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Charting the Contorted Outer Disk of the Milky Way with APOGEE

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ABSTRACT

The outer disk of the Milky Way is significantly distorted. The observed flaring of the outer disk, spatially-coherent substructures (e.g., the anticenter stream), and recently-observed vertical distortions in the positions and velocities of stars in this region all suggest that the outer disk has been significantly perturbed from ongoing and past accretion of satellite galaxies. Here, we map the chemical and kinematic structure of the outer disk using element abundances and spectrophotometric distances for red giant stars observed by the APOGEE surveys. We show that the element abundance distributions of stars in the disk vary smoothly as a function of mono-kinematic selections of stars (using actions) that extend to radii $R > 20$ kpc. We compare observed variations in the bulk vertical motions of stars and the (vertical) action distribution of stars with a high-resolution simulation of a Milky Way-like disk with a perturbing satellite on a Sagittarius-like orbit. We find that the observed vertical distortions and flaring of the outer disk can be qualitatively reproduced with this simulation, whereas these features cannot be explained by secular evolution of the disk (i.e. radial migration). The outer Milky Way disk provides a kinematic fossil record of perturbations whose kinematics will enable unique measurements of the dark matter content at this radii, and whose chemo-dynamical structures will enable further uncovering the accretion history and formation of the Galaxy.

Keywords: chemical abundances — galaxy dynamics — Milky Way dynamics — radial velocity — spectroscopy — stellar kinematics — surveys

1. INTRODUCTION

Sup.

2. DATA

Yo.

3. METHODS

3.1. *Computing Actions*

4. A TOUR OF THE OUTER DISK

4.1. *Position-based Selections*

4.2. *Action-based Selections*

5. RESULTS

5.1. *Revisiting Known Substructures*

Figure: some plot of Vphi, VR, Vz vs. Rg or R, show all stars + these stars

TriAnd, A13, GASS/Monoceros. Chemically consistent with low-alpha disk. Kinematics consistent with what the disk is doing out there, albeit f'ed!

ACS??

5.2. *Bulk Motion*

Bulk vertical and radial motion as a funtion of R or Rg. Same as what Antoja sees.

5.3. *Radial Migration?*

Look at Jz distribution, check against radial migration models? But need to factor in selection function.

6. COMPARISON TO SIMULATIONS

6.1. *Sagittarius + Milky Way*

6.2. *Milky Way + Secular Effects*

Sellwood sim?? Or qualitative comparison to expectations extracted from those simulations?

7. DISCUSSION

8. CONCLUSIONS

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Software: *Astropy* (Astropy Collaboration et al. 2013, 2018), *gala* (Price-Whelan 2017), *IPython* (Pérez & Granger 2007), *matplotlib* (Hunter 2007), *numpy* (Harris et al. 2020), *schwimmbad* (Price-Whelan & Foreman-Mackey 2017), *scipy* (Virtanen et al. 2020).

REFERENCES

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33, doi: 10.1051/0004-6361/201322068

Astropy Collaboration, Price-Whelan, A. M., Sipócz, B. M., et al. 2018, AJ, 156, 123, doi: 10.3847/1538-3881/aabc4f

Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, Nature, 585, 357, doi: 10.1038/s41586-020-2649-2

Hunter, J. D. 2007, Computing in Science & Engineering, 9, 90, doi: 10.1109/MCSE.2007.55

Pérez, F., & Granger, B. E. 2007, Computing in Science and Engineering, 9, 21, doi: 10.1109/MCSE.2007.53

Price-Whelan, A. M. 2017, The Journal of Open Source Software, 2, 388, doi: 10.21105/joss.00388

Price-Whelan, A. M., & Foreman-Mackey, D. 2017, The Journal of Open Source Software, 2, doi: 10.21105/joss.00357

Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, Nature Methods, 17, 261, doi: 10.1038/s41592-019-0686-2