Milky Way Potential and Disk Dynamics

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New Views From Galactoseismology: Rethinking the Galactic Disk-Halo Connection

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Abstract. We present preliminary results from a study exploring the origin of Milky Way substructures, and show initial evidence of a common "kicked-out" formation mechanism for two low-latitude substructures. In this scenario, stars in these substructures formed in the disk and were subsequently "kicked-out" by an external perturbation, such as the merger of an accreted satellite, which created an oscillation in the Galactic disk. To test this origin scenario, we found the fraction of different stellar populations – M giants and RR Lyrae stars – in the Monoceros Ring (also known as GASS) and A13, supplementing a study of stellar populations in the Triangulum-Andromeda cloud. This work provides: (1) the first analysis of the GASS and A13 features based upon their stellar populations; and (2) preliminary evidence of disk stars in the Milky Way that have been relocated to the disk-halo interface due to vertical oscillations of the Milky Way's disk.

Keywords. Galaxy: evolution, Galaxy: formation, Galaxy: disk

1. Introduction

With the release of wide/all-sky catalogs such as 2MASS and SDSS in the last two decades, our view of the Milky Way's halo has changed: we can now see small scale structures mapped over large swaths on the sky and draw connections between structures (Johnston *et al.* 2012). Stellar substructures are found both locally and in the outskirts of the stellar halo (Grillmair & Carlin 2016); networks of substructures can be found criss-crossing the Galaxy in a local volume (Bernard *et al.* 2016). The Galactic disk itself exhibits an asymmetric structure, in the form of north/south asymmetries in the density of stars (Widrow *et al.* 2012, Slater *et al.* 2014, Xu *et al.* 2015, Morganson *et al.* 2016, Ferguson *et al.* 2017) and motions (Carlin *et al.* 2013, Williams *et al.* 2013, Antoja *et al.*

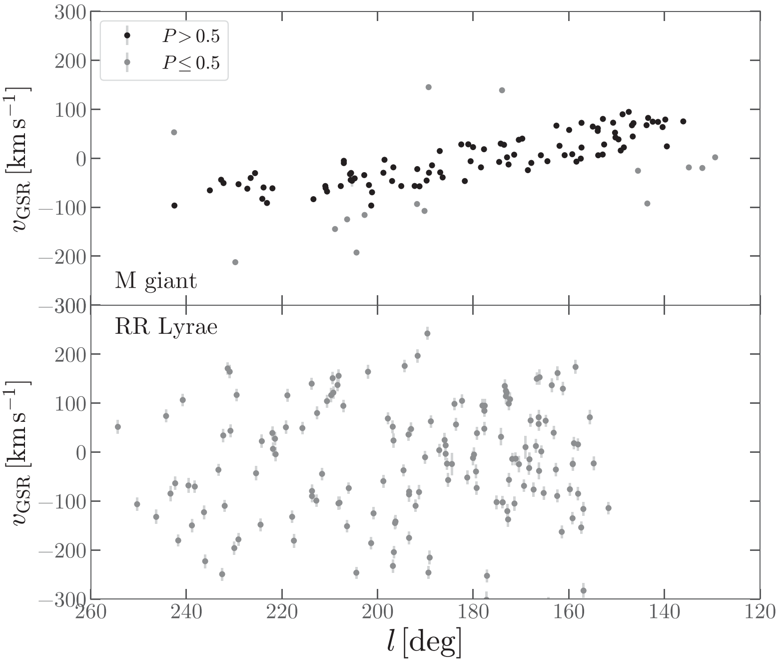

Figure 1. Velocity distribution of M Giants and RR Lyrae stars in the Mon/GASS+A13 substructure. The posterior probability P for all of the RR Lyrae stars are less than 0.5, which suggests that there are no RR Lyrae stars associated with this stellar feature. The final analysis of the velocity distribution will be presented in Sheffield *et al.* (in prep.).

2017). One of the goals of Galactoseismology is to understand the interactions between the Milky Way and its attendant satellites that led to this web of structure.

Vertical asymmetries in the disk may be attributed to an oscillation in the disk set in motion by an accreted satellite galaxy passing through the plane, causing stars to be displaced in vertical height (Gómez *et al.* 2013, Laporte *et al.* 2016). This type of dynamical perturbation to the disk points to a "kicked-out" disk origin for stars displaced by the collision, in which the stars formed in situ in the Galactic disk but are now located in the outer disk/inner halo (Zolotov *et al.* 2010, Sheffield *et al.* 2012, Hawkins *et al.* 2015), as opposed to being formed within the gas of an accreted satellite galaxy. Chemical tagging, cosmological simulations, and stellar population analysis can all be used to discriminate a kicked-out origin from an accreted origin scenario. We focus here on using stellar populations to trace the formation history of three substructures: the Monoceros Ring (Yanny *et al.* 2000, Newberg *et al.* 2003), the A13 overdensity (Sharma *et al.* 2010, Li *et al.* 2017), and the Triangulum-Andromeda (TriAnd) clouds (Majewski *et al.* 2004, Rocha-Pinto *et al.* 2004, Martin *et al.* 2007, Sheffield *et al.* 2014). The Monoceros Ring (also known as the Galactic Anticenter Stellar Structure, GASS; Rocha-Pinto *et al.* 2003, Crane *et al.* 2003) is nearly aligned with the midplane of the Galactic disk and understanding its origin is crucial to understanding the present structure of the disk.

2. Stellar Populations in Substructures

Xu *et al.* (2015) found that stars in the north/south Galactic disk asymmetry oscillate and proposed that Mon/GASS and the TriAnd cloud could both be part of this oscillation, rather than remnants of accreted satellites. Price-Whelan *et al.* (2015) used stellar

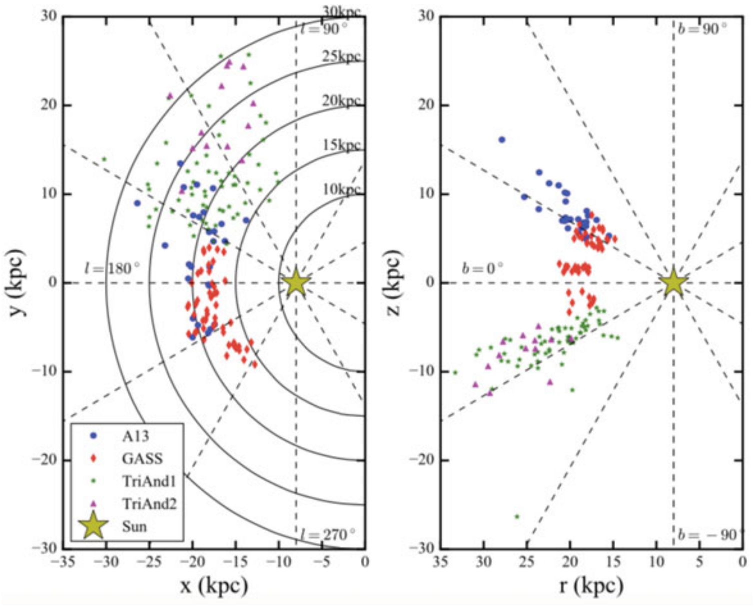

Figure 2. Projections, in Galactocentric coordinates, of M giants in Mon/GASS, A13, and the TriAnd cloud (the distinct TriAnd1 and TriAnd2 sequences found by Martin *et al.* 2007 and Sheffield *et al.* 2014 are indicated) in the x-y (left) and r-z (right) planes. Figure is from Li *et al.* (2017).

populations to assess the origin of the TriAnd cloud; by measuring the fraction of M giants to RR Lyrae stars, $f_{RR:MG}$, they found that the TriAnd cloud has a vanishingly small number of RR Lyrae stars. A very low $f_{RR:MG}$ is consistent with a kicked-out disk origin, as the Galactic disk is dominated by metal-rich stars and thus has a very low $f_{RR:MG}$.

In our extended study, we obtained low-resolution spectra of RR Lyrae stars in Mon/GASS and A13 to assess their origins (Sheffield *et al.*, in prep.). We used the same stellar populations technique as Price-Whelan *et al.* (2015), with Mon/GASS M giant velocities from Crane *et al.* (2003) and from Li *et al.* (2017) for the A13 M giants. Our preliminary results show that both Mon/GASS and A13 also have a kicked-out origin, based on the low value of $f_{RR:MG}$. Fig. 1 shows the preliminary distribution of $v_{\rm GSR}$ as a function of l for the M giants and RR Lyrae stars in Mon/GASS+A13 (stars from the two features were combined for this analysis). The RR Lyrae stars do not follow the low velocity dispersion trend seen in the M giants, suggestive of a kicked-out origin.

3. Connected Substructures?

Considering the evidence that all three substructures – Mon/GASS, A13, and TriAnd – have a kicked-out disk origin, the next question is whether they are connected to each other. Li *et al.* (2017) found that M giants in A13 have a cold velocity dispersion and follow the same velocity trend in l as those in Mon/GASS and the TriAnd cloud, which strongly suggests that these substructures are indeed related to each other. The distributions of the M giants in the x-y and r-z planes (Fig. 2) lend support to this idea: although there is smearing between the features in both planes, arc-like features that increase in vertical height with Galactocentric radius are seen, which is consistent with the results from models of perturbations to the disk that induce vertical oscillations, in particular those from Sgr piercing the disk (Laporte *et al.*, in prep). Our preliminary findings that Mon/GASS and A13 have a kicked-out disk origin further strengthens the notion that these features are part of an oscillation in the stellar Galactic disk, and lends support to the idea that these substructures derive from a common origin and are all related. The finding of such connected substructures in the Milky Way will shed new light on both the extent of the Galactic disk component and the critical role that satellite accretion has played on the dynamics of the disk.

References

Antoja, T., de Bruijne, J., Figueras, F., *et al.* 2017, *A&A*, 602, L13

Bernard, E. J., Ferguson, A. M. N., Schlafly, E. F., *et al.* 2016, *MNRAS*, 463, 1759

Crane, J. D., Majewski, S. R., Rocha-Pinto, H. J., *et al.* 2003, *ApJL*, 594, L119

Ferguson, D., Gardner, S., & Yanny, B. 2017, *ApJ*, 843, 141

Gómez, F. A., Minchev, I., O'Shea, B. W., *et al.* 2013, *MNRAS*, 429, 159

Grillmair, C. J. & Carlin, J. L. 2016, Tidal Streams in the Local Group and Beyond, 420, 87

Hawkins, K., Kordopatis, G., Gilmore, G., *et al.* 2015, *MNRAS*, 447, 2046

Johnston, K. V., Bullock, J. S., Sharma, S., *et al.* 2008, *ApJ*, 689, 936-957

Johnston, K. V., Sheffield, A. A., Majewski, S. R., Sharma, S., & Rocha-Pinto, H. J. 2012, *ApJ*, 760, 95

Laporte, C. F. P., Gómez, F. A., Besla, G., Johnston, K. V., & Garavito-Camargo, N. 2016, arXiv:1608.04743

Martin, N. F., Ibata, R. A., & Irwin, M. 2007, *ApJL*, 668, L123

Majewski, S. R., Ostheimer, J. C., Rocha-Pinto, H. J., *et al.* 2004, *ApJ*, 615, 738

Li, T. S., Sheffield, A. A., Johnston, K. V., *et al.* 2017, *ApJ*, 844, 74

Morganson, E., Conn, B., Rix, H.-W., *et al.* 2016, *ApJ*, 825, 140

Newberg, H. J., Yanny, B., Rockosi, C., *et al.* 2002, *ApJ*, 569, 245

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, J. D. 2003, *ApJL*, 594, L115

Rocha-Pinto, H. J., Majewski, S. R., Skrutskie, M. F., Crane, J. D., & Patterson, R. J. 2004, *ApJ*, 615, 732

Sheffield, A. A., Majewski, S. R., Johnston, K. V., *et al.* 2012, *ApJ*, 761, 161

Sheffield, A. A., Johnston, K. V., Majewski, S. R., *et al.* 2014, *ApJ*, 793, 62

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, *ApJ*, 801, 105

Yanny, B., Newberg, H. J., Kent, S., *et al.* 2000, *ApJ*, 540, 825

Zolotov, A., Willman, B., Brooks, A. M., *et al.* 2010, *ApJ*, 721, 738