Linking nearby stellar streams to more distant halo overdensities

E. Balbinot and A. Helmi

Kapteyn Astronomical Institute, University of Groningen, Postbus 800, 9700 AV Groningen, The Netherlands
e-mail: eduardo.balbinot@gmail.com

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ABSTRACT

Context. It has recently been shown that the halo near the Sun contains several kinematic substructures associated with past accretion events. For the more distant halo, there is evidence of large-scale density variations – in the form of stellar clouds or overdensities.

Aims. We study the link between the local halo kinematic groups and three of these stellar clouds: the Hercules-Aquila cloud, the Virgo Overdensity, and the Eridanus-Phoenix overdensity.

Methods. We perform orbital integrations in a standard Milky Way potential of a local halo sample extracted from Gaia EDR3 with the goal of predicting the location of the merger debris elsewhere in the Galaxy. We specifically focus on the regions occupied by the three stellar clouds and compare their kinematic and distance distributions with those predicted from the orbits of the nearby debris.

Results. We find that the local halo substructures have families of orbits that tend to pile up in the regions where the stellar clouds have been found. The distances and velocities of the cloud’s member stars are in good agreement with those predicted from the orbit integrations, particularly for Gaia-Enceladus stars. This is the dominant contributor of all three overdensities, with a minor part stemming from the Helmi streams and to an even smaller extent from Sequoia. The orbital integrations predict no asymmetries in the sky distribution of halo stars, and they pinpoint where additional debris associated with the local halo substructures may be located.

Key words. Galaxy: halo – Galaxy: kinematics and dynamics

1. Introduction

The importance of accretion in the buildup of the Galactic stellar halo was made evident by wide-field photometric surveys such as the Sloan Digital Sky Survey (SDSS; Yanny et al. 2000; Ivezić et al. 2012). They revealed a plethora of overdensities in the sky distribution of distant stars, such as the Sagittarius streams. Other notable examples are the Virgo Overdensity and the Hercules-Aquila Cloud (VOD and HAC; Vivas et al. 2001; Newberg et al. 2002; Belokurov et al. 2007; Juric et al. 2008; Bonaca et al. 2012; Conroy et al. 2018) and the more recently discovered Eridanus-Phoenix overdensity (EriPhe; Li et al. 2016). These three structures are sparse, span several hundred degree2, and have similar galactocentric distances of ~15–20 kpc.

The photometrically identified overdensities unambiguously demonstrate that the outer halo of the Milky Way was built via mergers and accretion. For the inner halo, the evidence was less compelling until the availability of large samples of stars with 6D phase-space information, particularly from the Gaia Data Release 2 (DR2; Gaia Collaboration 2018). This dataset revolutionised our view of the nearby halo and revealed that it is dominated by debris from Gaia-Enceladus (also known as the Sausage and hereafter G-E; Helmi et al. 2018; Belokurov et al. 2018; Haywood et al. 2018; Mackereth et al. 2019; Myeong et al. 2019) and from the disk that was present at the time and was dynamically perturbed (Helmi et al. 2018; Gallart et al. 2019; Di Matteo et al. 2019, see also Haywood et al. 2018; Mackereth et al. 2019; Myeong et al. 2019; Grand et al. 2020; Belokurov et al. 2020). Besides these major contributors, smaller kinematic substructures have been identified, such as the Helmi streams (HStr; Helmi et al. 1999; Koppelman et al. 2019a), Thammns (Koppelman et al. 2019b), Sequoia (Myeong et al. 2019), and several others (see e.g. Naidu et al. 2020).

It is natural to ask what the link between the overdensities identified at large distances and the nearby substructures is. For example, Deason et al. (2018) has argued that the break in the counts of halo stars at ~20–25 kpc (Deason et al. 2013) corresponds to the piling-up of stars from G-E at the apocentre of their orbits. Simion et al. (2018, 2019) have used the distances, line-of-sight velocities, and proper motion (PM) information of stars associated with the VOD and the HAC to argue that these are likely the distant counterparts of G-E because of their radially elongated orbits. Donlon et al. (2019, 2020) and Naidu et al. (2021) suggest a similar association based on N-body simulations, although the merger time inferred by Donlon et al. (2020) does not match that estimated for G-E using nearby stars (Helmi et al. 2018; Chaplin et al. 2020). Additionally, EriPhe (Li et al. 2016; Donlon et al. 2019, 2020) has been linked to those overdensities because of its similar heliocentric distance. Here we take a complementary approach and integrate the orbits of halo stars in the solar vicinity associated with various kinematic groups to predict where other stars with a different orbital phase but following similar orbits (as expected if they originate from the same progenitor) would be located. We also compare their PMs and line-of-sight velocities where available to those predicted by the orbit integrations. As we show in this paper, although many of the stars in the overdensities can be linked to G-E, this is likely not the only contributor.

This paper is organised as follows. In Sect. 2 we define our local halo sample and a set of distant tracers compiled from literature. We also describe the framework that we use to integrate the orbits of nearby halo stars. In Sect. 3 we explore the overlap, in observable space, of the nearby halo substructures’ orbits
with known stellar overdensities. Finally, in Sect. 4 we discuss and summarise our findings.

2. Data and methods

2.1. Nearby halo sample, streams, and orbit integration

We built a halo sample from the Gaia Early Data Release 3 (EDR3) 6D subset (Gaia Collaboration 2021), with a quality cut on parallax of \( \sigma(\pi)/\pi > 5 \) and with distances computed by inverting the parallaxes after applying a zero-point correction of 0.017 mas, as recommended by Lindegren et al. (2021). To obtain galactocentric velocities, we assumed \( v_{LSR} = 232.8 \text{ km s}^{-1} \) (McMillan 2017) and a peculiar motion for the Sun of \((U_0, V_0, W_0) = (11.1, 12.24, 7.25) \text{ km s}^{-1}\) (Schönrich et al. 2010). We also assumed the Sun to be located at \( R = 8.2 \text{ kpc} \) from the Galactic centre and \( z = 20.8 \text{ pc} \) above the plane (Bennett & Bovy 2019). We identified as nearby halo-like stars those with distances \( d_L < 2.5 \text{ kpc} \) and that satisfy \( \sqrt{V_L^2 + V_{LSR}^2} > 210 \text{ km s}^{-1} \). We had 20010 stars that matched these criteria.

For this halo sample, we computed their total energy \( E_{tot} \), the angular momentum in the \( z \)-direction \( L_z \), (which we set to be positive in the direction of Galactic rotation), and the circularity \( \eta = L_z/L_{tot}(E_{tot}) \), where \( L_{tot}(E_{tot}) \) is the angular momentum of a circular orbit in the Galactic plane with energy \( E_{tot} \) (see Wetzel 2011). We assumed the MWPotential from the dynamics package gala\(^1\) (Price-Whelan 2017). This Galactic potential has a spherical nucleus and bulge, a Miyamoto-Nagai disk (with parameters from Bovy 2015), and a spherical (Navarro et al. 1996) dark matter halo, where the values of the parameters have been obtained via fitting to a compilation of mass measurements of the Milky Way from 10 pc to \( \sim 150 \text{ kpc} \).

We used \( E_{tot}, L_z, \) and \( \eta \) to isolate four substructures following the work of Koppelman et al. (2019b), namely G-E, Sequoia, the HStr, and Thamnos. These authors split Thamnos into two groups, although for our analysis we treat them as one. In the top panel of Fig. 1 we show their distribution in \( L_z-E_{tot} \) space, with the various substructures colour-coded. The selection criteria adopted for each of them are:

- **G-E**: \(-1.30 < E_{tot}/u_E < -0.70\) and \(-0.20 < \eta < 0.13\),
- **HStr**: \(1.6 < L_z/u_L < 3.2\) (where \( L_{tot} \equiv (L_z^2 + L^2)^{1/2} \) and \(1 < L_z/u_L < 1.5 \) and \( E_{tot}/u_E < -0.9\)),
- **Sequoia**: \(-1.10 < E_{tot}/u_E < -0.90\) and \(-0.65 < \eta < -0.35\) and \( L_z/u_L > -2.1\),
- **Thamnos 1**: \(-1.00 < E_{tot}/u_E < -0.75\) and \( \eta < -0.75\),
- **Thamnos 2**: \(-1.52 < E_{tot}/u_E < -1.40\) and \(-0.75 < \eta < -0.4\),

where \( u_E = 10^5 \text{ km s}^{-2} \) and \( u_L = 10^3 \text{ kpc km s}^{-1} \).

We integrated the orbits of the stars in our sample backwards in time for 8 Gyr with a time sampling of 10 Myr in the same Galactic potential using a Dormand & Prince (1980) integrator. We refer to the time-sampled positions and velocities as ‘orbital points’. We expect in this way to pinpoint the locations of other stars that share the same progenitor as the substructures mentioned above but that have a different orbital phase.

2.2. Distant tracers and overdensities

We compiled a set of distant tracers that have reliable distance estimates that go beyond the Gaia EDR3 6D sample. For the VOD we took the combined sample of Vivas et al. (2016) and Sesar et al. (2017), which contains distances and radial velocity measurements for RR Lyrae stars. We note that this sample also contains stars associated with the Sagittarius stream, which can be filtered out by selecting only stars with \( d_L < 40 \text{ kpc} \).

For the HAC we used the sample from Simion et al. (2018), which comprises RR Lyrae derived distances plus radial velocities for 45 stars. This sample concentrates on a small portion of the reported extent of the HAC (see Grillmair & Carlin 2016).

Due to its recent discovery, EriPhE (Li et al. 2016) has not had any extensive spectroscopic follow-up, implying that there are no radial velocity measurements. Here we defined a list of possible members from the Dark Energy Survey (DES) Year...
3. Results

We now compare the spatial and kinematic characteristics of the orbits of the nearby halo substructures identified in \( L_\star - E_\text{tot} \) (Sect. 2.1) in the regions of the sky occupied by the more distant overdensities (Sect. 2.2). The hypothesis behind this comparison is that stars from a given progenitor have similar orbits, and that by selecting the stars near the Sun we sample objects with a specific orbital phase (i.e. those that happen to currently be passing through the solar volume). We thus expect other stars from that same progenitor to currently be located elsewhere in the Galaxy, along similar orbital tracks but with different orbital phases.

In Fig. 2 we show an all-sky HEALPix\(^2\) map of the density orbital points for the four nearby substructures mentioned in Sect. 2.1. The density is normalised for each panel separately and displayed in \( \log_{10} \) scale, and serves to indicate where we might expect to find contributions from the different substructures. The sky distributions for G-E and Sequoia cover a large range in latitudes (\( |b| \lesssim 60^\circ \)) but also reveal the presence of stars on low inclination orbits, which are presumably due to ‘contaminants’ (which follow a very different orbital family).

Figure 2 shows that the position on the sky of the VOD, the HAC, and EriPhe coincide with regions with a high density of orbital points from at least one of the halo substructures, which explains why the surveys have detected them in the first place. The occurrence of such stellar clouds is also related to the availability of high-quality homogeneous photometric data in low dust extinction regions. Given the lack of coverage in some regions, namely between \(-60^\circ < b < -30^\circ\) and \(280^\circ < l < 320^\circ\), we predict that they hold undiscovered debris. This region is also occupied by the Magellanic Clouds, which would make the detection of a sparse stellar cloud very difficult without extensive spectroscopic data. The ‘missing’ stellar clouds would link the VOD – which is known to extend down to \( b \sim 30^\circ \) in the northern galactic cap (Bonaca et al. 2012; Conroy et al. 2018) – to EriPhe, similar to the way the HAC has been detected on both sides of the disk.

\(^2\) http://healpix.sourceforge.net

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6 RR Lyrae catalogue (Stringer et al. 2021). We find 41 stars in the reported region and distance range for EriPhe (Li et al. 2016). The stars in the VOD and HAC samples were positionally cross-matched to Gaia EDR3 astrometry, while the EriPhe sample was cross-matched using the DES-provided Gaia DR2 source id, which was transformed to Gaia EDR3 id via the \( \text{dr2}_\text{neighbourhood} \) table, where the closest angular distance was selected as the best neighbour.

In the bottom panel of Fig. 1 we show the \( L_\star - E_\text{tot} \) distribution of distant tracers associated with the stellar clouds discussed above. We assume a 10% uncertainty in distances for the RR Lyrae. The radial velocity uncertainties are provided by each catalogue and range from 5–20 km s\(^{-1}\). We considered the correlation of uncertainties in \( \mu_\alpha \) and \( \mu_\delta \), while assuming the uncertainty in the on-sky position to be negligible. Although the total uncertainties are sizeable, we note from Fig. 1 that many of the stars, particularly those from the VOD, appear to be associated with G-E (as previously reported by Simion et al. 2019, on the basis of their angular momenta).

We computed the reported extent of the overdensities on the sky in Galactic coordinates using the galstreams package (Mateu et al. 2018), as shown in Fig. 2 with solid lines. For each of the samples described above, we also defined a region on the sky (in dashed lines) based on the convex hull of their observed members. We note that for the HAC the locus of spectroscopically confirmed members (in dashed lines) is smaller than the full extent of the cloud. The opposite is true for the VOD due to the inclusion of the more recent samples from Vivas et al. (2016) and Sesar et al. (2017).
We now explore the distribution of orbital points in the spaces of PM, galactocentric distance ($r$), and line-of-sight velocities corrected for the Galactic standard of rest frame ($V_{\text{GSR}}$). Figure 3 shows the distribution of orbital points and observed members of the HAC in two of these spaces. In PM we observe that the HAC shows a distribution that peaks at the expected value for G-E and also overlaps with the HStr. The galactocentric distance range for Thamnos is not consistent with that of the HAC members, although we note that the sample of Simion et al. (2018) was selected to have $15 < d_\odot/\text{kpc} < 20$. Furthermore, although the orbital points from Sequoia match the tail of the $V_{\text{GSR}}$ distribution, these points do not match the PM measured for the HAC stars. The most negative radial velocities of stars in the HAC appear to be related to G-E stars that have their orbital apocentre well beyond the distance range selected by Simion et al. (2018).

Figure 4 shows the same analysis as above but now for the VOD. We observe that its distribution in PM seems to be consistent with a combination of contributions, mostly from the HStr and G-E and to some extent also from Sequoia, as there is one group of stars with $\mu_\delta < -3$ mas yr$^{-1}$ and positive $V_{\text{GSR}}$ that also matches in distance. The stars that overlap with the HStr orbital points in PM have distances and $V_{\text{GSR}}$ that confirm an association to this object. Nonetheless, the majority of the VOD stars follow the distribution of the orbital points for G-E most closely.
4. Discussion and conclusions

Finally, in Fig. 5 we present the comparison for EriPhe. This stellar cloud has limited data, and its members were selected based solely on their distances. We observe, however, that the distribution in PM seems to match the predicted contributions of G-E and the HStr quite well. While there is some overlap in PM with Sequoia’s orbital points, this is for less than a handful of the EriPhe stars (with $-4 < \mu_\alpha < -3$ mas yr$^{-1}$, at distances 16–17.5 kpc), and on average EriPhe members tend to have smaller $r$ compared to what is expected from Sequoia’s orbital points. Just like for the VOD, EriPhe does not seem to be linked to Thamnos.

To better assess the association of clouds to halo substructures, we devised a test to map the degree of overlap in velocity space of these objects. At the region of the sky occupied by a cloud, we computed a kernel density estimation (KDE) for the orbital points in $(\mu_\alpha, \mu_\delta, V_{\text{GSR}})$ space, with the exception of EriPhe, where only PMs are available. We determined the volume in velocity space where 95% of the orbital points lie. Finally, we counted how many observed data points fall within this volume. In Fig. 6 we show the degree of overlap for each cloud-substructure pair. We find the degree of overlap to be consistent with our qualitative analysis, indicating a stronger link between G-E and all the clouds while also hinting at a connection between the VOD and EriPhe with the HStr.

On the basis of the very good match between the PM, distances, and radial velocities of HAC members with the orbital integrations of nearby members of G-E debris, we argue that they likely stem from this progenitor. Some minor overlap is present with the HStr and Sequoia; however, only detailed chemical abundances will be able to reveal the relative contributions of these accreted objects in the region of the Galaxy occupied by the HAC and put constraints on their (internal) properties.

The link between the majority of the stars in the VOD and nearby G-E debris is, similarly, also very clear. In particular, many of the VOD members appear to be associated with streams of stars wrapping around in their orbits and encompassing debris coming from and going towards their orbital apocentres. Some, but not all, of the groups identified by Vivas et al. (2016) on the basis of distances and radial velocities seem to correspond to different wraps of debris (some others do not, because their measured PMs are not consistent with clustering in phase space). A small fraction of the stars in the VOD appears to be related to the HStr. This is to some extent also apparent from the sky map of the orbit integrations of the VOD member stars shown in Simion et al. (2019, their Fig. 6, central panel).

Finally, EriPhe could be a mixture of debris from the HStr and G-E, as both again are expected to contribute in the region of the sky where this structure is located. The orbital points obtained from the integration of the trajectories of nearby stars from these objects jointly reproduce the PMs measured for stars in EriPhe. To confirm this and distinguish more clearly to which progenitor they might belong, line-of-sight velocity information as well as chemical abundances would be very helpful. The contribution of Sequoia to both EriPhe and the VOD appears to be marginal, while an association with Thamnos can be ruled out on the basis of very different distance distributions.

Our study confirms earlier suggestions that the three overdensities are related and shows how in a standard Galactic potential (in our case, the MWPotential from provided by the gala...
package) it is possible to match qualitatively the orbital distributions of stars from nearby substructures to those of distant over-densities. This lends support to their true association; the next step is to combine the distant and nearby tracers to constrain the properties of the Galactic potential in detail, using methods such as made-to-measure (Hunt & Kawata 2014) or Schwarzschild’s orbital superposition (as in Magorrian 2019), the latter in essence being similar to the approach presented in this paper.

Our orbital integrations allow us to pinpoint the regions of the Galaxy most likely to be occupied by different halo substructures and can thus be used in direct spectroscopic follow-up efforts to most efficiently probe them. They also show that after 8 Gyr of integration, and starting from the phase-space distribution of nearby stars, we expect a predominantly symmetric distribution of stars on the sky, both with respect to the Galactic plane and to the Galactic centre. For G-E debris the distribution on the sky is already relatively smooth after 2 Gyr of integration, implying that the debris is fully phase-mixed. In this context the asymmetries reported by Iorio & Belokurov (2019), if attributed to the merger of G-E, must be interpreted as being due to incomplete knowledge in the sky distribution. A-body simulations modelling this merger that have too short integration times (Donlon et al. 2020) or that do not include the growth of a massive (Galactic) disk that brings axial symmetry to the gravitational potential after the merger is completed (as in e.g. Villalobos & Helmi 2008; Naidu et al. 2021) predict unevenness in the spatial distribution of the distant debris. This unevenness should be apparent in asymmetries in, for example, the \( v_z \) distribution for nearby G-E stars, which are, in fact, not seen in the data (see e.g. Koppelman et al. 2019b). On the other hand, such kinematic asymmetries are seen for the HStr (and manifest themselves in feebly uneven sky distributions, as shown in the top right panel of Fig. 2) and have been used to constrain this accretion event to have taken place 5–8 Gyr ago (Koppelman et al. 2019a).

The established associations are also useful for probing different regions inside the progenitor before it was disrupted (Koppelman et al. 2020; Naidu et al. 2021). Comparisons in terms of stellar populations, their ages, and their chemistry could, for example, constrain the presence of gradients in the parent systems and, in this way, determine the characteristics of the building blocks at the time of accretion.

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