115. The Hercules stream

The earliest attempts to derive our Sun's motion through space, starting with William Herschel, assumed that the 'peculiar motions' of nearby stars are random. Early in the 20th century, Kapteyn found that they actually included two preferred directions, later designated the Hyades and Ursa Major streams.

I will fast forward almost a century, to the time before the Hipparcos results appeared in 1997. In large part due to the work of Olin Eggen over several decades (Eggen 1996, and references), the picture had become much more complex. In addition to open clusters showing clear common spatial and kinematic properties, sparser kinematic groups of 10–100 or more members had also been identified in the solar neighbourhood.

Variously described as (old) moving groups, kinematic groups, dynamical streams, or superclusters, these kinematically coherent groups of relatively old stars were recognisable because of their non-circular bulk motions, and their peculiar velocities well above the velocity dispersion of field stars of comparable age.

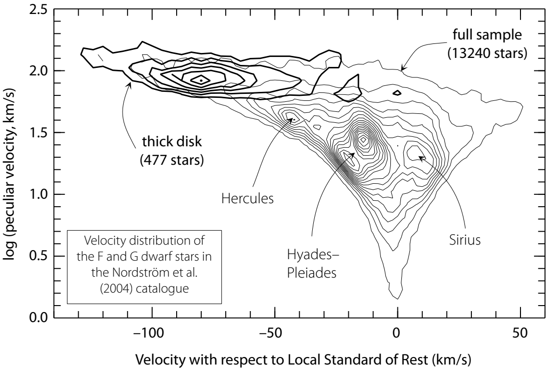
Fourteen such groups in the solar neighbourhood were listed by Soderblom & Mayor (1993), including the Hyades supercluster associated with the Hyades (600 Myr), sometimes referred to as Eggen's Stream I; the Ursa Major group (or Sirius supercluster) associated with the Ursa Major cluster (300 Myr), sometimes referred to as Eggen's Stream II; the Local Association or Pleiades moving group of young stars comprising embedded clusters and associations such as the Pleiades, α Per, NGC 2516, IC 2602, and the Sco–Cen association (20–150 Myr); the IC 2391 supercluster (35–55 Myr); and the Castor moving group (200 Myr).

Eggen hypothesised that these various groups were remnants of open clusters. Indeed, the fact that at least some have resulted from the evaporation of young clusters now seems secure. But wider interest in these systems has grown over the past 20–30 years as it became evident that others may be generated by a variety of global dynamical mechanisms, specifically by resonances forced by the rotating bar at the centre of the Galaxy, or linked with the dynamics of the spiral arms.

In Eggen's day, most distances had to be inferred, indirectly, in order to construct space velocities. As a result, the reality of such old streams was often questioned. More quantitative progress became possible with the distances and space velocities provided by Hipparcos, and more so today with the new advances in understanding that are being enabled by Gaia.

Modern data indeed confirms the reality of various old stellar streams. Helmi et al. (1999) found the signature of a cold stream in the velocities of halo stars from Hipparcos, which they interpreted as the tidal debris of a satellite galaxy accreted by the Milky Way. Similarly Navarro et al. (2004) argued that Eggens's Arcturus group is another debris stream, this time in the thick disk, and originating from an accretion event 5–8 Gyr ago.

More relevant in the present context, the Hipparcos data also confirmed the reality of moving groups in the velocity distribution of thin disk stars in the solar neighbourhood. Amongst these, Dehnen (1998) found new evidence for the existence of the Sirius–UMa, Pleiades–Hyades, and Hercules star streams.



Bensby et al. (2007)

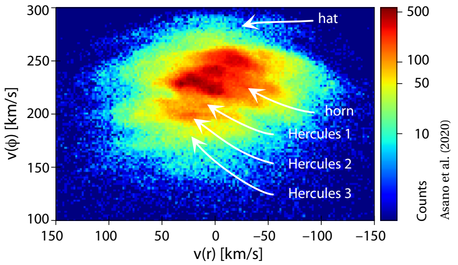
In efforts to understand their origin, Dehnen (2000) and Fux (2001) showed that the Hercules stream may be due to an outer Lindblad resonance with the Galaxy's central bar. Around the same time, Quillen & Minchev (2005) attributed the Sirius–UMa and Pleiades–Hyades streams to orbital resonances with spiral density waves.

While there is a story to tell about each of these groups, I will focus here on the contribution of Gaia to the understanding of the Hercules stream. This is a prominent moving group, trailing behind the local rate of Galactic rotation, and moving outwards in the disk.

Pre-Gaia, only some 100 stars were known to comprise the Hercules stream. With many tens of thousands of stars now in the relevant velocity slices, Gaia is transforming its characterisation, in turn allowing detailed dynamical modelling to clarify its origin.

Gaia DR2 revealed considerable trimodal structure in velocity space (Katz et al., 2018; Figure 22), comprising three sub-streams at $v_\phi \simeq 220$, 200, and 180 km s^{-1}. These, and other structures, have also been identified and interpreted by several other workers in the Gaia DR2 data (e.g. Monari et al., 2017; Hunt & Bovy, 2018; Ramos et al., 2018; Fragkoudi et al., 2019; Hunt et al., 2019; Trick et al., 2019; Asano et al., 2020; Li & Shen, 2020).

Interestingly, the stream denoted here as 'Hercules 3' is identical to Eggen's moving group HR 1614, also elucidated from Gaia DR2 by Kushniruk et al. (2020).



An aside on the relevant Galaxy-scale dynamical resonances is useful to appreciate the physics of bars and spirals which is involved here. In essay #112, I noted that three main orbital resonances are important for their understanding: the corotation resonance, and the inner and the outer Lindblad resonances.

The former occurs at the Galactic radius where the star's circular velocity is equal to that of the rotating potential. For a bar of fixed pattern speed, the mean position of a star then remains stationary with respect to the global bar pattern. The inner Lindblad resonance occurs where the rotating star 'overtakes' the potential, encountering its peak at the epicycle frequency. The outer Lindblad resonance, conversely, occurs where the potential overtakes the more slowly rotating star.

Dehnen (2000) modelled the stream by calculating positions and velocities in a static $m = 2$ bar potential, finding that stars trapped in the bar's 2:1 outer Lindblad resonance can create moving groups in the solar neighbourhood. The position of the structure in phase space depends on the location of the outer Lindblad resonance, which in turn depends on the pattern speed of the bar, Ω_B. To reproduce the observed features, he required a fast-rotating bar, $\Omega_\mathrm{B} = 53 \pm 3$ km s^{-1} kpc^{-1}.

Today, other work using Gaia DR2 suggests lower bar pattern speeds, e.g. 35.5 ± 0.8 km s^{-1} kpc^{-1} (Chiba et al. 2021b), 37.5 km s^{-1} kpc^{-1} (Clarke et al. 2019) and 41 ± 3 km s^{-1} kpc^{-1} (Sanders et al. 2019; Bovy et al. 2019).

The disparity in these inferred bar pattern speeds, and better data, has led to other origins being suggested for the Hercules stream. While most agree that resonant orbits due to non-axisymmetric structures, such as a bar and/or spiral arms, are responsible for the moving groups in the solar neighbourhood, the details differ.

Amongst these, Perez-Villegas et al. (2017) proposed that a Hercules-like stream can be made of stars orbiting the bar's Lagrange points. Others have explained the sub-structure as due to higher-order resonances of a slow bar. Hunt & Bovy (2018) attributed it to the 4:1 outer Lindblad resonance of a slow-rotating bar. Monari et al. (2017) showed that a corotation and 6:1 outer Lindblad resonance creates a Hercules-like stream and a horn-like structure, respectively. Michtchenko et al. (2018) suggested that it is associated with the spiral's 8:1 inner Lindblad resonance. Hattori et al. (2019) showed that such streams result from the 5:1 inner Lindblad resonance in the $m = 2$ slow-bar plus spiral potentials.

A different approach was adopted by Asano et al. (2020). They used an N-body simulation of the entire Milky Way (Fuji et al., 2019) to simulate a self-consistent well-resolved model, using 5.1 billion particles in the stellar bulge, bar, disk, and halo, evolved over 10 Gyr. The disk was composed of 200 million particles, with snapshots every 10 Myr.

Their results suggest that the stream is dominated by the 4:1 and 5:1 outer Lindblad and corotation resonances, comprising some 100 000 Gaia stars (15% of the total) together yielding a trimodal structure, and favouring a slow pattern speed of 40–45 km s^{-1} kpc^{-1}. In addition, the stars in the 2:1 and 3:1 outer Lindblad resonance match the 'hat' and 'horn' structures respectively.

I will not go further here with later insights from Gaia DR3, other than to recall a result I mentioned in essay #112. Chiba et al. (2021a) argued that the local stellar kinematics imply that the bar is *decelerating*, consistent with the effects of dynamical friction of a dark matter halo. As the bar slows, its resonances sweep through phase space, dragging along a portion of previously free orbits. This leads to certain multiple resonances seen in the Gaia data and, in particular, reproducing the details of the Hercules stream. They derived a current slowing rate of the bar of -4.5 ± 1.4 km s^{-1} kpc^{-1} per Gyr.

The final word on the Hercules stream has not yet been spoken, but future Gaia releases will surely further clarify this most remarkable dynamical structure. Olin Eggen would, I'm sure, have been delighted.