Antaeus: a retrograde group of tidal debris in the Milky Way’s disk plane

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ABSTRACT

We present the discovery of a wide retrograde moving group in the disk plane of the Milky Way using action-angle coordinates derived from the Gaia DR3 catalog. The structure is identified from a sample of its members that are currently almost at the pericenter of their orbit and are passing through the Solar neighborhood. The motions of the stars in this group are highly correlated, indicating that the system is probably not phase mixed. With a width of at least 1.5 kpc and with a probable intrinsic spread in metallicity, this structure is most likely the wide remnant of a tidal stream of a disrupted ancient dwarf galaxy (age ∼ 12 Gyr, ⟨[Fe/H]⟩ ∼ −1.74). The structure presents many similarities (e.g. in energy, angular momentum, metallicity, and eccentricity) with the Sequoia merging event. However, it possesses extremely low vertical action \( J_z \) which makes it unique even amongst Sequoia dynamical groups. As the low \( J_z \) may be attributable to dynamical friction, we speculate that these stars may be the remnants of the dense core of the Sequoia progenitor.

Keywords: Galactic Archeology — galaxies: disk — galaxies: kinematics and dynamics — Local Group

1. INTRODUCTION

The complex formation and merging history of the Milky Way (MW) can perhaps be best understood by examining its stellar halo, host to many tidal debris of disrupted galaxies and globular clusters. Dynamical times in the halo are long, so the debris can persist there as coherent phase space structures for billions of years (see e.g. Helmi & de Zeeuw 2000), making them easier for us to detect.

With the advent of the Gaia mission (Gaia Collaboration et al. 2016) and its superb astrometric data, the task of digging into the stellar halo to uncover the past has been made more accessible. The stellar halo of the MW is now understood to be the product of several important accretion events making up most of its population (Di Matteo et al. 2019), the biggest of which being Gaia-Sausage/Enceladus (Belokurov et al. 2018; Helmi et al. 2018). Stream finding algorithms (Malhan et al. 2018; Ibata et al. 2021) have now detected dozens of kinematically coherent structures which will help chart the acceleration field of our Galaxy, providing a wealth of model-agnostic information.

The Gaia data also makes it possible to use action coordinates \((J_r, J_\phi, J_z)\) to detect stellar structures. Actions keep relevance over very long times if the potential evolves slowly and are thus especially useful to trace past mergers. Recently, Yuan et al. (2020), Naidu et al. (2020) and Malhan et al. (2022) used these quantities to detect and construct maps of the MW’s dynamical groups and link them to important merger events.

A similar technique was employed by Myeong et al. (2018) to find several retrograde structures in the stellar halo, which were then tentatively associated to the \( \omega \) Centauri globular cluster, which Majewski et al. (2012) had already suspected of bringing in such material. Retrograde structures have been linked to accretion events for a long time (Carollo et al. 2007), and it has been confirmed by Helmi et al. (2017) that the less bound stars in the halo are typically on retrograde orbits. Sestito et al. (2021) also highlight the importance of the metal poor
Figure 1. Selection procedure. Top panel: Gaia DR3 stars from the selection process described in Section 2 (i.e. $\pi/\delta\pi > 10$, $r_{\text{apo}} \geq 25$ kpc and $d \leq 1.5$ kpc). Middle panel: zoom on the low $J_z$ region delimited by the rectangle in the top panel ($2500 \leq J_\phi \leq 3500$ km s$^{-1}$ kpc, $J_z \leq 150$ km s$^{-1}$ kpc). Bottom panel: same region as the middle panel, but for our final cut using distances $d \leq 1$ kpc from the Sun.

retrograde halo population for tracing the early building blocks of the galaxy.

Myeong et al. (2019) reexamined the structures from Myeong et al. (2018) and linked them to a substantial merger event they named Sequoia. The Sequoia progenitor galaxy could have brought those retrograde groups and possibly $\omega$ Centauri as well. The fact that its stellar population is distinct in metallicity and orbital parameters from the Gaia-Sausage makes the event another important piece of the stellar halo puzzle.

In this work we present the discovery of Antaeus$^1$, a retrograde high energy group of tidal debris in the MW’s disk plane, made using action-angle coordinates derived

$^1$ In Greek mythology, Antaeus is the child of Gaia and Poseidon, a giant whose name comes from “opponent”.
from the Gaia DR3 catalogue (Gaia Collaboration 2022) and the Stäckel fudge implemented in Agama (Vasiliev 2019). The new structure has several properties which are similar to those of Sequoia stars, so we discuss its possible affiliation to this event, although both its position in the disk of the MW and its extraordinary low vertical action make it stand out.

2. SELECTION PROCESS

Throughout this article, we use the right-hand side Galactic Cartesian coordinates for the MW with the Sun located at \((x, y, z)_{⊙} = (−8.2240, 0, 0.0028)\) kpc (taking the Solar radius from Bovy 2020 and the height above the mid-plane from Widmark et al. 2021) having peculiar velocity \((v_x, v_y, v_z)_{⊙} = (11.10, 7.20, 7.25)\) km s\(^{-1}\) (Schönrich et al. 2010, but with the velocity in the direction of Galactic rotation taken from Bovy 2020). Our starting point is the Radial Velocity Spectrometer (RVS) sample of Gaia DR3, for which we derive action-angle coordinates \((J_, J_\phi, J_z)\) and orbital parameters using Agama (Vasiliev 2019) in the MW gravitational potential of McMillan (2017). From this catalogue, we take the stars with good parallax measurements \((Δϖ/δϖ ≥ 10)\) and \(d ≤ 1.5\) kpc so as to retain a good quality Solar neighborhood sample. Since our aim is to investigate the structures that are falling down onto the Milky Way, we choose to select stars with large apocenter distances, \(r_{apo} ≥ 25\) kpc. These cuts leave us with 3624 stars; we plot the resulting selection in the \(J_0J_z\) plane, coloured by \(r_{apo}\), in Figure 1 (top panel).

Among the many interesting structures that stand out from this view, we focus our attention on the low \(J_z\), retrograde moving group of stars delimited by the black rectangle \((2500 ≤ J_φ ≤ 3500\) km s\(^{-1}\) kpc, \(J_z ≤ 150\) km s\(^{-1}\) kpc), into which we zoom in Figure 1 (middle panel). We notice a good agreement in apocenters for stars in this region, further suggesting the presence of a stellar structure with coherent motion.

Finally, we experimented with the heliocentric distance cut to see how the selection changes. We noticed that by selecting stars within a distance of \(d ≤ 1\) kpc from the Sun (Figure 1, bottom panel) the agreement

![Figure 2](image-url)
individual values ranging from $[\text{Fe/H}] = -1.33 \pm 0.23$ to $[\text{Fe/H}] = -2.09 \pm 0.30$. The colour magnitude diagram (CMD) of the sample is shown on Figure 3, compared to old metal poor isochrones (12 Gyr, $[\text{Fe/H}] = -1.75$ and $[\text{Fe/H}] = -1.50$) from the PARSEC library (Bressan et al. 2012). The photometry is corrected for interstellar extinction using the 3D extinction estimates calculated by Anders et al. (2022).

Finally, we integrate back in time the orbits of the Antaeus stars in the McMillan MW potential for 1.5 Gyr, and in the MWPotential2014 (Bovy 2015); we show the results in Figure 4. Here also the structure appears very coherent dynamically. We find, for the McMillan MW potential ($M_{\text{vir}} = 1.3 \times 10^{12} M_\odot$), a mean pericenter radius of $r_{\text{peri}} = 7.3$ kpc, a mean apocenter radius of $r_{\text{apo}} = 39.3$ kpc, a mean orbital eccentricity of $e = 0.69$, and a mean orbital time of $t_{\text{orb}} = 1.1$ Gyr. For the lighter MWPotential2014 however ($M_{\text{vir}} = 8 \times 10^{11} M_\odot$), those values become mean $r_{\text{peri}} = 7.3$ kpc, mean $r_{\text{apo}} = 71.9$ kpc, mean $e = 0.81$, and mean $t_{\text{orb}} = 1.5$ Gyr. The 8 LAMOST stars, whose orbits are plotted in solid black, appear to be good representative members of the stream.

The mean actions of stars in the structure are ($J_r = 1761, J_\phi = 2990, J_z = 39$) kpc km s$^{-1}$, and their mean energy is $E = -10^5$ km$^2$ s$^{-2}$ (in the McMillan 2017 potential model).

4. DISCUSSION AND CONCLUSIONS

Based on the characteristics derived in Section 3, in particular the thickness of the structure ($\sim 1.5$ kpc) and the range of metallicity of its constituent stars, it seems highly likely that this group of stars is the remnant of a tidal stream of a disrupted dwarf galaxy. The CMD (Figure 3) seems to indicate that the progenitor is likely to be very old, probably around $\sim 12$ Gyr in age. The agreement is better with a model metallicity of $[\text{Fe/H}] = -1.50$, although we derive a mean value of $[\text{Fe/H}] = -1.74^{+0.06}_{-0.07}$. It would thus be very helpful to extend our sample of metallicities to help decide the matter.

The mean $J_\phi$, energy, and eccentricities of our sample of Antaeus stars show many similarities with the Arjuna/Titoi/Sequoia group of mergers (Naidu et al. 2020). However Antaeus seems more akin to the retrograde structures of Myeong et al. (2018) and to the retrograde tail of the Sequoia event (Myeong et al. 2019), especially when factoring in the metallicity of its population. The $\sim 12$ Gyr age derived from the CMD comparison is also consistent with estimates for Sequoia groups (Ruiz-Lara et al. 2022). Nonetheless, Antaeus’ extraordinarily low mean $J_z$ and its position in the disk plane of the MW

Figure 3. Colour magnitude diagram for our sample of Antaeus stars, compared to PARSEC model isochrones (Bressan et al. 2012) of age 12 Gyr and metallicities $[\text{Fe/H}] = -1.75$ (red) and $[\text{Fe/H}] = -1.50$ (green). The colorbar gives the $[\text{Fe/H}]$ for the 8 LAMOST stars.

in apocenters is slightly better, removing in particular some extreme values from the previous cut. This leaves a sample of 80 stars which are listed in Table 1.

3. SAMPLE CHARACTERISTICS

We show the positions and velocities of our selection of stars in Figure 2 (top panel). It appears clear that the stars belong to a coherent structure dynamically, moving in a retrograde motion in the disk plane of the MW. The structure is rather thick, with a width of at least 1.5 kpc. We identify some outliers from this bulk motion, which all have a distinctive positive velocity in the $x$ direction ($v_x \geq 0$). For the remainder of this study, we will exclude those 15 outliers from our sample, leaving us with 65 stars of the Antaeus stream. In Figure 2 (top panel), we plot velocity planes $v_x, v_\phi, v_r, v_z$, with this separation taken into account, showing the compactness of Antaeus stars in those projections.

We crossmatch our selection with the LAMOST DR8 catalogue (Wang et al. 2022) and find 8 stars in common, for which we obtain metallicities from their “FEH_PASTEL” values. These LAMOST stars have a mean $[\text{Fe/H}] = -1.74^{+0.06}_{-0.07}$, with an intrinsic spread of $\sigma = 0.11^{+0.10}_{-0.04}$ (correcting for the LAMOST metallicity uncertainty estimates) and in

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both make it unique, even when compared to the global atlas of halo structures from Malhan et al. (2022). If the structure is indeed related to Sequoia, this difference has to be explained.

The mere existence of such a streamy, retrograde structure in the disk of the MW is very puzzling. It is not clear how such kinematic coherence could be retained if this population came in with Sequoia $9 \sim 11 \text{ Gyr ago}$ (Myeong et al. 2019). Of course Antaeus’ progenitor could have arrived initially with a small inclination, although this possibility appears somewhat contrived. It seems more natural to explain the very low quantity of vertical motion by dissipation due to dynamical friction, which might be consistent with an early arrival in the MW. This scenario would invite the possibility that Antaeus is the debris of the dense core of the Sequoia progenitor, which would have stabilized in the disk through dynamical friction before tidal disruption completely destroyed it.

The discovery of Antaeus opens many exciting possibilities for follow-up studies. A first step would be finding other members of the structure in Gaia with the information we now possess. Creating an $N$-body model for the infall of the progenitor dwarf galaxy in the potential well of the MW and exploring the possibilities for its survival in the disk would also be highly informative. Finally, it would be very helpful to measure the metallicity of more stars of our selection in order to facilitate discussions regarding the origin of the structure, and links to Sequoia in particular.

**DATA AVAILABILITY**

The data used in this contribution is available in Table 1.

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**Figure 4.** Orbits of Antaeus stars seen in Galactic Cartesian coordinates, integrated backwards in the McMillan (2017) MW potential for 1.5 Gyr (top panel), and in the MWPotential2014 model for 2.5 Gyr (bottom panel). Notice the change of scales, as stars go farther when integrated in the lighter MWPotential2014. Orbits of the LAMOST sample (8 stars) are in solid black, and orbits of the rest of our sample (57 stars) are in purple.
Table 1. Sample from the 80 stars of our selection from Section 2. The full sample is available in electronic format.

| Gaia source ID     | RA    | DEC   | \(J_r\) | \(J_\phi\) | \(J_z\) | \(r_{\text{peri}}\) | \(r_{\text{apo}}\) | \(e\) | \([\text{Fe/H]}\) |
|-------------------|-------|-------|---------|-----------|---------|-------------------|-------------------|-----|----------------|
| 3857833427353671808 | 159.91 | 4.08  | 1843.09 | 106.55    | 2976.68 | 7.31              | 40.78             | 0.70 | −2.09 ± 0.30  |
| 1558668134509319040 | 204.99 | 49.77 | 698.65  | 99.50     | 2846.51 | 8.19              | 25.57             | 0.51 | −1.97 ± 0.12  |
| 137489335770878848 | 232.59 | 35.38 | 1936.15 | 45.67     | 3216.25 | 7.72              | 43.03             | 0.70 | −1.88 ± 0.10  |
| 950636673976295688 | 102.78 | 40.33 | 1505.39 | 83.11     | 2634.22 | 6.55              | 34.23             | 0.68 | −1.77 ± 0.13  |
| 383916510915273856 | 139.71 | −0.89 | 1963.74 | 9.28      | 2799.33 | 7.09              | 41.87             | 0.71 | −1.62 ± 0.12  |
| 2657496656325125888 | 347.59 | 1.19  | 1963.74 | 9.28      | 2799.33 | 7.09              | 41.87             | 0.71 | −1.62 ± 0.12  |
| 23128462236707584 | 57.75  | −0.89 | 1680.13 | 33.76     | 2664.73 | 6.34              | 36.15             | 0.70 | −1.33 ± 0.23  |
| 3834229356541509760 | 147.87 | 0.89  | 1466.15 | 47.20     | 2770.15 | 6.84              | 34.32             | 0.67 | −1.33 ± 0.23  |
| 1950571427690143616 | 322.99 | 34.92 | 1216.32 | 14.63     | 3083.68 | 7.90              | 32.92             | 0.61 |              |
| 2340952515729081728 | 359.75 | −21.81| 1340.28 | 91.00     | 2532.56 | 6.35              | 31.65             | 0.67 |              |

Note—The information is derived from the MW potential of McMillan (2017).

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REFERENCES

Anders, F., Khalatyan, A., Queiroz, A. B. A., et al. 2022, A&A, 658, A91, doi: 10.1051/0004-6361/202142369

Belokurov, V., Erkal, D., Evans, N. W., Koposov, S. E., & Deason, A. J. 2018, MNRAS, 478, 611, doi: 10.1093/mnras/sty982

Bovy, J. 2015, ApJS, 216, 29, doi: 10.1088/0067-0049/216/2/29

Di Matteo, P., Haywood, M., Lehnert, M. D., et al. 2019, A&A, 632, A4, doi: 10.1051/0004-6361/201834929

Gaia Collaboration. 2022, Astronomy & Astrophysics, doi: 10.1051/0004-6361/202243940

Helmi, A., Babusiaux, C., Koppelman, H. H., et al. 2018, Nature, 563, 85, doi: 10.1038/s41586-018-0625-x

Helmi, A., & de Zeeuw, P. T. 2000, MNRAS, 319, 657, doi: 10.1046/j.1365-8711.2000.03895.x

Helmi, A., Veljanoski, J., Breddels, M. A., Tian, H., & Sales, L. V. 2017, A&A, 598, A58, doi: 10.1051/0004-6361/201629990
Ibata, R., Malhan, K., Martin, N., et al. 2021, ApJ, 914, 123, doi: 10.3847/1538-4357/abfcc2
Majewski, S. R., Nidever, D. L., Smith, V. V., et al. 2012, ApJL, 747, L37, doi: 10.1088/2041-8205/747/2/L37
Malhan, K., Ibata, R. A., & Martin, N. F. 2018, MNRAS, 481, 3442, doi: 10.1093/mnras/sty2474
Malhan, K., Ibata, R. A., Sharma, S., et al. 2022, ApJ, 926, 107, doi: 10.3847/1538-4357/ac4d2a
McMillan, P. J. 2017, MNRAS, 465, 76, doi: 10.1093/mnras/stw2759
Myeong, G. C., Evans, N. W., Belokurov, V., Sanders, J. L., & Koposov, S. E. 2018, MNRAS, 478, 5449, doi: 10.1093/mnras/sty1403
Myeong, G. C., Vasiliev, E., Iorio, G., Evans, N. W., & Belokurov, V. 2019, MNRAS, 488, 1235, doi: 10.1093/mnras/stz1770
Naidu, R. P., Conroy, C., Bonaca, A., et al. 2020, ApJ, 901, 48, doi: 10.3847/1538-4357/abae6f
Ruiz-Lara, T., Matsuno, T., Sofie Løvdal, S., et al. 2022, arXiv e-prints, arXiv:2201.02405.
https://arxiv.org/abs/2201.02405
Schönrich, R., Binney, J., & Dehnen, W. 2010, MNRAS, 403, 1829, doi: 10.1111/j.1365-2966.2010.16253.x
Sestito, F., Buck, T., Starkenburg, E., et al. 2021, MNRAS, 500, 3750, doi: 10.1093/mnras/staa3479
Vasiliev, E. 2019, MNRAS, 482, 1525, doi: 10.1093/mnras/sty2672
Wang, C., Huang, Y., Yuan, H., et al. 2022, ApJS, 259, 51, doi: 10.3847/1538-4365/ac4df7
Widmark, A., de Salas, P. F., & Monari, G. 2021, A&A, 646, A67, doi: 10.1051/0004-6361/202039852
Yuan, Z., Myeong, G. C., Beers, T. C., et al. 2020, ApJ, 891, 39, doi: 10.3847/1538-4357/ab6ef7