Exploring Halo Substructure with Giant Stars. XV. Discovery of a Connection between the Monoceros Ring and the Triangulum–Andromeda Overdensity?*

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Abstract

Thanks to modern sky surveys, over 20 stellar streams and overdensity structures have been discovered in the halo of the Milky Way. In this paper, we present an analysis of spectroscopic observations of individual stars from one such structure, “A13,” first identified as an overdensity using the M giant catalog from the Two Micron All Sky Survey. Our spectroscopic observations show that stars identified with A13 have a velocity dispersion of \( \lesssim 40 \; \text{km s}^{-1} \), implying that it is a genuine coherent structure rather than a chance superposition of random halo stars. From its position on the sky, distance (\( \sim 15 \) kpc heliocentric), and kinematical properties, A13 is likely to be an extension of another substructure at low Galactic latitude—the Galactic Anticenter Stellar Structure (also known as the Monoceros Ring)—toward smaller Galactic longitude and greater distance. Furthermore, the kinematics of A13 also connect it with another structure in the southern Galactic hemisphere—the Triangulum–Andromeda overdensity. We discuss these three connected structures within the context of a previously proposed scenario in which one or all of these features originate from the disk of the Milky Way.

Key words: galaxies: interactions – Galaxy: disk – Galaxy: formation – Galaxy: halo – Galaxy: structure

1. Introduction

Over the last two decades, large-area digital sky surveys such as the Two Micron All Sky Survey (hereafter 2MASS; Skrutskie et al. 2006) and the Sloan Digital Sky Survey (hereafter SDSS; York et al. 2000) have provided deep and global photometric catalogs of stars in the Milky Way. A variety of substructures in the Galactic halo have been revealed as a result of mapping the Milky Way with these modern surveys using various stellar tracers. The most prominent structures are the tidal tails of the Sagittarius dwarf galaxy (Ibata et al. 1994; Majewski et al. 2003), which provide dramatic evidence that the Milky Way is still being shaped by the infall and merging of neighboring smaller galaxies. These observational results have lent strong support to the hierarchical picture of galaxy formation under the ΛCDM model (Bullock et al. 2001; Johnston et al. 2008; Helmi et al. 2011).

While the discovery of local overdensities in stellar surveys by visual inspection has proven successful, the scale and sophistication of the data provided by current and future sky+ surveys motivate an exploration of methods that can instead objectively and automatically identify structures (Sharma et al. 2011a). Sharma et al. (2011b) developed a density-based hierarchical group-finding algorithm Enlink to identify stellar halo substructures and applied it to a catalog of M giant stars selected from 2MASS (Sharma et al. 2010, hereafter S10). This algorithm uncovered 16 candidate substructures in the Milky Way halo, 6 of which had not been previously identified.

This paper presents the moderate-resolution spectroscopic analysis of stars in one of the substructures reported by S10, namely the A13 candidate. The goal of this study is to determine, using their kinematical and chemical properties, whether the M giants in A13 are genuinely associated with each other—an important test of the performance of the group-finding algorithm for finding substructure in the Milky Way halo using 2MASS photometry.

This work also aims to explore associations between A13 and other known substructures. Its position on the sky—close to the Galactic anticenter with Galactic latitude \( b \sim 30^\circ \)—is suggestive of a possible connection between it and two structures at low Galactic latitude—the Monoceros Ring (Mon) and the Triangulum–Andromeda overdensity (TriAnd).

Mon was first discovered by Newberg et al. (2002) using main-sequence turnoff stars selected from SDSS. Mon appears to be a ring-like structure at low Galactic latitude near the Galactic anticenter. It was independently mapped using
on how these overdensities were formed and may be related to each other by adding position, kinematics, and metallicities for the stars in A13 and allowing a direct comparison between all the structures using a single tracer. The origins of both GASS/Mon and TriAnd are still under debate. While many studies argue that GASS/Mon and TriAnd could be the remnants of past accretion events (see, e.g., Crane et al. 2003; Martin et al. 2004; Peñarrubia et al. 2005; Sollima et al. 2011; Sheffield et al. 2014; Slater et al. 2014), more recent works suggest the possibility that GASS/Mon and TriAnd may be the result of a strong oscillation in the outer disk that throws disk stars to large scale heights (see, e.g., Price-Whelan et al. 2015; Xu et al. 2015). A clear picture of the origins of these stellar structures may also have more general implications for how the Milky Way formed, and particularly for the extent to which the stellar halo has grown from stars accreted from other systems relative to stars formed in our own Galaxy.

This paper is organized as follows. Section 2 describes our sample, the observations, and data reductions. In Section 3, we present the properties of our target stars derived from the spectra, including their kinematics, metallicities, and distances. In Section 4 we present a discussion of the possible connection of A13 to GASS/Mon and TriAnd. Section 5 summarizes the results.

2. Observation and Data Reductions

2.1. Target Selection

The spectroscopic targets for this study were selected from the 2MASS catalog (Skrutskie et al. 2006) with dereddening applied star-by-star using the extinction maps of Schlegel et al. (1998). More detailed selection criteria are provided in S10. We give a brief description here.

M giants begin to separate from M dwarfs in the near-infrared \((J - H, J - K_S)\) color–color diagram (Bessell & Brett 1988), so that M giant candidates can be efficiently selected using only near-infrared photometry. In S10, the stars were selected to be M giants in the Galactic halo by applying a selection criterion similar to those used by Majewski et al. (2003) to identify the tidal tails of the Sagittarius dwarf galaxy. While Majewski et al. (2003) restricted their sample to stars with \((J - K_S) > 0.85\), S10 selected stars with \((J - K_S) > 0.97\) and \(K_S > 10\) (labeled with subscript 0 for dereddened 2MASS photometry hereafter). The first condition in S10 (i.e., \((J - K_S) > 0.97\)) minimized the contamination by disk M dwarfs by restricting the sample to a redder population, and the second criterion (i.e., \(K_S > 10\)) is chosen to probe deeper into the Galactic halo. Furthermore, regions of high extinction (typically at low Galactic latitude) were masked from the analysis. The resulting M giant candidates were further subjected to a group-finding algorithm Enlink (Sharma & Johnston 2009) to locate overdense regions, and A13 was one of the overdensities revealed by Enlink in S10.

Based on the analysis of S10, A13 contains 54 candidate M giant stars, spanning \(130^\circ < l < 210^\circ\) and \(25^\circ < b < 40^\circ\), lying just north of the edge of one of the rectangular masks \((b \sim 25^\circ)\) for high-extinction regions (see Figure 1 or Figure 7 in S10 for the locations of the masks). The range in brightness of the stars in A13 is \(10 < K_{S,0} < 11.3\) and the estimated distance is \(23 \pm 11\) kpc. The properties of these 54 program stars are listed in Table 1. In this study, we have targeted all 54 stars from S10 spectroscopically to further understand the nature of A13.
Spectra for this work were collected over five observing runs using telescopes at MDM Observatory, Kitt Peak National Observatory (KPNO), and McDonald Observatory. The observing nights, telescopes, and instruments are summarized in Table 2. For all five observing runs, biases were taken at the beginning and end of each night to verify that there was no significant variation over time in the zero noise level. Flats were taken every night using a quartz lamp. To ensure accurate radial velocity measurements, calibration arc frames were taken throughout the night at the same sky position as each target, to account for telescope flexure. XeNeAr lamps were used for both Goldcam and Modspec, and NeAr lamps were used for ES2. All three instruments were set up so that they covered the spectral range 8000–8900 Å, with a spectral resolution of ~4 Å and a pixel scale of 1.4 Å pixel⁻¹. This spectral range covers
both the Na I doublet lines around 8200 Å, which are used to discriminate foreground M dwarfs (see, e.g., Schiavon et al. 1997), and the Ca II triplet lines (CaT) around 8500–8700 Å, which are used to derive the radial velocities and metallicities. The target spectra had a mean signal-to-noise ratio (S/N) ~ 25 per pixel around the CaT feature. Most spectra taken during the MDM and McDonald runs have S/N > 30 per pixel, while the spectra from the KPNO run have S/N ~ 15 per pixel. A handful of radial velocity (RV) standard M giant stars and one telluric standard star were observed every night along with the program stars. The RV standards observed are taken from the Astronomical Almanac and have similar spectral types to the program stars.

We reduced the data with the standard routines in IRAF. We began by subtracting the bias level using the overscan strip on each frame. A normalized flat was created for each night using the median-combined flats, and the science frames were divided by the normalized flat. The apall task was used for one-dimensional spectral extraction and the identify task was used for deriving the pixel-to-wavelength calibration. The resulting dispersion solution was applied to the spectra using the dispcor task. Finally, we used the continuum task to normalize the continuum of the spectra to one. The wavelength-calibrated spectra for several program stars are shown in Figure 2. Spectra from the three telescopes/instruments show similar resolution and wavelength coverage.

3. Data Analysis and Results

3.1. Dwarf/Giant Separation

To check that our sample is purely M giants, with no foreground contamination from M dwarfs, the gravity-sensitive Na I (λλ8183, 8195) doublet was analyzed for all of the targets. We discriminate dwarfs and giants by measuring the equivalent widths (EWs) of the Na I doublet (see, e.g., Schiavon et al. 1997). We first applied a telluric correction to our spectra using the telluric task in IRAF with the telluric standard star to remove the water vapor absorption around 8227 Å. We then shifted the spectra to the rest frame using the RV derived in Section 3.2. Next we numerically integrated the bandpass 8179–8199 Å to measure the EW. All 54 candidates have EWs less than 2 Å, thus confirming that the candidates are all giants. The lack of dwarf contamination in our sample is consistent with the fact that the candidates are fairly bright (10 < Kₜₜ < 11.3) and with the assessment of Majewski et al. (2003), who state that severe contamination from M dwarfs should only be a concern with Kₜₜ > 12.5. This also matches the rate of M dwarf contamination seen in the sample of Sheffield et al. (2014), where the rate of M dwarf contamination is zero at Kₜₜ < 11.5.

Table 2

| UT            | Observatory | Telescope  | Spectrograph |
|---------------|-------------|------------|--------------|
| 2011 Nov 10   | MDM         | Hilger 2.4 m | Modspec     |
| 2011 Nov 15–20| KPNO        | 2.1 m      | Goldcam     |
| 2012 Nov 28–30| McDonald    | Otto Struve 2.1 m | ES2         |
| 2012 Oct 27–29| MDM         | Hilger 2.4 m | Modspec     |
| 2014 Jan 9–12 | McDonald    | Otto Struve 2.1 m | ES2         |

3.2. Radial Velocities

The program stars were cross-correlated against the nightly RV standard stars using the fxcor task in IRAF to calculate the relative velocities. The heliocentric velocities of the program stars were derived after the Earth’s motion was corrected for using the vcorrect task.

For every night, the RV standard stars were also cross-correlated against each other to check the level of stability of the instrument. The average velocity precision as determined from cross-correlating the RV standards is ~5.3 km s⁻¹. Twenty-three out of 54 program stars were observed on multiple runs using different instruments. The standard deviation of velocities from repeated measurements was calculated for each star, and the average standard derivation for 23 stars is 5.5 km s⁻¹, which is very close to the RV precision derived from cross-correlating the standards for every night. Therefore, we conclude that σ ~ 5.5 km s⁻¹ is the velocity precision for this study. The heliocentric radial velocities for all 54 targets are presented in Table 1. For the stars observed on multiple runs, the averages of velocities are presented.

We then converted the heliocentric radial velocities, vHelioc, to the radial velocities in the Galactic standard of rest (GSR) frame, vGSR. This conversion removes the motion of the Sun with respect to the Galactic center. We adopted the circular orbital velocity of the Milky Way at the Sun’s radius as θ₀ = 236 km s⁻¹ (Bovy et al. 2009) and a solar motion of (U☉, V☉, W☉) = (11.1, 12.2, 7.3) km s⁻¹ (Schönrich et al. 2010).

The distribution of vGSR of the 54 stars in A13 is shown in the left panel of Figure 3. The stars in A13 show a prominent peak at vGSR ~ 50 km s⁻¹. As a comparison, we also show the velocity distribution of a synthetic sample of Milky Way field stars generated from the Galaxia model (Sharma et al. 2011a). The synthetic sample is selected to be within the same patch of the sky (i.e., 130° < l < 210° and 25° < b < 40°) with the same magnitude and color range (i.e., 0.97 < (J − Kₜₜ) < 1.11 and 10 < Kₜₜ < 11.3) as the A13 sample and is mostly composed of halo stars. It is apparent that the A13 sample has a much smaller velocity dispersion than expected for a random distribution of halo stars as predicted by Galaxia, as shown in Figure 3.

The RV data also show a velocity gradient in the sense that vGSR is increasing as the Galactic longitude of stars decreases (see right panel of Figure 3), consistent with a prograde rotation. We apply a linear fit to vGSR as a function of Galactic
longitude, in the process of removing 2.5σ outliers iteratively. Three stars (A13-06, A13-08, and A13-30) are removed as outliers.13 From a linear fit of the remaining 51 members, we derive the velocity dispersion, the gradient, and the velocity at \( l = 180° \) to be

\[
\sigma_v \lesssim 40 \text{ km s}^{-1}
\]

\[
dv_{GSR}/dl = -1.57 \pm 0.28 \text{ km s}^{-1} \text{deg}^{-1}
\]

\[
v_{GSR|180°} = -12.0 \pm 7.9 \text{ km s}^{-1}.
\]

The dispersion of \( \sigma_v \lesssim 40 \text{ km s}^{-1} \) is much colder than the velocity dispersion for the kinematics of random halo stars, as shown by the Galaxia model, but hotter than the \( v_{GSR} \) dispersion for the Sagittarius tidal stream \( (\sigma_v \sim 10–25 \text{ km s}^{-1}) \), Majewski et al. 2004a; Gibbons et al. 2017 and the Orphan stream \( (\sigma_v \sim 10 \text{ km s}^{-1}) \); Newberg et al. 2010. The measured velocity dispersion is likely affected by unidentified outliers, which bias the measured dispersion toward higher values. Still, the velocity dispersion of A13 is closer to that of disk stars.

3.3. Metallicities

The Ca II triplet (CaT) has been historically used to determine the metallicities of the stars in globular and open clusters whose distances are known (see, e.g., Armandroff & Zinn 1988; Rutledge et al. 1997; Cole et al. 2004; Warren & Cole 2009; Carrera 2012). Battaglia et al. (2008) show that CaT–[Fe/H] relations calibrated on globular clusters can also be applied with confidence to RGB stars in composite stellar populations. Carrera et al. (2013) derived a relation between the [Fe/H], luminosity, and the EWs of the CaT lines using 500 RGB stars in clusters and 55 metal-poor field stars. To date, many studies have used this calibration relation to derive the metallicities for giant stars, especially in dwarf spheroidal galaxies (see, e.g., Hendricks et al. 2014; Simon et al. 2015). However, most of the RGB stars used in these calibration works have temperatures higher than our M giant sample. Furthermore, as our sample has no precise distance measurement, the luminosities of the stars are unknown and we cannot use the relation derived from the aforementioned studies.

We therefore developed an empirical method to derive the metallicities of the M giants in the A13 sample from the CaT EWs and assumed a linear relation between the metallicity and the CaT EWs for M giants. This method is similar to that described by Sheffield et al. (2014) but with a larger sample of calibration stars. We collected spectra for 22 giants of late spectral type with published metallicities in our 2014 McDonald run. To include more calibrators, we extend the range of \((J - Ks)\) color from \((J - Ks) > 0.97\) to \((J - Ks) > 0.82\). The information on the 22 red calibrators is listed in Table 3. The most metal-poor calibration star, HD 37828, with \((J - Ks) = 0.83\), is also the bluest star in the calibration sample. We included this star to get a wider metallicity range even though it is much bluer than our program stars. Including HD 37828 should not introduce large additional systematic errors, because the other 21 calibration stars do not show a correlation between [Fe/H] and \((J - Ks)\).

We compute a spectral index for each of the Ca II triplet lines (\( \lambda \lambda 8498, 8542, 8662 \)). The spectral indices are a pseudo EW measured in angstrom, which is defined as

\[
EW = \int_{\lambda_1}^{\lambda_2} \left( 1 - \frac{F_i(\lambda)}{F_c(\lambda)} \right) d\lambda,
\]

where \( \lambda_1 \) and \( \lambda_2 \) are the edges of bandpasses for the CaT lines, \( F_i(\lambda) \) is the flux of the line, and \( F_c(\lambda) \) is the continuum flux. The continuum flux is computed as a linear fit using the red and blue continuum bandpasses. We evaluated EWs using the
The dashed lines are where CaT is the summation of the spectral indices from the near-IR calcium triplet. Right panel: the CaT index and the published [Fe/H] values. The dashed lines are ±0.25 dex away from the one-to-one (solid) line. For both panels, each symbol is also color-coded with its literature surface gravity, log \( g \).

We then derive a linear empirical relation between the CaT index and the published [Fe/H] index and the published [Fe/H] values. The bandpasses defined by Du et al. (2012) give a smaller standard deviation of the residuals between the published and derived metallicities for the 22 metallicity calibrators. Therefore, we chose to use the bandpasses defined by Du et al. (2012) for the final metallicity calibration relation. Our derived CaT-[Fe/H] relation for the 22 metallicity calibrators is shown as the solid line in the left panel of Figure 4. In the right panel of Figure 4, the [Fe/H] derived from the CaT index is plotted against the published [Fe/H] values. The dashed lines in the right panel are ±0.25 dex away from the one-to-one (solid) line. The estimated error in the derived metallicities is ±0.25 dex, considering that most of the derived [Fe/H] values for the calibrators fall within

### Table 3

Properties of the Giants for Metallicity Calibration

| ID      | R.A.      | Decl. | V   | J   | Ks  | \( T_{\text{eff}} \) | log \( g \) | [Fe/H] | Ref. | EWb |
|---------|-----------|-------|-----|-----|-----|---------------------|----------|--------|------|-----|
| HD 5780 | 00:59:23.3| 00:46:44 | 7.65 | 5.37 | 4.22 | 3848 | 1.07 | −0.70 | 1   | 7.58 |
| HD 6833 | 01:09:52.3| 54:44:20 | 6.77 | 5.00 | 4.04 | 4450 | 1.40 | −1.04 | 2   | 7.09 |
| HD 9138 | 01:30:11.1| 06:38:38 | 4.84 | 2.52 | 1.66 | 4040 | 1.91 | −0.39 | 3   | 7.74 |
| HD 13520| 02:13:13.3| 44:13:54 | 4.84 | 2.34 | 1.33 | 3970 | 1.70 | −0.24 | 3   | 8.44 |
| HD 29139| 03:35:55.2| 16:30:33 | 0.86 | −2.10 | −3.04 | 3910 | 1.59 | −0.34 | 3   | 8.76 |
| HD 30834| 03:42:38.0| 36:42:11 | 4.79 | 2.32 | 1.39 | 4130 | 1.86 | −0.37 | 3   | 8.50 |
| HD 37828| 05:40:54.6| −11:12:00| 6.88 | 4.89 | 4.06 | 4430 | 1.50 | −1.39 | 4   | 6.41 |
| HD 39853| 05:54:43.6| −11:46:27 | 5.64 | 2.90 | 1.98 | 3994 | 1.00 | −0.40 | 1   | 8.03 |
| HD 50778| 06:54:11.4| −12:02:19 | 4.09 | 1.54 | 0.64 | 4000 | 1.80 | −0.37 | 3   | 8.17 |
| HD 69267| 08:16:30.9| 09:11:08 | 3.52 | 1.19 | 0.19 | 4010 | 1.71 | −0.24 | 3   | 8.83 |
| HD 70272| 08:22:50.1| 43:11:17 | 4.26 | 1.26 | 0.38 | 3900 | 1.59 | −0.03 | 3   | 9.11 |
| HD 81797| 09:27:35.2| −08:39:31 | 2.00 | −0.26 | −1.13 | 4120 | 1.77 | −0.12 | 3   | 9.07 |
| HD 82308| 09:31:43.2| 22:58:05 | 4.32 | 1.45 | 0.59 | 3900 | 1.60 | 0.05  | 5   | 9.17 |
| HD 90254| 10:25:15.2| 08:47:05 | 5.64 | 2.38 | 1.40 | 3706 | 1.40 | −0.09 | 6   | 8.85 |
| HD 99167| 11:24:36.6| −10:51:34 | 4.82 | 1.93 | 1.01 | 3930 | 1.61 | −0.38 | 3   | 8.52 |
| HD 112300| 12:55:36.2| 03:23:51 | 3.38 | −0.11 | −1.19 | 3652 | 1.30 | −0.09 | 6   | 8.33 |
| HD 115478| 13:17:15.6| 13:40:33 | 5.33 | 3.30 | 2.38 | 4240 | 2.21 | −0.12 | 3   | 7.88 |
| HD 183439| 19:28:42.3| 24:39:54 | 4.45 | 1.71 | 0.71 | 3847 | 1.40 | −0.38 | 6   | 8.47 |
| HD 211073| 22:13:52.7| 39:42:54 | 4.51 | 2.26 | 1.29 | 4110 | 1.94 | 0.02  | 3   | 9.11 |
| HD 216174| 22:49:46.3| 55:54:10 | 5.44 | 3.58 | 2.63 | 4390 | 2.23 | −0.53 | 1   | 7.40 |
| HD 217459| 23:00:42.9| 03:00:42 | 5.85 | 3.91 | 2.94 | 4170 | 2.07 | −0.18 | 3   | 8.00 |
| HD 220009| 23:20:20.6| 05:22:53 | 5.08 | 2.89 | 1.99 | 4435 | 1.98 | −0.64 | 7   | 7.17 |

Notes.

* References: (1) Cenarro et al. (2003), (2) Fulbright (2000), (3) McWilliam (1990), (4) Ryan & Lambert (1995), (5) Fernandez-Villacanas et al. (1990), (6) Smith & Lambert (1986), (7) Luck & Heiter (2007).

b EW is calculated using the bandpasses defined by Du et al. (2012).
0.25 dex of the published values. In both panels, we also color-code the published log g value. The stars with higher log g tend to have smaller CaT at a given metallicity, as expected. As the CaT index comprises absorption lines of ionized calcium, the line strength gets smaller for stars with larger surface gravity. The errors caused by the difference in surface gravity are smaller than 0.25 dex for our calibration stars, which have a range of surface gravity of $1.0 < \log g < 2.2$.

We next apply this derived relation to determine metallicities for the 27 out of 51 A13 stars\textsuperscript{14} that have S/N $> 25$. The mean [Fe/H] derived from the CaT index for the 27 stars in A13 is [Fe/H] = $-0.57 \pm 0.21$, where $\pm 0.21$ dex is the standard deviation of the metallicities for the 27 stars. The [Fe/H] derived from the 27 A13 stars spans from $-1.1$ to $-0.1$, as shown in the left panel of Figure 5. It is possible that there are more metal-poor stars belonging to this structure, but the color criterion with $(J - K_S) > 0.97$ biases the sample against metal-poor stars.

As mentioned earlier, to include more calibration stars, we extended the color range of the calibration sample to $(J - K_S) > 0.82$, while our program stars have $(J - K_S) > 0.97$. As a test of the impact of the difference in color range, we computed the CaT–[Fe/H] relation using only the 10 calibrators with $(J - K_S) > 0.95$. The derived mean [Fe/H] for the 27 program stars changes from $-0.57$ to $-0.55$. Moreover, because the CaT index tends to have a weak correlation with surface gravity, we also compute the CaT–[Fe/H] relation using 11 calibrators with $1.0 < \log g < 1.7$. The derived mean [Fe/H] changes from $-0.57$ to $-0.63$. Thus, the systematic errors in the metallicity calibration as a result of changing the characterization of our calibration sample are less than 0.1 dex.

3.4. Heliocentric Distances

To compute stellar distances, we adopted the metallicity-dependent $M_{K_S}(J - K_S)$ relation derived in Sheffield et al. (2014). That is,

$$M_{K_S} = (3.8 + 1.3 \text{ [Fe/H]}) - 8.4(J - K_S).$$  \hspace{1cm} (6)

For the 27 stars with calculated metallicity, the heliocentric distances were derived individually for each star using the $(J - K_S)$ color and [Fe/H] derived previously. As shown in the right panel of Figure 5, the heliocentric distances for A13 stars range from 10 to 22 kpc, with a mean of $\sim 15$ kpc. S10 estimated the distance for A13 to be $23 \pm 11$ kpc based on an assumption of a more metal-poor population. As an uncertainty of $\pm 0.25$ dex in [Fe/H] will change $M_{K_S}$ by $\pm 0.32$ mag, the uncertainty of the distance for each star is at least $15\% - 20\%$.

4. Discussion

4.1. Relation to the Galactic Anticenter Stellar Structure

We first compare the A13 results with the properties of M giants in GASS/Mon from Crane et al. (2003, hereafter the C03 sample). As shown in Figure 1, more than half of the C03 sample are close to the Galactic plane ($b < 20^\circ$), while stars in the A13 sample have $b > 25^\circ$. This difference in sky positions could be due to selection effects. The C03 sample was not identified by the group-finding algorithm in S10 as part of the A13 group for two reasons. First, about two-thirds of the C03 sample have $b < 25^\circ$ and therefore they are excluded by the S10 rectangular masks for extinction regions (see Section 2.1). Second, most of the C03 sample has $K_{S,0} < 10$ (see the top panel of Figure 6) while S10 made a cut of $K_{S,0} > 10$ on their initial sample selection to exclude the nearby stars.

The top panel of Figure 6 compares the magnitude distributions of the stars. Because most of the stars in A13 are fainter than GASS, the average heliocentric distance of A13 stars ($d \sim 15$ kpc) is greater than that of GASS stars ($d \sim 11$ kpc), as shown in the middle panel of Figure 6.

The bottom panel of Figure 6 demonstrates that, while the structures may have different locations on the sky, our M giant sample in A13 follows a similar trend in radial velocities to the M giants in GASS/Mon. There is one star observed in both samples, which is A13-01 in Table 1. The observed $v_{\text{hel}}$ is $100.2 \pm 5.3$ km s$^{-1}$ in our work and $95.6 \pm 2.7$ km s$^{-1}$ in C03.

\textsuperscript{14} Three are rejected as outliers based upon their kinematics.
calibration relation in a similar way to TriAnd in Sheffield et al. (2014) to minimize any systematic effects in metallicities and distances across different samples. For GASS/Mon, Crane et al. (2003) used two of the three CaT lines (λ8498, 8542) and one Mg I line (λλ8807) as the spectral indices. The derived mean [Fe/H] is −0.4 ± 0.3 for GASS/Mon, which is slightly more metal-rich than what we get for A13, i.e., [Fe/H] = −0.57 ± 0.21. Meanwhile, Sheffield et al. (2014) derived the mean [Fe/H] from the CaT index of [Fe/H] = −0.62 ± 0.44 for TriAnd1 and [Fe/H] = −0.63 ± 0.29 for TriAnd2, which are very close to the metallicity derived for A13.\textsuperscript{15} Sheffield et al. (2014) also derived the metallicity by fitting a grid of isochrones to 2MASS and SDSS photometric data simultaneously. The metallicity derived from isochrone fitting ([Fe/H] ∼ −0.9) tends to be more metal-poor than the metallicities derived from the CaT index. Such a systematic bias might also present in A13 and GASS/Mon. Metallicity measurements from high-resolution spectroscopy are needed to provide accurate [Fe/H] and will be presented in a future paper (M. Bergemann et al. 2017, in preparation).

4.3. Comparison with the Pan-STARRS Substructures Map

We further compare these structures with the density map of main-sequence turnoff stars from the work of Bernard et al. (2016) based on the Pan-STARRS catalog (Chambers et al. 2016). Figure 7 is similar to their Figure 1 but in Galactic coordinates and at a heliocentric distance of ∼16 kpc, which is close to the average distance of A13. The M giants, especially in A13, are in good positional alignment with the structures in the Pan-STARRS map. This coincidence further suggests that A13 is likely to be an extension of GASS toward lower Galactic longitude (and greater distance) as discussed in Section 4.1. The southern overdensity seems to match the TriAnd structure in the density map, but less prominently. The clear vertical structure in the density map is the Sagittarius tidal stream. We therefore expect some contamination of nonmember stars from the Sagittarius stream, which may slightly inflate the velocity dispersion of A13, as mentioned in Section 3.2.

Slater et al. (2014) also made similar density maps with main-sequence turnoff stars using an earlier version of the Pan-STARRS catalog. It is worth noting that our M giant samples are in good agreement with the Monoceros Ring features highlighted in their paper (see, e.g., Features A, B, C, and D in Figure 3 of Slater et al. 2014).

4.4. Toward a Unified Picture?

Overall, our study suggests similar kinematical and spatial properties and trends with position in the Galaxy for all three major anticenter stellar structures—TriAnd (including TriAnd1 and TriAnd2), GASS/Mon, and A13—at least when using M giants as the stellar tracer. These commonalities are strongly suggestive of physical connections, and even possibly a single origin for all of these features. Hypotheses for the origin of these structures range from them being associated with the Galactic disk to having been accreted from an infalling satellite galaxy.

Xu et al. (2015) hypothesized that overdensities like GASS/Mon and TriAnd could be the large-scale signatures of vertical oscillations of the Galactic disk. Asymmetries in the velocity

\textsuperscript{15} Note that the quoted uncertainties for A13, GASS, and TriAnd are all calculated as the standard deviation of the metallicities of individual stars.
and spatial distributions of stars above and below the plane of the Galaxy in the vicinity of the Sun had already been detected in both SDSS (Widrow et al. 2012) and the RAVE survey (Williams et al. 2013). Xu et al. (2015) proposed that GASS/Mon (closer to the Sun) and TriAnd (farther from the Sun) could be associated with the same locally apparent disturbance, as the northern and southern parts of a vertically oscillating ring propagating outward from the Galactic center. Price-Whelan et al. (2015) provided the first concrete support for this hypothesis with evidence that the Galactic disk was the original birthplace of stars in TriAnd. They found a very low number ratio of RR Lyrae to M giant stars in TriAnd, consistent with the metal-rich stellar population of the disk and quite unlike the populations seen in surviving satellite galaxies. Many recent simulation studies have tried to understand the origin of such vertical structures of the Milky Way disk (e.g., Gómez et al. 2017). Using N-body and/or hydrodynamical simulations, Laporte et al. (2016) and Gómez et al. (2016) have shown that Milky Way satellites could produce strong disturbances and might lead to the formation of vertical structure in the Galactic disk.

Figure 8 schematically illustrates a possible scenario where GASS, A13, TriAnd1, and TriAnd2 are the results of ringing disk oscillations. In this scenario, GASS and A13 are two sequences of the northern rings, while TriAnd1 and TriAnd2 are two sequences of the southern rings. The symbol \(\odot\) indicates the location of the Sun.

Figure 7. (Top) Stellar density map (in Galactic coordinates) of main-sequence turnoff stars at \(\sim 16\) kpc from the Pan-STARRS catalog, with brighter areas indicating higher surface densities. The Galactic anticenter is in the middle. (Bottom) Same density map but overplotted with M giants from GASS (red), A13 (blue), TriAnd1 (green), and TriAnd2 (magenta). The M giants trace the overdensities seen in Pan-STARRS well, especially for the A13 stars. The vertical structure in the density map is the Sagittarius tidal stream.

Distance measurements have very large uncertainty, it is hard to determine from these projections whether the description of these overdensities as concentric rings or wrapped spiral structure in Xu et al. (2015) and Price-Whelan et al. (2015) is really an accurate representation of their morphology. It is also worth noting that the large overlaps in distances of the GASS and A13 stars, as well as TriAnd1 and TriAnd2 stars, as shown in Figure 9, do not support the picture in Figure 8 where a clear gap in distance should exist between the two sequences. This could be explained either (1) by the large distance uncertainties in the data, which blur the gap between the two sequences (as Martin et al. 2007 show with distinct distances for TriAnd1 and TriAnd2 for turnoff stars using MegaCam data), or (2) by a more complicated model of disk oscillations where the multiple sequences may have overlap in distance depending on the azimuthal line of sight.

From the evidence above, we do not yet have a clear enough picture to conclusively prove that stars in these overdensities...
were born in the disk rather than in an accreted satellite galaxy. Morphologically, concentric rings and/or arcing overdensities can be produced in either the ringing disk model (see, e.g., Gómez et al. 2013; Price-Whelan et al. 2015) or the satellite accretion model (see, e.g., Peñarrubia et al. 2005; Sheffield et al. 2014). Slater et al. (2014) also compare the Pan-STARRS density maps with mock data from simulations and show that those stream-like features can be produced by either tidal debris of a dwarf galaxy or large disk distortion. While the stellar populations of TriAnd have been shown to be more like those of the disk than those of known satellites of the Milky Way (Price-Whelan et al. 2015), detailed analyses of chemical abundance patterns for stars in GASS/Mon and TriAnd show that these structures are more likely to be reminiscent of satellite galaxies (Chou et al. 2010, 2011). Furthermore, Chou et al. (2011) also show that the chemical abundance patterns of TriAnd are distinct from those of GASS/Mon, suggesting that the two systems are unrelated. A more extensive and complete study of the abundance patterns and stellar populations of A13 and a comparison with GASS/Mon and TriAnd will help distinguish one scenario from the other.

Proper motions could also play a deciding role: Sheffield et al. (2014) found that the magnitude difference of (i.e., spatial offsets between) TriAnd1 and TriAnd2 could only be produced by a satellite disrupting on a retrograde orbit with respect to the disk, while kicked-out disk material would be expected to be on prograde orbits. As these M giants are relatively bright ($V \sim 13–16$ mag), these hypotheses could be tested with the proper motions from the upcoming Gaia data release.

Admittedly, as the M giant samples discussed here for GASS, A13, and TriAnd have different selection criteria (e.g., magnitude and color selection, Galactic extinction masks, etc.) between different studies, our comparisons might be affected by selection effects. Therefore, a consistent target selection and analysis of the M giants at low Galactic latitude with ongoing or future surveys (e.g., LAMOST, APOGEE, DESI, etc.) will provide a better understanding of these structures near the anticenter of the Galaxy.

5. Conclusions

This paper presents a study of A13, an overdensity of M giant star counts reported in Sharma et al. (2010). We derived the kinematics and metallicities of candidate members of A13 via moderate-resolution spectroscopic observations. Our results support two key conclusions.

First, the candidate M giant members have a relatively small velocity dispersion ($\lesssim 40$ km s$^{-1}$), implying that A13 is a genuine structure rather than the chance superposition of random halo stars. The confirmation of the A13 structure is an interesting result in itself, because it demonstrates the ability of the group-finding algorithm of Sharma et al. (2010) to find substructures in large-scale photometric stellar catalogs.
Second, from the position of A13 on the sky and its kinematic substructures, A13 may be associated with two other known substructures in this region: the GASS/Mon and TriAnd overdensities. The radial velocities of the stars in A13 follow the same trend in Galactic longitude as the stars in both GASS/Mon and TriAnd, and the stars in each have similar dispersions.

The data collected so far—with large errors on metallicities and distances—do not allow us to map the morphology and motions of these structures with enough resolution to present a conclusive single scenario for the nature of these overdensities. Further studies on chemical abundance and stellar populations are necessary to understand the nature of these structures. In particular, a more extensive and complete spectroscopic analysis of these three structures with ongoing or future surveys (e.g., LAMOST, APOGEE, DESI) will provide a better understanding of these structures near the anticenter of the Galaxy.

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References

Armandroff, T. E., & Zinn, R. 1988, AJ, 96, 92
Battaglia, G., Irwin, M., Tolstoy, E., et al. 2008, MNRAS, 383, 183
Belokurov, V., Evans, N. W., Bell, E. F., et al. 2007, ApJL, 657, L89
Bernard, E. J., Ferguson, A. M. N., Schlaufy, E. F., et al. 2016, MNRAS, 463, 1759
Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Bovy, J., Hogg, D. W., & Rix, H.-W. 2009, ApJ, 704, 1704
Bullock, J. S., Kravtsov, A. V., & Weinberg, D. H. 2001, ApJ, 548, 33
Carrera, R. 2012, A&A, 544, A109
Carrera, R., Pancino, E., Gallart, C., & del Pino, A. 2013, MNRAS, 434, 1681
Cenarro, A. J., Cardiel, N., Gorgas, J., et al. 2001, MNRAS, 326, 959
Cenarro, A. J., Gorgas, J., Vaizezakis, A., Cardiel, N., & Peletier, R. F. 2003, MNRAS, 339, L12
Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv:1612.05560
Chou, M.-Y., Majewski, S. R., Cunha, K., et al. 2010, ApJL, 720, L5
Chou, M.-Y., Majewski, S. R., & Cunha, K., 2011, ApJL, 731, L30
Cole, A. A., Smecker-Hane, T. A., Tolstoy, E., Bosler, T. L., & Gallagher, J. S. 2004, MNRAS, 347, 367
Crane, J. D., Majewski, S. R., Rocha-Pinto, H. J., et al. 2003, ApJL, 594, L119
Du, W., Luo, A. L., & Zhao, Y. H. 2012, AJ, 143, 44
Fernandez-Villanuca, J., L., Rego, M., & Cornide, M. 1990, AJ, 99, 1961
Fulbright, J. P. 2000, AJ, 120, 1841
Gibbons, S. L. J., Belokurov, V., & Evans, N. W. 2017, MNRAS, 464, 794
Gómez, F. A., Minchev, I., O’Shea, B. W., et al. 2013, MNRAS, 429, 159
Gómez, F. A., White, S. D. M., Grant, R. J. J., et al. 2017, MNRAS, 465, 3446
Gómez, F. A., White, S. D. M., Marinacci, F., et al. 2016, MNRAS, 456, 2779
Grillmair, C. J. 2006, ApJL, 651, L29
Grillmair, C. J. 2011, ApJL, 738, 98
Helmi, A., Cooper, A. P., White, S. D. M., et al. 2011, ApJL, 733, L7
Hendricks, B., Koch, A., Walker, M., et al. 2014, A&A, 572, A82
Ibata, R. A., Gilmore, G., & Irwin, M. J. 1994, Natur, 370, 194
Johnston, K. V., Bullock, J. S., Sharma, S., et al. 2008, ApJ, 689, 936
Laporte, C. F., Gómez, F. A., Besla, G., Johnston, K. V., & Garavito-Camargo, N. 2016, arXiv:1608.04743
Lucy, R. E., & Heatter, U. 2007, AJ, 133, 2464
Majewski, S. R., Kunkel, W. E., Law, D. R., et al. 2004a, ApJ, 609, 245
Majewski, S. R., Ostheimer, J. C., Rocha-Pinto, H. J., et al. 2004b, ApJL, 615, 738
Majewski, S. R., Skrutskie, M. F., Weinberg, M. D., & Ostheimer, J. C. 2003, ApJ, 599, 1082
Martin, N. F., Ibata, R. A., Bellazzini, M., et al. 2004, MNRAS, 348, 12
Martin, N. F., Ibata, R. A., & Irwin, M. 2007, ApJL, 668, L123
McWilliam, A. 1990, ApJS, 74, 1075
Newberg, H. J., Willott, B. A., Yanny, B., & Xu, Y. 2010, ApJ, 711, 32
Newberg, H. J., Yanny, B., Rockosi, C., et al. 2002, ApJL, 569, 245
Peharubbia, J., Martínez-Delgado, D., Rix, H. W., et al. 2005, ApJL, 626, 128
Price-Whelan, A. M., Johnston, K. V., Sheffield, A. A., Laporte, C. F. P., & Sesar, B. 2015, MNRAS, 452, 676
Rocha-Pinto, H. J., Majewski, S. R., Skrutskie, M. F., & Crane, D. J. 2003, ApJL, 594, L115
Rocha-Pinto, H. J., Majewski, S. R., Skrutskie, M. F., Crane, D. J., & Patterson, R. J. 2004, ApJL, 615, 732
Rutledge, G. A., Hessell, J. E., & Stetson, P. B. 1997, PASP, 109, 907
Ryan, S. G., & Lambert, D. L. 1995, AJ, 109, 2068
Schiavon, R. P., Barbay, B., Rossi, S. C. F., & Milone, A. 1997, ApJ, 479, 902
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJL, 500, 525
Schönherr, R., Binney, J., & Dehnen, W. 2010, MNRAS, 403, 1829
Sharma, S., Bland-Hawthorn, J., Johnston, K. V., & Binney, J. 2011a, ApJL, 730, 3
Sharma, S., & Johnston, K. V. 2009, ApJL, 703, 1061
Sharma, S., Johnston, K. V., Majewski, S. R., & Muñoz, R. R. 2011b, ApJL, 728, 106
Sheffield, A. A., Johnston, K. V., Majewski, S. R., Bullock, J., & Muñoz, R. R. 2011b, ApJL, 722, 750
Simon, J. D., Drlica-Wagner, A., Li, T. S., et al. 2015, ApJL, 808, 95
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Slater, C. T., Bell, E. F., Schlafly, E. F., et al. 2014, ApJL, 791, 9
Smith, V. F., & Lambert, D. L. 1986, ApJL, 311, 843
Sollima, A., Valls-Gabaud, D., Martínez-Delgado, D., et al. 2011, ApJL, 730, L6
Warren, S. R., & Cole, A. A. 2009, MNRAS, 393, 272
Widrow, L. M., Gardner, S., Yanny, B., Dodelson, S., & Chen, H.-Y. 2012, ApJL, 750, L41
Williams, M. E. K., Steinmetz, M., Binney, J., et al. 2013, MNRAS, 436, 101
Xu, Y., Newberg, H. J., Carlin, J. L., et al. 2015, ApJL, 801, 105
York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, AJL, 120, 1579