity for these stars is much lower than for the ab

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6. [http://nessi.cacr.caltech.edu/DataRelease/](http://nessi.cacr.caltech.edu/DataRelease/)
7. [https://www.sdss.org/dr12/](https://www.sdss.org/dr12/)
Table 1
Heliocentric Radial Velocity for the RR Lyrae Stars from Individual SDSS DR12 Spectra

| Survey | ID | Spectroscopic Survey | HJD (d) | Exp. Time (s) | $V_r$ (km s$^{-1}$) | $\sigma V_r$ (km s$^{-1}$) |
|--------|----|----------------------|---------|--------------|-------------------|-------------------|
| LSQ    | 662| sdss                 | 2451929.00553 | 4500.0       | 212.5             | 3.3               |
| LSQ    | 662| sdss                 | 2451660.75730 | 3600.0       | 221.9             | 3.5               |
| QUEST  | 224| sdss                 | 2451609.90278 | 3600.0       | 6.2               | 3.9               |
| LSQ    | 1195| seguel              | 2454581.74483 | 2700.0       | −43.5             | 2.0               |
| LSQ    | 902| boss                 | 2455321.74094 | 3603.3       | −11.5             | 12.9              |

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

Table 2
Heliocentric $H\beta$ and $H\gamma$ Radial Velocity for the RR Lyrae Stars Observed with the SOAR Telescope

| Survey | ID | HJD (d) | Exp. Time (s) | $V_r$ ($H\beta$) (km s$^{-1}$) | $\sigma V_r$ ($H\beta$) (km s$^{-1}$) | $V_r$ ($H\gamma$) (km s$^{-1}$) | $\sigma V_r$ ($H\gamma$) (km s$^{-1}$) |
|--------|----|---------|--------------|-----------------|-----------------|-----------------|-----------------|
| LSQ    | 501| 2456736.69039 | 2700       | 312.5           | 15.0            | 303.6           | 22.7            |
| LSQ    | 525| 2456736.64124 | 2700       | 324.6           | 13.0            | 362.3           | 25.7            |
| LSQ    | 532| 2456709.87263 | 900        | 41.8            | 15.5            | 44.4            | 15.6            |
| LSQ    | 550| 2456736.79199 | 3600       | 30.5            | 26.0            | −22.1           | 43.0            |
| LSQ    | 691| 2456736.74014 | 2700       | 74.4            | 10.1            | 89.8            | 17.9            |
| LSQ    | 726| 2456736.85050 | 2700       | 174.3           | 31.9            | 154.1           | 16.1            |

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

Table 3
Heliocentric $H\alpha$, $H\beta$, and $H\gamma$ Radial Velocity for the RR Lyrae Stars Observed with the WIYN Telescope

| Survey | ID | HJD (d) | Exp. Time (s) | $V_r$ ($H\alpha$) (km s$^{-1}$) | $V_r$ ($H\beta$) (km s$^{-1}$) | $V_r$ ($H\gamma$) (km s$^{-1}$) |
|--------|----|---------|--------------|-----------------|-----------------|-----------------|
| LSQ    | 629| 2455572.94156 | 2700       | −164.7          | −175.3          | −146.5          |
| LSQ    | 629| 2455574.95754 | 2700       | −124.4          | −131.3          | −95.7           |
| LSQ    | 606| 2455572.94156 | 2700       | 203.9           | 184.8           | 194.1           |
| LSQ    | 606| 2455574.95754 | 2700       | 215.9           | 207.3           | 193.0           |
| LSQ    | 611| 2455572.94156 | 2700       | 207.5           | 192.2           | 236.9           |

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

types, of the order of 30 km s$^{-1}$, and thus it is not expected that it will have a large effect on the final velocities. In practice, however, the exposure times are rarely as large as 2 hr and have a median of 1 hr.

In order to avoid the large discontinuity observed in the radial velocity curve of ab-type RRLSs at maximum light, we excluded any spectrum taken near the maximum light phase of the pulsation cycle of the ab-type RRLSs ($\phi > 0.90$ or $\phi < 0.10$). No restriction in phase was applied to the c-type stars since the discontinuity is not observed in these stars (e.g., Vivas et al. 2008). To implement this last restriction, we calculated the phase of observation using the HJD of the spectrum at midexposure and the ephemerides and periods of the RRLSs from the photometric catalogs. As said above, we gave preference to ephemerides provided by LSQ in the case of stars in common among several catalogs. Heliocentric radial velocities were obtained from the keyword $elodierfinal$ in Table $sppParams$ in the case of the SDSS spectrograph, and from keyword $elodieZ$ in Table $specObjAll$ for BOSS spectra.

In addition to the SDSS spectra, several RRLSs were observed by our team with the 4.1 m Southern Astrophysical Research (SOAR) (Cerro Pachón, Chile) and the 3.5 m Wisconsin Indiana Yale and NOAO (WIYN) (Kitt Peak, USA) telescopes. At SOAR, we used the Goodman spectrograph with the 600 l/mm grating, which yields a dispersion of 0.65 Å pixel$^{-1}$ and a wavelength coverage from 3500 to 6160 Å. Six RRLSs were observed with this telescope in 2014 February and March. With WIYN, we used the Hydra multifiber positioner and grating 600@10.1 with the bench spectrograph to observe 26 additional RRLSs (49 individual spectra) in the wavelength range 4000–6800 Å at 4.6 Å resolution. Comparison lamps were obtained before and after each target spectrum with the Goodman spectrograph and after each spectrum with the WIYN bench spectrograph to ensure accurate wavelength solutions. The data were reduced using standard IRAF packages.

For the SOAR data, radial velocities were measured using Fourier cross-correlation with IRAF task $fxcor$ and ELODIE radial velocity standards selected by Duffau et al. (2014) as templates. Following Sesar et al. (2013b), we used $fxcor$ in two different ranges of wavelength, centered on H$\beta$ (4630–5000 Å) and H$\gamma$ (4160–4630 Å). For the WIYN data, better results were obtained by fitting profiles to individual lines and measuring their centers. In this case we also measured the $H\alpha$ line. All velocities were corrected for the Earth’s orbital motion, and they are reported in Tables 2 and 3.

To complement our sample, we added the velocity measurements of RRLSs in the region that are already in the literature. This includes data from Duffau et al. (2014) (79 stars with distances < 22 kpc), Vivas et al. (2005) (10 stars in the Sgr stream located at distances in the range 40–55 kpc), as well as
five SEKBO RRLs (Prior et al. 2009), which are located in this region of the sky. Finally, new observations for 14 distant QUEST stars (distances >30 kpc) were taken from a spectroscopic study of the Sagittarius tidal tails (S. Duffau et al. 2016, in preparation). These stars were observed with Gemini South, Magellan, and Very Large Telescope (FORS2) telescopes with instrumental setups similar to others used in this work. The reduction techniques and the method of measurement of radial velocities were similar to the ones used by Duffau et al. (2014).

There are stars in common between the different spectroscopic data sets described above. Their systemic velocities were determined by fitting a radial velocity curve to the available observations. In total, we used 681 individual spectra of 472 RRLs. The distribution in the sky of our final sample is shown in Figure 1. This spectroscopic sample corresponds to ~30% of the known RRLs in this region of the sky.

3. SYSTEMIC RADIAL VELOCITIES

To obtain the systemic radial velocity of RRLs, it is necessary to subtract the velocity due to the pulsation of the star. In this work, we adopted the radial velocity curves provided in Sesar (2012), which are based on an extensive set of measurements for six type-ab RRLs. The advantage of using these templates is twofold. First, there are separate templates for the Balmer lines Hα, Hβ, and Hγ and for metallic lines. We can then choose the appropriate template(s) for the wavelength range of a particular spectrum. Second, Sesar (2012) provides a calibration between the amplitude of the light curve and the amplitude of each one of the radial velocity curve templates. The use of these templates and calibration represents an improvement for the determination of the systemic velocities compared to the traditional use of the model of a single star (X Arietis), which was constructed with measurements of the Hγ line and had a fixed amplitude that was assumed to hold for any RRLs (see, for example, Layden 1995; Vivas et al. 2005, 2008; Prior et al. 2009; Duffau et al. 2014). For uniformity, we used these templates to recalculate the systemic velocities of all stars in our sample, including the ones previously reported in the literature.

For type-ab stars, we followed the following steps in order to derive the systemic radial velocities:

1. Depending on the wavelength range of each particular spectrum, we selected which template(s) were to be used for correcting the pulsation velocity. For example, SDSS velocities are measured by Fourier cross-correlations using the complete spectral range, which contain the three Balmer lines considered above and a wealth of metallic lines. Consequently, all four templates were used on these spectra. On the other hand, for the SOAR spectra, we only used the Hβ and Hγ templates, while for the WIYN data, the three Balmer line templates were used.

2. Each template was scaled by the amplitude of the light curve of the RRLS according to Equations (2)–(5) in Sesar (2012).

3. Having calculated the mean phase of observation of a spectrum, we interpolated in each one of the selected radial velocity templates to obtain a pulsation velocity at that phase.

4. The pulsation velocity was subtracted from the measured velocity to give the systemic velocity for each template. In the case of SDSS spectra, the measured velocity is the one reported in Table 1, while for the SOAR and WIYN spectra it is the velocity measured for the specific Balmer line of the template.

5. The results from the different templates were weighted by their errors and then averaged to yield our final systemic velocity. The resulting systemic velocities derived from each template were not very different. For example, for the SDSS data, the standard deviation of the four velocities obtained from each template averaged 15 km s\(^{-1}\).

6. If more than one spectrum for the same star was available, the systemic velocities were averaged.

7. The errors of the systemic velocities were estimated following Sesar (2012) and Sesar et al. (2013b), which included the error in the velocity measurement and the error of the template at the phase of observation.

Figure 2 illustrates the radial velocity curve fitting for star LSQ 652 (V = 17.0), which was observed with the WIYN telescope at two different phases.

The same approach described above was followed to recalculate the systemic velocities in the catalog of Duffau et al. (2014) since they used X Arietis as the radial velocity template. A comparison of the present results with those of Duffau et al. (2014) shows that the mean difference in radial velocity for the stars in common is only 1 km s\(^{-1}\), with a standard deviation of 19 km s\(^{-1}\). The differences are partly due to the use of the new radial velocity templates, but a significant contribution comes from our use of updated ephemerides in this work (those from the LSQ survey). Indeed, if we use the same ephemerides as Duffau et al. (2014) to fit the new radial velocity curves, the standard deviation of the velocity differences decreases to only 9 km s\(^{-1}\). This suggests that the results of previous investigations that used only X Arietis as a template are not seriously biased by the choice of template.

As mentioned before, we included five RRLs with kinematic data from Prior et al. (2009) that lie in the range 183° < α < 208° and −3° < δ < −10°. These stars are important because they extend our coverage toward southern declinations. The systemic radial velocities of these stars were
calculated using the star X Arietis as a template, and we were unable to recalculate the velocity using the new templates because there was no information on the individual spectra for each star in Prior et al. (2009). The above comparison with the results of Duffau et al. (2014) suggests that the velocities given by Prior et al. (2009) may be used without any correction.

RRLs of type c have smaller variations in the radial velocities during the pulsation cycle. For these stars, we used the template given in Vivas et al. (2008) and Duffau et al. (2014) to derive the systemic radial velocities.

The final sample of RRLs with radial velocities in the Virgo region consists of 412 stars, which is roughly six times larger than the sample in Duffau et al. (2014), and it covers a much larger area and range of distances from the Sun (~4–75 kpc). The final results are shown in Table 4. The table contains the photometric survey and the identification number of the RRL in that survey, coordinates, type of RR Lyrae, mean V magnitude, period of pulsation, amplitude in the V band, distance from the Sun, number of useful spectra used to derive the systemic radial velocity, heliocentric radial velocity, radial velocity in the galactic standard of the rest frame and associated error, and, finally, the group number to which the star belongs according to our analysis in the next section.

About one-third of the sample (116 stars) have more than one spectrum taken at different phases. In several cases, the spectra were taken with different instruments. In order to check the consistency of our method, we calculated the standard deviation of the systemic velocities obtained by stars with more than one spectrum available (Figure 3). The median value is only 8 km s\(^{-1}\), which is encouraging that we are correcting appropriately the pulsation velocity of the RRLs and that there are no large systematic differences between different instrumental setups. Only a few stars had standard deviations in their velocities of the order of 25–45 km s\(^{-1}\). Every time the standard deviation from multiple spectra was larger than the error in the systemic velocity (which includes both the observational and the template error), we adopted the former as the final error.

The average error in radial velocity for all the stars in the sample is 13.8 km s\(^{-1}\). There is no significant trend of the radial velocity errors with distance to the star, and thus we adopted this mean error for the analysis described next. In distance, we assumed a 7% error, following Zinn et al. (2014).

Star LSQ 394 (QUEST 167) requires further explanation. This star was used by Casetti-Dinescu et al. (2009) to determine a preliminary orbit for the Virgo stellar stream (VSS), which was later confirmed by Carlin et al. (2012) using stars consistent with the color–magnitude diagram (CMD) of the VSS. The radial velocity calculated by Casetti-Dinescu et al. (2009) used the same SDSS spectra used here and the ephemerides given by the QUEST survey, which was based on a light curve with 29 observations. LSQ has a superior light curve based on 158 epochs, which we have used to rederive the radial velocity. We obtained \(V_{\text{gr}} = 180 \text{ km s}^{-1}\), which is higher than the value of 134 km s\(^{-1}\) reported by Casetti-Dinescu et al. (2009), but still consistent within error to the mean velocity of proper-motion VSS stars in Carlin et al. (2012). The LSQ distance, however, is compromised because the photometric calibration for this star was flagged as being poor, which means it can produce distance errors of \(12\%\) (Zinn et al. 2014). Consequently, we adopted for this star the distance determined by the QUEST survey, 16.9 kpc.

4. KINEMATICAL GROUPS

4.1. Method

We searched for kinematical grouping in the data using the method developed in our previous study of the region (Duffau et al. 2014) with some modifications, which are explained below. This new implementation of the method makes it more robust in a sample covering a large range of distances, as encountered here. The method is basically a friends-of-friends algorithm that selects pairs of stars that are located in nearby (3D) positions in the sky and share a similar velocity or, formally, stars that have a four-distance value less than a critical value, or \(4d < e\) (Starkenburg et al. 2009). Pairs with common stars (friends of friends) form a group. The 4d parameter is defined as

\[
(4d)_{ij}^2 = \omega_{3d}^2(3d)_{ij}^2 + \omega_{v}^2(v_i - v_j)^2, \tag{1}
\]

where \((3d)_{ij}\) is the mean physical separation between stars \(i\) and \(j\), which can be calculated using their Galactocentric Cartesian coordinates (assuming \(R_{\odot} = 8\) kpc):

\[
3d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2}. \tag{2}
\]

As defined in Starkenburg et al. (2009) and Duffau et al. (2014), the weights \(\omega_v\) and \(\omega_{3d}\) in Equation (1) depend on both the maximum possible range for those quantities and the observational errors. In the case of \(\omega_{v}\), the observational error appeared in the form of a relative error \((\sigma_v/d)\). Using those
Table 4
Position, Light Curve Parameters, Distance, and Radial Velocity for the RR Lyrae Stars

| Survey | ID   | R.A.(2000.0) | Decl.(2000.0) | Type | Mean V | Period (d) | Amp V (mag) | Distance (kpc) | $N_{spec}$ | $V_h$ (km s$^{-1}$) | $V_{sys}$ (km s$^{-1}$) | $\sigma V_h$ (km s$^{-1}$) | Group |
|--------|------|--------------|---------------|------|--------|------------|-------------|-----------------|-----------|----------------|-------------------------|--------------------------|-------|
| LSQ    | 381  | 178.18130    | 7.10520       | ab   | 16.21  | 0.48523    | 1.29        | 13.3            | 1         | 254             | 167                     | 16                         | ...   |
| LSQ    | 384  | 178.31850    | −3.42868      | ab   | 16.80  | 0.56959    | 0.81        | 17.2            | 1         | 182             | 64                      | 17                         | ...   |
| QUEST  | 717  | 178.64810    | −4.23051      | ab   | 15.63  | 0.66514    | 1.01        | 10.0            | 2         | 229             | 110                     | 14                          | 9     |
| LSQ    | 393  | 178.79402    | −2.44436      | ab   | 16.84  | 0.53839    | 0.95        | 17.6            | 1         | 206             | 92                      | 18                         | ...   |
| CRTS   | CSS_J115524.9 + 041414 | 178.85396    | 4.23725       | ab   | 18.20  | 0.68168    | 1.02        | 31.8            | 1         | 50              | −45                     | 17                         | ...   |

(This table is available in its entirety in machine-readable form.)
weights, we searched for substructures in Duffau et al. (2014) using \( \varepsilon = 0.045 \), which implied a separation between stars in a pair \( \leq 25 \text{ km s}^{-1} \) and \( \leq 3 \text{ kpc} \), in velocity and separation in the sky, respectively. The maximum of 3 kpc for the separation of stars in a pair was adequate given the distance for the RRLs used in Duffau et al. (2014), which were all located closer than 23 kpc from the Sun (hence, with errors in distance < 1.6 kpc). In the present investigation, we have stars at > 50 kpc, which implies errors in distance > 3.5 kpc. Obviously, we do not want to limit the search to pairs of stars with separations less than the errors in their distances.

Thus, in this implementation of the algorithm, we modified the 4d equation in order to use the absolute error in distance (instead of its relative error), and we normalized it in such a way that a value of \( \varepsilon \) corresponds to a maximum separation of \( N \) times the error in both distance and velocity. Weights have the form

\[
\omega_v = \frac{a}{(v_{\text{max}})^2}; \quad \omega_{3d_{ij}} = \frac{b}{((3d_{\text{max}})^2},
\]

where the denominators are the maximum possible range for stars in our sample, which are needed in order to make 4d a dimensionless variable. The values \( a \) and \( b \) are determined by the following procedure.

When two stars in a pair have the same position \( (3d_{ij} = 0) \), they differ only in velocity. The value of \( \varepsilon \) sets the maximum possible difference in velocity for the stars in a pair. From Equation (1):

\[
4d_{ij} = \sqrt{\omega_v((v_i - v_j)_{\text{max}})^2} = \varepsilon. \tag{4}
\]

We request that the maximum difference in velocity scales with the error in velocity, that is, \( (v_i - v_j)_{\text{max}} = N\sigma_v \). Thus,

\[
a = \left(\frac{\varepsilon}{N}\right)^2 \frac{(v_{\text{max}})}{\sigma_v}. \tag{5}
\]

Similarly, a maximum separation of two paired stars in the sky \( (\text{Sep}_{\text{max}}) \) is achieved if their velocities are the same \( (v_i - v_j = 0) \), which gives

\[
4d_{ij} = \sqrt{\omega_{3d_{ij}}(\text{Sep}_{\text{max}})^2} = \varepsilon. \tag{6}
\]

In this case we require that \( \text{Sep}_{\text{max}} = N\sigma_{d_{ij}} \) and obtain

\[
b = \left(\frac{\varepsilon}{N}\right)^2 \left(\frac{(3\sigma_{d_{ij}})^2}{(3d_{\text{max}})^2}\right). \tag{7}
\]

Combining (5) and (7), we obtain

\[
a \cdot \left(\frac{\sigma_v}{v_{\text{max}}}ight)^2 = b \cdot \left(\frac{\sigma_d}{(3d_{\text{max}})^2}\right). \tag{8}
\]

Choosing (arbitrarily) \( a = 1 \), we can solve for \( b \) and obtain the following relationship for the four-distance:

\[
(4d_{ij})^2 = \left(\frac{1}{v_{\text{max}}}ight)^2 \left(\frac{\sigma_v}{\sigma_{d_{ij}}}ight)^2 (3d_{ij})^2 + \left(\frac{1}{v_{\text{max}}}ight)^2 (v_i - v_j)^2 < \varepsilon \tag{9}
\]

and \( \varepsilon = N\sigma_v/v_{\text{max}} \).

Here, \( \sigma_v \) is the mean error in radial velocity of the full sample, while \( \sigma_{d_{ij}} \) is the mean error in distance of the stars in a pair. Using \( N = 2.0 \), a pair of stars will have a maximum possible difference in velocity of two times the mean error in the radial velocity, which translates to 27.6 km s\(^{-1}\) given the mean error of our sample. Unless the stars are located in exactly the same spot, the velocity difference between them will be less than this value. Similarly, a pair can have a maximum separation of two times the error in the mean distance of the pair, which equals 1.4 kpc at 10 kpc or 7 kpc at 50 kpc, if the stars have exactly the same radial velocity.

Applying Equation (9) to our sample, we found 558 pairs of stars (Figure 4) and 22 groups (Figure 5). Most of the groups of RRLs have a small number of members (\( \leq 8 \)), but two of them have a particularly large number of stars, one with 18 members at a distance of \( \sim 19 \text{ kpc} \) and another one with 113 members at \( \sim 45 \text{ kpc} \).

It is likely that some of these groups, particularly the ones with a small number of members, are produced by random variations in a smooth distribution of stars. In order to quantify how frequently these cases may occur, we simulated a large number of random samples of halo stars, which were used as input in our group-finding algorithm. We then quantified the likelihood of formation of random groups as a function of the number of members, mean radial velocity, mean distance, velocity dispersion, and distance dispersion. With this procedure, we were able to identify which of the RRLs groups
are unlikely to be simply formed by random in a smooth distribution of stars.

We made 10,000 simulated samples with the following recipe. First, we estimated how many RRLSs are expected in this area of the sky in the range of distances between 4 and 70 kpc by integrating the RRLS number-density profile provided in Zinn et al. (2014). For simplicity, the area of observations was approximated to a rectangular region with limits $175^\circ < \alpha < 210^\circ$ and $-4^\circ < \delta < 10^\circ$, which is where most of our spectroscopic sample is found (see Figure 1). This integration yielded 767 RRLSs in this volume of the halo. Because the completeness of the LSQ survey (which was used to derive that profile) is estimated to be 70%, we divided this number by 0.7 to obtain the true expected number of RRLSs. However, our spectroscopic sample is not complete; only 30% of the real RRLSs have at least one spectrum available. Taking into account this factor, we simulated samples of stars having $N_{\text{stars}} \pm \sqrt{N_{\text{stars}}}$, where $N_{\text{stars}} = 329$. Although the spectroscopic completeness varies somewhat with location on the sky because the different data sets were combined, we assumed for simplicity uniform completeness in our simulations.

To each star in the simulated sample, we assigned a random position, heliocentric distance, and radial velocity. The positions were randomly assigned within the rectangular region defined above. Distances were randomly drawn from a distribution that is based on the number-density radial profile of RRLSs (Zinn et al. 2014) in the range of galactocentric distances ($R_{gc}$) from $\sim 7$ to 90 kpc. This profile has a flattening of $c/a = 0.7$ and a double power law with a steeper slope beyond $\sim 30$ kpc. A 7% error, similar to the observational error of the real RRLSs, was added to the resulting distance. Radial velocities ($V_{\text{gsl}}$) were randomly assigned following a Gaussian distribution with mean 0 km s$^{-1}$ and standard deviation that was a function of the distance from the galactic center, following the velocity dispersion profile given by Brown et al. (2010) for BHB stars in the halo. Brown et al.’s profile is defined from $R_{gc} = 15$ to 80 kpc. We assumed that the velocity dispersion at 15 kpc (103 km s$^{-1}$) also holds to the inner limit of our sample ($R_{gc} \sim 7$ kpc). The assumed velocity dispersion at a given distance took into account the errors in the profile derived by Brown et al. (2010). Noise with the typical observational error of 13.8 km s$^{-1}$ was added to the assigned radial velocity.

4.2. Results

As expected, our algorithm detected pairs and groups in the simulated samples. The mean number of pairs found in the simulated samples is 148, which is significantly lower than the 558 pairs found among the RRLSs. This suggests that this region of the sky contains substructures. The number of groups, however, are about the same, 21 on average in the simulated data and 22 in the real data. Evidently, many of the pairs in the real data originate in only a few substructures. The real data indeed contain two relatively large structures, with 113 and 18 members, in which our algorithm connected many pairs of stars. In contrast, the simulations produced mostly groups with small numbers of members (Figure 6). The median number of members among the 210,298 groups formed in the 10,000 simulations is four stars. The 95th percentile of the distribution of the number of members is 14, and the largest group formed in all 10,000 simulations has 83 members. Based on size alone, the most populous groups in the RRLS sample are very likely to be real, and in fact they are due to the previously well-documented stream of stars from the Sgr dSph galaxy and the VSS.

It is much less clear that any of the smaller groups that we have detected in the RRLS sample (Figure 5) are in fact real halo substructures. To examine this question, we compare in Figure 7 the values of $|V_{gsl}|$ and distance from the Sun of the groups in the RRLS sample with the distributions of these quantities among the fake groups produced by the simulations. The lines in the diagrams in Figure 7 indicate the values of $|V_{gsl}|$ and distance corresponding to the 5th, 10th, 25th, 75th, 90th, and 95th percentiles of the distribution of fake groups in the 10,000 simulations as a function of the group size $N_{\text{members}}$. Any group whose velocity or distance is far from the mean values of these quantities in fake groups of the same $N_{\text{members}}$ is likely real and will be flagged as significant. The group of RRLSs with 113 members is not plotted because none of the fake groups was so populated.

To illustrate the usefulness of Figure 7, consider the group of RRLSs plotted as blue upside-down triangles. It has only five
Figure 7. For each group of RR Lyrae stars (colored symbols), we show the absolute value of the mean radial velocity (top) and mean heliocentric distance (bottom) as a function of the number of members in each group. The color and type of the symbol for the RRLS groups are the same as the ones used in Figure 5. The lines represent the 5th and 95th percentiles (solid red lines), 10th and 90th percentiles (dashed blue lines), and 25th and 75th percentiles (dotted black lines) of the distribution of those parameters in the fake groups found in our simulations. Only the 95th, 90th, and 75th are shown for the top panel. Some groups of RRLSs are located well above the 95th percentile line in velocity and distance, indicating very few random groups are formed with those parameters.

members, and groups of that size are frequently produced in the simulations (Figure 6). But the mean $|V_{gsr}|$ of this group is 184 km s$^{-1}$, and comparable values are very rarely seen in five-member groups in the simulations (the upper 95th percentile is $\sim$130 km s$^{-1}$) because this value is in the tail of the velocity distribution of halo stars. This strongly suggests that this group of five RRLSs is part of a real halo substructure.

In Table 5, we identify as groups of high significance the ones that have either more than 14 members or values of $|V_{gsr}|$ and distance that lie outside the regions in Figure 7 enclosed by the solid lines (5th and 95th percentiles). Groups of lower significance are identified if they fall outside the regions enclosed by the dashed lines in Figure 7 (10th and 90th percentiles). The parameters that caused a group to be identified as significant are printed in boldface. RRLSs that are members of significant groups are identified by their group number in the last column of Table 4.

### 4.2.1. Relation with Spatial Overdensities

In Figure 8 we show the significant groups of RRLSs plotted over the spatial density of RRLSs in the LSQ survey (modified from Zinn et al. 2014), on a scale where darker gray indicates higher density. It is clear that the two most numerous groups of RRLSs selected by our friends-of-friends algorithm agree quite well with the location of the largest densities of RRLSs. The added information from radial velocity measurements reveals smaller groups that are not obvious in the spatial distribution. Some of the less significant spatial overdensities (lighter levels of gray in Figure 8) may be nothing more than random fluctuations in density because we did not find significant

| Group | $(V_{gsr})$ (km s$^{-1}$) | $d$ (kpc) | $N_{members}$ | Symbol/color |
|-------|--------------------------|-----------|---------------|---------------|
| 1     | $-41.3$                  | $44.7$    | $113$         | triangles/red |
| 2     | $135.2$                  | $18.9$    | $18$          | circles/green |
| 3     | $-84.8$                  | $10.4$    | $7$           | squares/orange|
| 4     | $184.2$                  | $12.4$    | $5$           | upside-down triangles/blue |
| 5     | $109.4$                  | $47.4$    | $3$           | diamonds/green|
| 6     | $-30.7$                  | $56.4$    | $3$           | asterisks/blue |

Note: Bold values indicate they triggered the flag of significant group.
5. **DISSENTANGLING THE SUBSTRUCTURES IN THE VOD REGION**

In order to understand better the extent and location of the significant groups of RRLSs, we have plotted their location in the sky in the distance–velocity diagram and their distance and velocity versus R.A. in Figure 10. These diagrams also display the expected Sgr debris in this part of the sky from the models of Law & Majewski (2010). We discuss the properties of the VOD and Sgr groups below. The different views help to disentangle the different structures, several of which lie along the same line of sight.

### 5.1. The VOD

In the distance range of the VOD, the largest group of RRLSs in our study has 18 members (group 2, green circles in Figure 10). This group is highly significant. It not only has a large number of members, but its large mean radial velocity is also hard to reproduce in our simulations. It also has a compact size compared to the fake groups formed in the simulations. The mean separation of the stars from the center of the group is 2.11 kpc, and less than 10% of all fake groups with 18 members have mean separations equal to or less than that value. Its velocity and distance clearly correspond to the VSS (Duffau et al. 2006, 2014; Newberg et al. 2007). With our new implementation of the 4d and our extended sample, this group now has twice the number of RRLS members of Duffau et al. (2014). Stars in this group strongly concentrate around 19 kpc, although there are stars between 16 and 21.3 kpc. The mean velocity is 135.2 km s\(^{-1}\) with a standard deviation of 28.1 km s\(^{-1}\). After subtracting in quadrature the mean observational error of the stars in this group (17.5 km s\(^{-1}\)), we obtain a true dispersion of 22 km s\(^{-1}\). Panels (b) and (c) in Figure 10 show that there is no gradient in either distance or in velocity as a function of R.A. There is a trend of decreasing velocity with increasing distance (panel (a)). Among the three groups in the VOD distance range, this is not only the most numerous group but also the most extended one in the sky, covering 178\(^\circ\) < \(\alpha\) < 194\(^\circ\) and \(-8^\circ.4 < \delta < 6^\circ.1\) (panel (d)). This region includes the two fields in which Newberg et al. (2007) observed the velocities of F-type main-sequence stars. The most prominent peak in their velocity distribution was at 130 ± 10 km s\(^{-1}\), which coincides with what we find here for group 2, and there is also reasonable agreement in distance from the Sun as well. The red giant group 175 in Janesh et al. (2016) (see above), other red giants measured by Casey et al. (2012), some main-sequence stars observed by Brink et al. (2010), and a few BHB stars (Duffau et al. 2014) are also likely members of the VSS. There is little doubt that the VSS is a diffuse cloud-like halo overdensity.

Along the same line of sight of the VSS, we find four other groups that have distances in the range of the VOD. They cover large areas of the sky, although not as large as the VSS. The group at 12 kpc (group 4) is a combination of groups H and F already reported in Duffau et al. (2014). No new member was found here, and, indeed, not all members in Duffau et al.
were picked here due to our stricter criteria in the separation between stars forming a pair at short distances. Group 4 seems to be confined to $-4^\circ < \delta < 0^\circ$, and it was flagged as significant because its velocity is very high. Group 293 in Janesh et al. (2016) overlaps in distance and velocity with this group of RRLSs, but its stars are clumped around $d = 10.6$. Groups 2 and 4 lie in approximately the same region of the sky, and in the velocity–distance diagram, group 4 appears to be an extension of group 2 to higher $V_{\text{gsr}}$ and shorter distance. Their separate identities could be simply a consequence of our strict criteria on group membership. Conversely, they could truly separate and originate in separate accretion events, or they might be different wraps of the stellar streams from one event. These groups actually remain separated even if we increase the criteria to $N = 2.3\sigma$. Measurements of the proper motions of the RRLSs are required to sort this out.

Low-significance group 9 lies at approximately the same distance as group 4. Because group 9 has a significantly lower velocity, it was not linked to group 4. While more similar to group 2 in velocity, group 9 is much in the foreground of that group.

Two other groups along the same line of sight, groups 3 and 8, have negative velocities but quite different distances, 10.4 and 17.0 kpc, respectively. A number of other studies of the VOD have detected negative velocity peaks (Newberg et al. 2007; Brink et al. 2010; Carlin et al. 2012; Casey et al. 2012), which overlap with the velocities of these groups of RRLSs. Given the large distance uncertainties inherent in the main-sequence stars and red giants observed in these other studies, it is not clear that these observations relate to Sgr debris at $\sim 40$ kpc, as suggested by these authors, or are a mixture Sgr debris and the same structures as RRLS groups 3 and 8.

As shown in Figure 10, group 3 and another group of RRLSs with negative velocity, group 9, overlap in distance and velocity with a weakly populated feature of the Law & Majewski (2010) model of the Sgr streams, which is due to its trailing tail. Again, proper-motion data are needed to test the reality of the RRLS groups and this possible association.

5.2. Sgr Debris

Three high-significance groups of RRLSs are located at distances larger than 40 kpc. In the background of Figure 10,
we show the location of Sgr debris in this region of the sky from the models of Law & Majewski (2010). Following the same color scheme in that paper, we used magenta dots to mark particles that became gravitationally unbound in recent passages of Sgr, while cyan dots indicate particles stripped off in older passages. The magenta dots are the ones that match observations from 2MASS and SDSS (Law & Majewski 2010). Our numerous group 1 RRLSs (red triangles) closely follow the debris indicated by the magenta dots. The agreement in the sky (panel (d)) and in velocity (a) is remarkably good. There seems to be a systematic offset of \( \sim 5 \) kpc in heliocentric distance (see panel (b)), with the model being farther away than our group. This discrepancy, which was also noticed by Zinn et al. (2014), may be due to differences in the adopted distance scale between the model and our data. A similar discrepancy was recently observed using numerous main-sequence stars in the Next Generation Virgo Cluster Survey (Lokhorst et al. 2016). Nonetheless, our RRLS group displays the same gradients in distance and velocity as a function of R.A. as the models. In position, distance, and velocity, group 1 agrees well with the observations by Yanny et al. (2009) of BHB and M giants in the Sgr stream. The velocities of the group 1 stars also overlap with the major peaks in the velocities of the main-sequence stars observed by Brink et al. (2010) and the red giant stars observed by Casey et al. (2012) in relatively small fields in the VOD. Both papers identified the velocity peaks with the Sgr stream.

Two other groups in Table 5, which have only three members each, were judged significant because they are very distant. The most distant group (group 6, blue asterisks) has a mean distance of 56 kpc and a velocity similar to that of the main Sgr group. It is, however, located west of this group (see panels (b) and (c)). At its location (\( \alpha \sim 182^\circ \)), the most recent wrap of Sgr debris, according to the model of Law & Majewski (2010), is expected to have a very low density and be closer than this group of RRLSs by \( \sim 15 \) kpc without any correction for a difference in the distance scale and \( \sim 20 \) kpc with correction. A better match is obtained with the predicted debris from the earlier wrap (cyan dots in Figure 10), although a difference of \( \sim 10 \) kpc still exists. Zinn et al. (2014) have concluded from the spatial distribution of the LSQ RRLSs that this wrap may not exist in this area of the sky. On the basis of these factors, we conclude that group 6 is probably not Sgr debris.

The other distant group, group 5 (green diamonds), overlaps in space with group 1, which is undoubtedly Sgr debris, but its velocity is quite different. While groups of such small numbers of stars must be viewed with some caution, if groups 5 and 6 are indeed real, they provide additional evidence that the outer halo is laced with accretion debris, as predicted by recent models of galaxy formation (e.g., Cooper et al. 2015; Pillepich et al. 2015).

A more complete discussion on the Sgr stream as seen by its RRLSs in a more extended sample is deferred to a future publication.

5.3. Virgo Z and Related Overdensities

At \((\alpha, \delta) = (185^\circ 077, -1^\circ 35)\), there is a candidate dwarf galaxy identified by Walsh et al. (2009) in the footprint of SDSS and located at \( \sim 40 \) kpc from the Sun. The existence of this galaxy has been challenged by Barbuy et al. (2013), who claim that there is a distant cluster of galaxies at that position of the sky that may have been confused for a stellar overdensity in the shallower SDSS data. However, Jerjen et al. (2013) built deep CMDs in this location and in a neighbor one, at \((\alpha, \delta) = (191^\circ 992, -0^\circ 75)\), and concluded that both fields indeed contain a population of stars, not at 40 kpc but at 23 kpc. The fact that the main sequence observed in both fields is similar makes the authors believe that they were detecting not a dwarf galaxy but an extended structure likely related to the VOD. They also ruled out the presence of a significant stellar population at 19 kpc, where the VSS RRLSs are concentrated. This nondetection of a main sequence at the distance of the VSS by Jerjen et al. (2013) may be due to the low surface brightness of the feature and the small areas of the fields observed by Jerjen et al. (2013). Note that the main sequence of the VSS is well documented by the studies of Newberg et al. (2002) and Newberg et al. (2007) in other fields.

Zinn et al. (2014) identified four RRLSs in the LSQ survey that are located within \( 1^\circ \) of the alleged position of Virgo Z, but at distances more compatible with the main sequence observed by Jerjen et al. (2013). Those four stars are included in our spectroscopic sample (LSQ 515, LSQ 525, LSQ 532, and LSQ 550), and we can investigate any possible association among them. Table 6 contains the distance and radial velocities obtained for these stars.

Examining Table 6, it is clear that star LSQ 525 has a velocity significantly different from the others. However, none of the other three stars paired with each other using \( 4d < 20 \) kpc, weakening the hypothesis that they were part of a stellar system in the region, and none of these stars is a member of the significant kinematical group identified in this work (Table 5). Each of the three stars with negative velocities belong to separate groups among the several detected in our sample at those distances (Figure 5). But none of those groups was flagged as significant after considering our halo simulations.

We note, however, that star LSQ 532 is a member of the group with \( (V_{\text{gsr}}) = -24 \) km s\(^{-1}\), \( (d) = 24 \) kpc (eight members, dark green pentagons in Figure 5). The group extends in R.A. between \( 177^\circ \) and \( 194^\circ \), and consequently it overlaps with both detections of Jerjen et al. (2013). This group could be the horizontal branch counterpart to the main-sequence detection of Jerjen et al. (2013), even though it did not pass our significance criteria. The measurement of the radial velocities of the main-sequence stars is needed to test this possibility.

It is also possible that the main stellar population of the structures is too young to produce RRLSs, and there is an indication that this may indeed be the case since Jerjen et al. (2013) estimated an age of 8.2 Gyr and an [Fe/H] \( \sim -0.7 \) for the main sequence they detected. Few, if any, RRLSs are likely to be produced by a stellar population of these attributes (e.g., Bono et al. 2016). Some could still be present if there is a minority population of older and more metal-poor stars.

| ID     | Distance (kpc) | \( V_{\text{gsr}} \) (km s\(^{-1}\)) |
|--------|---------------|-------------------------------------|
| LSQ 515 | 20.2          | -93 ± 18                            |
| LSQ 525 | 26.0          | 238 ± 19                            |
| LSQ 532 | 26.4          | -23 ± 20                            |
| LSQ 550 | 26.8          | -65 ± 37                            |
We have used 3D maps in combination with radial velocities to identify and disentangle multiple substructures present in the galactic halo in the line of sight of the VOD. Several different kinematical groups were identified in the sample of more than 400 RRLs covering the distance range from 4 to 75 kpc and more than 500 sq. deg. of the sky. The technique used to identify groups is based on the proximity of stars in both location in the sky and velocity, as well as on extensive simulations of halo stars that allowed us to detect cases that are unlikely to be due to random grouping. We have applied the technique to a region of the sky with a known and extensive location in the sky and velocity, as well as on extensive overdensities. The new large-scale spectroscopic surveys such as Gaia, RAVE, and APOGEE will provide interesting samples of stars to examine for substructures in different parts of the sky.

The two most significant features in our sample of RRLs in the VOD region are the debris from the Sgr dSph galaxy and the VSS, in agreement with previous studies (Duffau et al. 2006; Newberg et al. 2007; Prior et al. 2009; Brink et al. 2010; Carlin et al. 2012; Casey et al. 2012; Duffau et al. 2014; Zinn et al. 2014; Janesh et al. 2016) that used RRLs, main-sequence stars, and red giants as probes. The precise distance determinations afforded by RRLs have allowed us to identify some other potentially interesting groups of RRLs at both small and large distances, which less precise distance indicators would have blended together with the Sgr debris or the VSS. Some of these groups lie in the distance range estimated for the VOD, which suggests that it may be a composite of several different structures, as discussed previously by several authors (e.g., Newberg et al. 2007; Vivas et al. 2008; Duffau et al. 2014). At large distances, there are a few sparsely populated groups of RRLs, which, if they are real halo substructures, suggest that the outer halo is littered with debris from accretion events.

Although this work has expanded the area of spectroscopic study of the VOD significantly, we still cannot answer the basic questions of what is the origin of this feature and what is its relationship (if any) with other similar cloud-like features found in the halo at similar heliocentric distances. The new generation of spectroscopic and astrometric surveys may answer these questions in the near future.

This research was conducted as part of the Cerro Tololo Inter-American Observatory REU Program, which is supported by the National Science Foundation under grant AST-1062976 respectively. R.Z. acknowledges support from NSF grant AST-1108948. Support for S.D. is provided by the Ministry of Economy, Development, and Tourism’s Millennium Science Initiative through grant IC12009, awarded to The Millennium Institute of Astrophysics, MAS. This research is based in part on observations obtained at the Southern Astrophysical Research (SOAR) telescope, which is a joint project of the Ministério da Cincia, Tecnologia, e Inovao (MCTI) da República Federativa do Brasil, the US National Optical Astronomy Observatory (NOAO), the University of North Carolina at Chapel Hill (UNC), and Michigan State University (MSU). It is also partly based on observations at Kitt Peak National Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation. Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the participating institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III website is http://www.sdss3.org/. SDSS-III is managed by the Astrophysical Research Consortium for the participating institutions of the SDSS-III Collaboration, including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, Carnegie Mellon University, the University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofisica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, the Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University. We thank the anonymous referee for useful comments.

Facilities: WIYN (Hydra), SOAR.
Software: IRAF, Topcat.

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