SPECTROSCOPIC CONFIRMATION OF THE PISCES OVERDENSITY[*]

JUNA A. KOLLMEIER[1], ANDREW GOULD[2], STEPHEN SHECTMAN[1], IAN B. THOMPSON[1], GEORGE W. PRESTON[1], JOSHUA D. SIMON[1],
JEFFREY D. CRANE[1], ŽELJKO IVEZIĆ[3], AND BRANIMIR SESAR[3]

[1] Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101, USA
[2] Department of Astronomy, The Ohio State University, 4051 McPherson Laboratory, Columbus, OH 43210, USA
[3] Department of Astronomy, University of Washington, P.O. Box 351580, Seattle, WA 98195-1580, USA
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ABSTRACT

We present spectroscopic confirmation of the "Pisces Overdensity," also known as "Structure J," a photometric overdensity of RR Lyrae stars discovered by the Sloan Digital Sky Survey at an estimated photometric distance of ~ 85 kpc. We measure radial velocities for eight RR Lyrae stars within Pisces. We find that five of the eight stars have heliocentric radial velocities within a narrow range of -87 km s^{-1} $< v_r <$ -67 km s^{-1}, suggesting that the photometric overdensity is mainly due to a physically associated system, probably a dwarf galaxy or a disrupted galaxy. Two of the remaining three stars differ from one another by only 9 km s^{-1}, but it would be premature to identify them as a second system.

Key words: galaxies: dwarf – Galaxy: halo – Galaxy: structure – stars: individual (RR Lyrae)

1. INTRODUCTION

In the currently favored picture of galactic structure formation, the Milky Way had a tumultuous early history. Continuously bombarded from an early age by other galaxies big and small, the Milky Way has been roiled by mergers—a picture first put forth by Searle & Zinn (1978). The fossil record of the Milky Way's history can be seen today in the debris left over from this cosmic carnage—the stellar streams that appear to be the shredded remains of galaxies past. The Sloan Digital Sky Survey (SDSS) has had a major impact in breaking open this field. A variety of photometric techniques have been developed to search through the large photometric database of the SDSS to uncover these systems (e.g., Newberg et al. 2002; Willman et al. 2005; Belokurov et al. 2006; Grillmair & Dionatos 2006). The primary search algorithms rely on a combination of correlations in position on the sky and position in the color–magnitude diagram (CMD). To date, a significant number of such structures have been located. However, the census of structures is still very far from complete, particularly at large Galactocentric distances. The key issue is sensitivity: at very low intrinsic luminosities these objects can only be disentangled from foreground stars interior to ~ 50 kpc and SDSS star counts are only sensitive to surface brightnesses above ~ 30 mag arcsec^{-2}. An interesting technique, first recognized by Kinman & Wirtanen (1963), to push the limits of finding substructure within the Milky Way is to make use of the photometric variability of RR Lyrae stars (e.g., Vivas et al. 2005; Duffau et al. 2006; Prior et al. 2009; Morrison et al. 2009).

The repeated scans of SDSS Stripe-82 have allowed the discovery of Milky Way substructures via their populations of RR Lyrae stars, which are standard candles, can be seen to large distances, and show distinctive light curves. The structure discussed in this Letter was first identified as an overdensity of RR Lyrae stars by Sesar et al. (2007) as part of a larger study of all RR Lyrae stars in Stripe-82. They termed this overdensity "Structure J," one among several such structures located. In a subsequent work, Watkins et al. (2009) independently found

what appears to be the same structure, which they termed the "Pisces Overdensity." The photometric identification of these overdensities is a crucial first step in locating more streams and galaxies interior to the virial radius of the Milky Way. However, photometry provides two phase-space dimensions very accurately (angular position) and a third only very crudely (distance). In order to show definitively whether photometric overdensities are, in fact, truly part of a common structure as opposed to a chance concentration, it is necessary to obtain data for additional phase-space dimension(s), which could in principle be either radial velocities or proper motions (e.g., Simon & Geha 2007). In this Letter, we report on the first results of a campaign to confirm distant structures in the Milky Way halo as defined by RR Lyrae and giant stars.

2. OBSERVATIONS

2.1. Target Selection

In Figure 1, we show all of the identified RR Lyrae stars in the apparent magnitude range $19.9 \leqslant V_0 \leqslant 20.8$ that lie in SDSS Stripe-82, which covers a $3° \times 118°$ stripe along the celestial equator. The positions and V_0 magnitudes of these objects come from the latest Stripe-82 RR Lyrae catalog (Sesar et al. 2009). There is a very clear overdensity in the R.A. interval $335°$–$360°$. With only about 30% of the stripe area, this subregion contains 24 of the 31 RR Lyrae stars (77%). For our first campaign, we focused on the concentration located at R.A. $\sim 355°$ and selected eight objects near this overdensity based on their close two-dimensional proximity and their similar median magnitudes.

2.2. Light Curve Analysis

Obtaining a single-epoch spectrum for an RR Lyrae star yields only a velocity of the stellar photosphere, which for these pulsating variables can deviate from the systemic velocity by several tens of km s^{-1}. However, the dense temporal sampling of Stripe-82 enables us to obtain accurate ephemerides by phase folding the ~ 70 epochs in the SDSS photometric archive. We can then correct velocity measurements made at known phase to the barycentric velocities for these stars (Joy 1938). We extracted the light curves from the SDSS archive and determined their
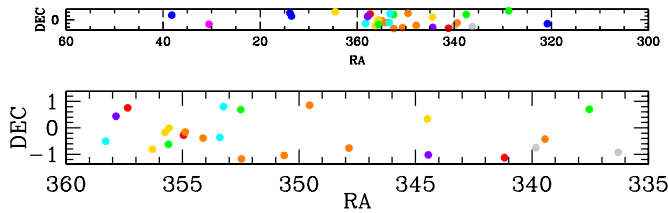

Figure 1. RR Lyrae stars in Stripe-82. Top panel: positions of RR Lyrae stars with magnitudes $19.9 < V_0 < 20.8$ in the SDSS Stripe-82, color coded in 0.1 mag intervals, brightest to faintest: gray, red, orange, yellow, green, cyan, blue, magenta, purple. Note the extreme concentration at R.A. $335°$–$360°$. Bottom panel: zoom of Panel A in the region of the concentration.

periods based on a variant of the "Phase Dispersion Minimization" technique (Stellingwerf 1978). We first identified potential bad data points by performing a regression on g versus r flux, and flagging 2.5σ outliers (as determined from the scatter—not the formal errors). While the colors of RR Lyrae stars change during their pulsation cycle, the 2.5σ criterion allows an adequate range for normal color variation. We then removed near-achromatic points that were substantially fainter than the remaining points, which are probably due to some joint photometric anomaly, but in any case would not fit any RR Lyrae-like light curve. Finally, we varied the period and minimized the sum of the squares of the photometric differences between successive points. Our derived g-band light curves for our eight target objects are shown in Figure 2. In all but one case, periods derived from the g-band data were nearly identical to periods derived from the r-band data. Based on these differences, we estimate the period error to be $\sigma(P) = 3 \times 10^{-6}$ day. The light curve for object 5 is noisier than the others. Examination of the underlying images reveals that it is sitting on a faint background galaxy, which is probably the explanation. In principle, it is possible that the "noise" actually signals that this is an RRd star with two periods. However, a search for additional periods failed to reveal any. We therefore treat this as a normal RRab star.

Our derived periods are surprisingly similar, with a dispersion of only 0.026 days. The objects are all RRab type variables and with median brightnesses of about $g \sim 20.5$ these stars are at a distance of about 85 kpc, assuming an absolute magnitude $M_V = 0.6$ for RR Lyrae stars (the g-band extinction values for our target stars are small, ranging from 0.09 to 0.15 mag as determined from the Schlegel et al. 1998 extinction map). We have estimated metallicities from the periods and amplitudes of the eight stars using Equation (6) of Sandage (2004), assuming that the V-band amplitude is equal to 42% of the g-band amplitude plus 58% of the r-band amplitude. The metallicities range from [Fe/H] ~ -1.3 to -1.9. We have additionally measured the metallicity using the technique described in Gratton et al. (2004). We find a range of [Fe/H] ~ -1.2 to -1.85, in excellent agreement ($\langle([Fe/H]_G - [Fe/H]_S)^2\rangle^{1/2} = 0.13$) with the estimates from the Sandage (2004) method. While these estimates are necessarily crude, we can conclude that all of the eight stars are relatively metal-poor.

2.3. Spectroscopic Observations

The spectroscopic observations were obtained using the Magellan Echellette Spectrograph (MagE[4]; Marshall et al. 2008) mounted on the 6.5 m Clay Telescope at Las Campanas Observatory. In all cases, two equal-length exposures bracketed

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[4]   http://www.lco.cl/telescopes-information/magellan/instruments/mage/
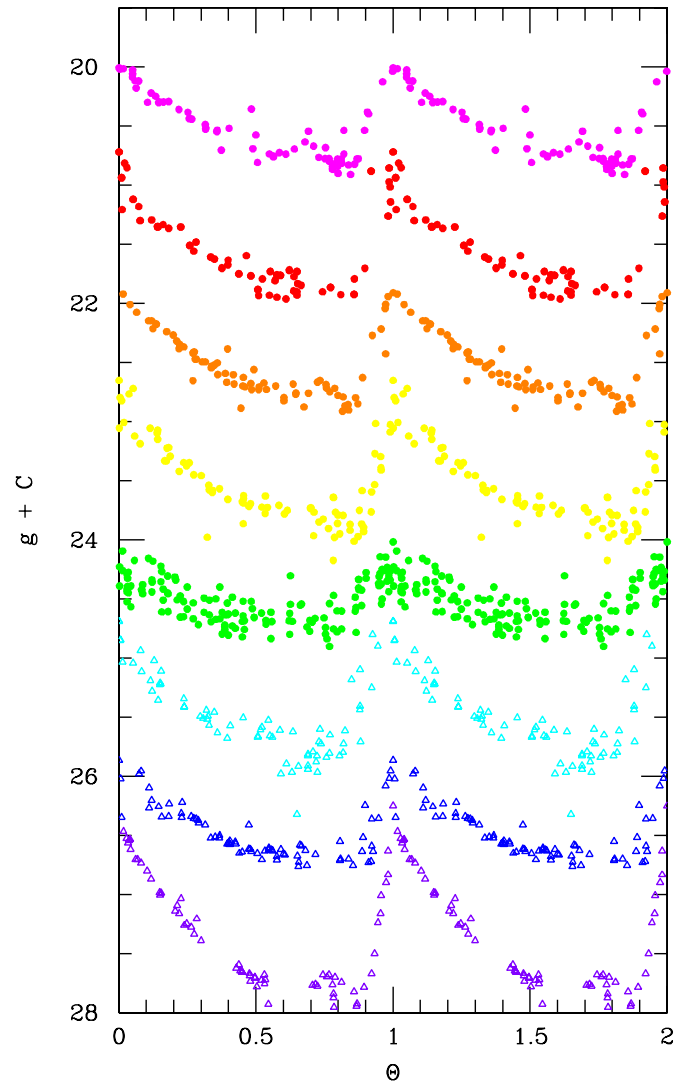

Figure 2. Light curves for targeted RR Lyrae stars in Stripe-82. Light curves are ordered as they appear in Table 1. The top five are part of the common-velocity structure near -75 km s^{-1}.

an observation of a ThAr lamp. The data were reduced using a pipeline written by D. Kelson following Kelson (2003). Post-extraction processing of the spectra was done with the IRAF[5] ECHELLE package. A $1''$ slit was used, resulting in a resolution of ~ 4100, and the signal-to-noise ratio of the final spectra ranged from 7 to 16 per 0.36 Å pixel at 4700 Å. Exposure times varied from 3600 s to 4000 s depending on the observing conditions. Velocities were measured with the IRAF FXCOR routine using a MagE observation of the blue metal-poor star CS22874-009 ($V_{helio} = -36.6$ km s^{-1}; Preston & Sneden 2000) as the template. The cross correlations were made on the wavelength interval 4000–5600 Å with the hydrogen lines masked out.

We adopt the time-averaged velocity of the pulsation curve as the center-of-mass velocity of the star. Integration of detailed velocity curves of the RRab variables WY Ant, XZ Aps, DT Hya, and RV Oct (G. W. Preston 2009, in preparation) shows that the pulsation velocity is equal to the star's time-average velocity at phase 0.37, reckoned relative to maximum

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[5]   IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
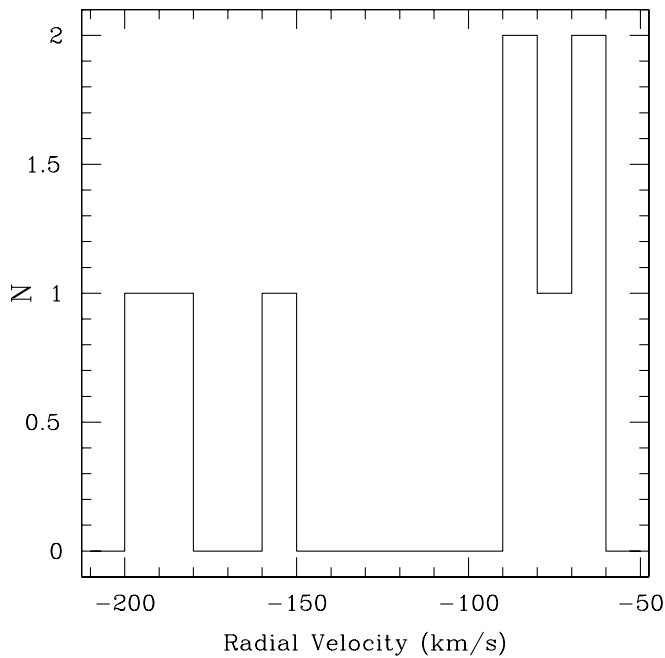
Figure 3. Histogram of heliocentric radial velocities for eight RR Lyrae stars in the Pisces Overdensity. The concentration at -75 km s^{-1} is obvious. The clump at ~ -190 km s^{-1} is also of note.

Figure 4. RR Lyrae targets for this program. Green and blue symbols correspond to median magnitude ranges of $20.5 \leqslant g_{med} < 20.6$ and $20.6 \leqslant g_{med} < 20.7$, respectively. Star symbols correspond to targets with velocity greater than -90 km s^{-1} and triangles are all other targets for which we have obtained a radial velocity.

light. This is very similar to the value obtained by Liu (1991) in which synthetic velocity curves are derived from a larger sample of RRab stars. Our observations were all made as close to this phase as possible, and velocity corrections were applied adopting $k = 92.7$ km s^{-1} per unit phase for the mean slope of the pulsation velocity curve at phase 0.37 for these four stars.

A journal of the observations is presented in Table 1. Columns 1 and 2 list the R.A. and decl. of the star followed by the number of photometric data points in the light curve, the median g-band magnitude, the adopted pulsation period, the heliocentric Julian date at maximum light (zero phase), the heliocentric Julian date at mid-observation, the observed heliocentric velocity and the error as estimated from the FXCOR measurement, the pulsation phase at mid-observation, the velocity correction, the final adopted heliocentric velocity, and the metallicities as determined from Gratton et al. (2004) and Sandage (2004), respectively.

3. RESULTS

We were able to obtain accurate radial velocity measurements for eight RR Lyrae stars associated within the apparent Pisces Overdensity. We show in Figure 3 a histogram of the heliocentric radial velocities measured for our targets. There is a clear velocity peak, containing five of the eight objects, at approximately -75 km s^{-1}. The other three stars also have an interesting velocity distribution to which we return later. Figure 4 shows our targets coded by velocity and magnitude. The spatial concentration at (R.A., decl.) $\sim (355^\circ, -0°3)$, $(l, b) \sim (88^\circ, -58^\circ)$, is suggestive of a coherent structure. However, our radial velocity measurements reveal a more nuanced picture. The three central stars (marked as triangles in the figure) within this concentration have measured radial velocities[6]
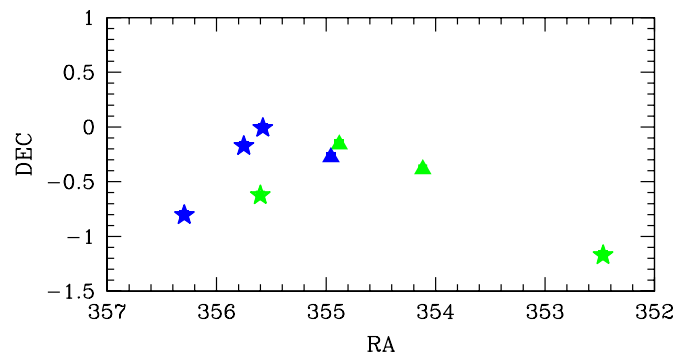
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[6] The single object with differing g-band and r-band period has a barycentric velocity of -197.7 km s^{-1} if the g-band period is adopted and -182.7 km s^{-1} if the r-band period is adopted.

-198 km s^{-1} $< v_r < -155$ km s^{-1}. Four stars in the central concentration and a fifth further away, however, have radial velocities that lie within the main velocity peak. We therefore seem to have two co-spatial velocity structures, one robustly identified in phase space and one that is suggestive but too sparsely sampled at present to warrant detailed analysis. While few data exist at these distances in the stellar halo, a Besançon model (Robin et al. 2003) of the heliocentric velocity distribution at this position in the sky suggests that the expected velocity distribution of the smooth stellar halo is centered at ~ -120 km s^{-1} with a dispersion of ~ 90 km s^{-1}. In Section 4, we focus exclusively on the main velocity peak.

4. DISCUSSION

4.1. Is the Velocity Group Physically Associated?

In order to determine the random chance that a grouping of five out of eight stars could have velocities within 20 km s^{-1} of one another, we performed a Monte Carlo test by random samplings from a Gaussian distribution with a dispersion of 90 km s^{-1}. We find this probability to be less than 0.6%. This is a fair test (and not an a posteriori justification of a curious velocity structure found serendipitously) because this corresponds to exactly the velocity signature we were looking for when we undertook the observations. The group is therefore physically associated at high confidence in a fully Bayesian sense. The fact that the stars all have very similar magnitudes qualitatively strengthens the case for physical association. However, this cannot be placed on a quantitative basis because the initial target selection was done by position and magnitude.

4.2. Bound or Unbound?

When looking at the spatial and kinematic information, the first question one must ask is whether these stars are part of a bound or unbound system, i.e., is this an intruding galaxy, or the extended debris of a galaxy/star cluster? While information on more stars (e.g., giants and horizontal branch stars), would be important to address this question fully, some simple estimates are useful in providing guidance.

If the system is assumed to be bound, we can estimate the mass using a virial estimator (e.g., Heisler et al. 1985; Gould 1993)

$$M_{VT} = \frac{3\pi}{2G} \frac{\sigma^2}{\langle 1/R_{\perp,ij} \rangle_{i \neq j}}, \qquad (1)$$

Table 1
RR Lyrae Targets

R.A.	Decl.	N	g_{med}	P_g	HJD$_{\Theta,0}$[a]	HJD[a]	$v_{r,obs}$	Θ_{obs}	Δv	$v_{r,bar}$	[Fe/H]$_G$	[Fe/H]$_S$
352.46991	−1.17125	65	20.545	0.5973118	3352.5903	5043.8323	−62.8	0.422	−4.8	−67.6	−1.25	−1.2
356.29469	−0.80489	84	20.655	0.5955986	4008.7571	5042.9037	−73.0	0.315	5.1	−67.9	−1.85	−1.5
355.75079	−0.17316	74	20.603	0.5938712	3270.7662	5012.8432	−65.1	0.425	−5.1	−70.2	−1.30	−1.3
355.57762	−0.00838	80	20.628	0.5949283	2911.7877	5013.9018	−81.9	0.388	−1.7	−83.6	−1.55	−1.6
355.60088	−0.62351	142	20.524	0.6314823	3635.7693	5044.8612	−83.5	0.404	−3.2	−86.7	−1.50	−1.4
354.11676	−0.38425	70	20.569	0.6016641	4418.7158	5042.8593	−156.2	0.362	0.7	−155.5	−1.82	−1.9
354.87899	−0.15772	74	20.569	0.5902998	3668.7372	5014.8779	−191.6	0.436	−6.1	−197.7	−1.23	−1.2
354.95545	−0.27631	66	20.607	0.5310617	3996.7940	5012.8932	−191.7	0.335	3.2	−188.5	−1.56	−1.6

Note. [a] HJD-2450000.

where σ is the velocity dispersion of the system and $R_{\perp,ij}$ is the projected distance between each of the two stars. In order to measure the velocity dispersion, we must account for the errors in our velocities. There are two main (identifiable) sources of velocity error. The primary one is the error due to the signal-to-noise ratio, which is reported in Table 1. A secondary source of uncertainty comes from our imprecise knowledge of the zero phase point due to the finite sampling of the Stripe-82 data. This error is $k/(\sqrt{2}N) = 65$ km s$^{-1}/N$, where N is the number of data points in each light curve. For our data, this has a maximum value of 1 km s^{-1} and therefore does not affect our dispersions significantly. The phase errors induced by the period errors are similar.

Assuming all five stars in the main velocity structure are part of the same physical structure, we obtain a velocity dispersion of $6.8^{+3.9}_{-2.6}$ km s^{-1} which yields a mass of $1.4^{+1.7}_{-0.7} \times 10^8$ $M_\odot$. A more conservative possibility is that only the "clump" of four stars near (R.A.,decl.) = $(356°, 0°.3)$ is part of a bound structure, from which the star at $\sim 352°$ either has been tidally stripped or perhaps was not originally associated with the main structure. In this case, Equation (1) yields $8.5^{+14.3}_{-5.4} \times 10^7$ $M_\odot$, whose 1σ range is not far from the typical value of 1×10^7 $M_\odot$ for the mass interior to 300 pc found by Strigari et al. (2008) for dwarfs with a wide range of luminosities. Moreover, the apparent $0°.5$ radius of the concentration corresponds to about 750 pc, rather than 300 pc, and this difference could account for the level of discrepancy in mass. Hence, this structure is possibly virialized, and if so represents a new satellite of the Milky Way. We note that our estimate is significantly larger than the lower limit of $M > 10^4$ $M_\odot$ quoted by Watkins et al. (2009). We also note that the structure could not be bound, or have been nearly bound in the recent past, unless it were substantially more massive than the Watkins et al. (2009) limit. Given the small number of confirmed stars and the large physical size, however, we cannot at this point rule out the possibility that it is being (or has been) tidally disrupted.

If the apparent structure is physical (and not a chance superposition) then whether it is bound or not, the presence of four RR Lyrae stars within a ~ 0.5 deg^2 rectangle implies that there must be a concentration of other stars within the system. If enough giant stars are associated with the RR Lyrae star overdensity, then this could potentially be probed with existing photometry. We do not know how many giants are associated with the system but we can obtain a lower limit from the fuel consumption theorem, which then provides a framework for comparing the surface brightness of this system to that of other known systems. By the fuel consumption theorem, S_{RR}, the RR Lyrae specific frequency (the number per V-band luminosity, normalized to $M_{V,norm} = -7.5$; Suntzeff et al. 1991) can be cast

in terms of the fraction of He burning that takes place within RR Lyrae stars, η_{RR}:

$$S_{RR} = \frac{m_{He} - m_C/3}{4m_H - m_{He}} \frac{\eta_{RR}}{1 - \eta_{He}} 10^{0.4\Delta M_{bol}} = 360\eta_{RR}, \quad (2)$$

where m_X is the atomic mass of X, $\eta_{He} \sim 25\%$ is the initial abundance of He, $\Delta M_{bol} = M_{V,RR} - M_{V,norm} + \Delta BC$, $M_{V,RR} = 0.6$, and $\Delta BC = 0.45$ is the difference in bolometric corrections between RR Lyrae stars and typical giant stars. The highest observed value is $S_{RR} = 158$ for Palomar 13 (Siegel et al. 2001), i.e., $\eta_{RR} = 0.44$. The surface brightness of the Pisces concentration may be expressed as $\mu_V = (34.0 + 2.5 \log \eta_{RR})$ mag arcsec^{-2}, and hence to be "recognizable" as a $\mu_V = 30$ mag arcsec^{-2} overdensity would require $\eta_{RR} < 0.025$ or $S_{RR} < 9$. Such systems do exist (Harris et al. 1996), but they are far from universal. We cannot, therefore, probe whether the Pisces structure is a physical (or chance) association based on the presence (or absence) of an already known photometric counterpart in giants. Deeper imaging data of this region as well as further spectroscopic follow up of giant and horizontal branch stars in this region of the sky are necessary to confront this hypothesis.

4.3. Unbound Case: Galaxy or Globular Cluster?

If the object is an unbound stream, as opposed to a bound system, we must ask whether this represents the disrupted remnant of a globular cluster system or the remnant of a satellite galaxy. Robust characterization of streams and disrupted galaxies, both theoretically and observationally, is a challenge. The predicted phase-space morphology depends on a variety of initial conditions including initial mass, M/L, stellar density profile, and orbit parameters, and the observations are demanding and not always conducive to multiplexing due to the low density of targets. A thin physical extent transverse to the direction of motion on the sky, a uniform stellar CMD, and a narrow velocity dispersion would typically indicate a globular cluster stream as opposed to a galaxy stream. The large width of our structure suggests that if it is disrupting, it is a satellite galaxy as opposed to a globular cluster. The velocity dispersion is comparable to what is observed within the Sagittarius stream (Majewski et al. 2004) or within the Anticenter Stream (Grillmair et al. 2008).

If the Pisces Overdensity is indeed a disrupted satellite, it is interesting that located near the central core of this structure are three stars with similar velocities but offset from the main structure by nearly 100 km s^{-1}. As such large velocity offsets are not plausible simply by disruption effects alone, these stars are either a separate, perhaps bound, structure or they are random interlopers. The latter scenario is of little interest. In the former

scenario it is intriguing, but perhaps not surprising, that we observe two overlapping streams at this position in the halo. More locally, the Sagittarius system is so extensive and has made a sufficiently large number of orbits that many objects have been found overlapping it (e.g., Segue 1) that can only be disentangled using velocity and metallicity information. Farther out in the Galaxy, Bell et al. (2008) have determined that at least 50% of the stellar density is in a clumpy form. Detailed comparison with cosmologically motivated models for the spaghetti-like nature of the halo would be useful in determining whether such self-overlapping systems are rare or commonplace in the Milky Way at these distances.

5. CONCLUSIONS

We present spectroscopic confirmation of the photometric overdensity observed in RR Lyrae stars toward the constellation Pisces. We suggest that this system is a dwarf galaxy—possibly in the process of disruption, possibly already disrupted, or possibly bound with very low surface brightness.

The nature of the stellar halo at distances of ~ 100 kpc is still relatively uncharted territory. Using RR Lyrae stars to explore this regime of phase space is an exciting way forward. Large photometric data sets such as those provided by SDSS in conjunction with experiments to obtain spectra with large ground-based telescopes should yield important insight into the nature of the Milky Way's perhaps troubled, perhaps tranquil past.

REFERENCES

Bell, E. F., et al. 2008, ApJ, 680, 295
Belokurov, V., et al. 2006, ApJ, 642, L137
Duffau, S., Zinn, R., Vivas, A. K., Carraro, G., Méndez, R. A., Winnick, R., & Gallart, C. 2006, ApJ, 636, L97
Gould, A. 1993, ApJ, 403, 37
Gratton, R. G., Bragaglia, A., Clementini, G., Carretta, E., Di Fabrizio, L., Maio, M., & Taribello, E. 2004, A&A, 421, 937
Grillmair, C. J., Carlin, J. L., & Majewski, S. R. 2008, ApJ, 689, L117
Grillmair, C. J., & Dionatos, O. 2006, ApJ, 643, L17
Harris, W. E. 1996, AJ, 112, 1487
Heisler, J., Tremaine, S., & Bahcall, J. N. 1985, ApJ, 298, 8
Joy, A. 1938, PASP, 50, 302
Kelson, D. D. 2003, PASP, 115, 688
Kinman, T. D., & Wirtanen, C. A. 1963, ApJ, 137, 698
Liu, T. 1991, PASP, 103, 205
Majewski, S. R., et al. 2004, AJ, 128, 245
Marshall, J. L., et al. 2008, Proc. SPIE, 7014, 169
Morrison, H. L., et al. 2009, ApJ, 694, 130
Newberg, H. J., et al. 2002, ApJ, 569, 245
Preston, G. W., & Sneden, C. 2000, AJ, 210, 1014
Prior, S. L., Da Costa, G. S., Keller, S. C., & Murphy, S. J. 2009, ApJ, 691, 306
Robin, A. C., Reylé, C., Derrière, S., & Picaud, S. 2003, A&A, 409, 523
Sandage, A. 2004, AJ, 128, 858
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Searle, L., & Zinn, R. 1978, ApJ, 225, 357
Sesar, B., et al. 2007, AJ, 134, 2236
Sesar, B., et al. 2009, ApJ,
Siegel, M. H., Majewski, S. R., Cudworth, K. M., & Takamiya, M. 2001, AJ, 121, 935
Simon, J. D., & Geha, M. 2007, ApJ, 670, 313
Stellingwerf, R. F. 1978, ApJ, 224, 953
Strigari, L. E., Bullock, J. S., Kaplinghat, M., Simon, J. D., Geha, M., Willman, B., & Walker, M. G. 2008, Nature, 454, 1096
Suntzeff, N., Kinman, T. D., & Kraft, R. P. 1991, ApJ, 367, 528
Vivas, A. K., Zinn, R., & Gallart, C. 2005, AJ, 129, 189
Watkins, et al. 2009, MNRAS, 398, 1757
Willman, B., et al. 2005, AJ, 129, 2692