190. More phase-space features

In the early days of the Gaia studies, Adriaan Blauuw, ESO's second Director General, a supporter of space astrometry, and chair of the scientific selection committee for Hipparcos, asked me: was I concerned that Gaia would generate *too much* data… too big a step after Hipparcos… more than astronomers could handle?

It's an interesting viewpoint. The main Hipparcos catalogue of 120 000 stars in five printed volumes occupies half a meter of shelf space. The same format for Gaia would extend to 10 km. Nobody can ever look at every Gaia light curve: just 1 s each would require 60 years.

But with today's computing power, the huge stellar content is one of Gaia's great strengths: a vast net that can catch fleeting stages of stellar evolution, define statistically useful samples of rare star types, find tiny features in the HR diagram that point to exotic physics, and sift through millions of stars to seize on a few that are the fossil record of a galaxy captured billions of years ago.

And it is the number and variety of complex phase-space features in our Galaxy that has been one of Gaia's greatest contributions to studies of its structure and evolution to date. Recent studies have uncovered still more.

It is easy to feel lost in the labyrinth of Gaia science, so let me start by listing some of the dynamical features that Gaia has discovered (marked *) or substantially advanced, where numbers refer to my own essays.

These include: the Hercules stream attributable to dynamical resonances (115); the origins for the Arcturus and HR 1614 streams (116); discovering some 100 halo streams* (156); the breathing motion of spiral arms* (173); detecting the bar's deceleration due to the dark matter halo* (112); the disk warp (72); the Gaia phase-space spiral, attributed to a massive collision* (117); characterising globular cluster and open cluster tidal tails (109); identifying the primordial heart of the Milky Way* (102); measuring aberration due to Galaxy rotation* (32); discovering the Radcliffe Wave as an instability or perturbation structure* (127).

Here I look at four more recent discoveries: one each related to the inner and outer halo, one to the central disk, and one to our Galaxy's cosmological evolution.

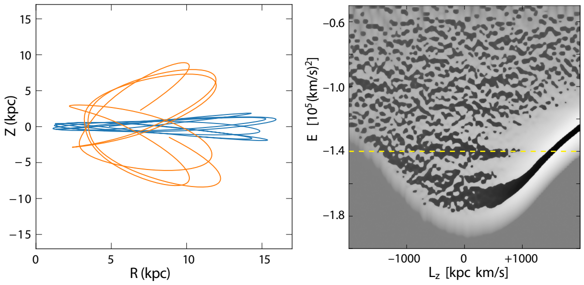
The Galaxy's central bar drives complex dynamical behaviour in the stellar disk, responsible for some of the clumps of space velocities in the solar neighbourhood, including the Hercules stream (essay 115).

The Gaia data have already identified specific resonances in the local disk driven by the bar (essay 112). Local kinematics are consistent with a bar pattern speed $\Omega_\mathrm{b} = 35.5\,\mathrm{km\,s^{-1}\,kpc^{-1}}$, and possibly a deceleration due to the dark matter halo of $-4.5\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ per Gyr (Chiba et al., 2021; Chiba & Schönrich, 2021).

A recent Gaia result by Dillamore et al. (2023) suggests that these resonances also extend to halo stars, consistent with some earlier suggestions (Hattori et al., 2016; Myeong et al., 2018; Schuster et al., 2019).

Dillamore et al. (2023) used DR3 astrometry and RVS radial velocities (for 22 million stars with 6D phase space and [Fe/H] data) to identify a prominent feature in the phase-space distribution of halo stars: a 'ridge' at constant energy and positive angular momentum, and consistent with $\Omega_\mathrm{b} \simeq 35 - 40\,\mathrm{km\,s^{-1}\,kpc^{-1}}$. Their simulations associate this with stars trapped in resonance orbits with the bar, particularly at the corotation resonance, many with large vertical (halo-like) excursions.

The resonances give the inner stellar halo a net spin in the direction of the bar's rotation (cf. Weinberg, 1985; Athanassoula, 2002). And the variation of rotational velocity with radius is similar to that seen for metal-poor stars in the APOGEE survey (Abdurro'uf et al., 2022).



Dillamore et al. (2023)

Left: two simulated orbits in the $R - Z$ plane, some of which are disk-like (blue), and some are halo-like (orange). Right: the Gaia data in the $E - L_z$ plane, where dark regions correspond to overdensities. The dashed line marks the ridge-like resonance.

Let me mention that an important contribution to the use of Gaia's astrometry, and exploited below, are the low-resolution spectra, BP and RP. Mean spectra were made available with DR3 for 220 million stars, along with derived estimates of [M/H], $T_{\rm eff}$, and $\log g$.

The spectra have been re-calibrated by a number of groups (essay 189). As an example, Andrae et al. (2023), provide 175 million stars with a precision of 0.1 dex in [M/H], 50 K in $T_{\rm eff}$, 0.08 dex in $\log g$, with a higher quality subset of 17 million bright ($G < 16$) red giants.

Growing evidence that the halo comprises substantial debris from an early massive accretion event has been brought into sharp focus by Gaia, through its ability to identify stars, mixed in phase space, but sharing the same metallicity and the same conserved integrals of motion. The present picture is that the Gaia–Sausage–Enceladus (GSE) merger, 8–10 Gyr ago and $[\mathrm{Fe/H}] \simeq -1.2$, contributed a large fraction of the stellar halo, at least out to ~30 kpc (essays 15 and 71).

Whether the merger was prograde or retrograde is still debated. Evidence for the latter includes the Arjuna stream, of similar metallicity, considered as a possible remnant of its early-stripped tail (Naidu et al., 2020).

Beyond 10–20 kpc lie several 'overdense' regions. The Hercules–Aquila Cloud, and the Inner Virgo and the Eridanus–Phoenix overdensities, have been suggested to be its apocentric pile-ups. The Pisces Overdensity at 70 kpc (Sesar et al., 2010; Carlin et al., 2012), and the Outer Virgo Overdensity at 80 kpc (Sesar et al., 2017), might be other distant remnants of the same merger.

Chandra et al. (2023) have made a major step in disentangling and interpreting these structures by making use of Gaia DR3 astrometry, supplemented by metallicities from Gaia's low-resolution prism spectra. They used 200 000 red giant branch stars out to 100 kpc, with full 5D (and some with 6D) kinematics, using isochrone-based distances constrained by their measured metallicity.

They identified a large population of retrograde debris representing most distant 'echoes' of the GSE merger, linking the more distant northern Outer Virgo Overdensity and the southern Pisces Overdensity to successive apocentres. The majority beyond 40 kpc follow a great-circle track consistent with the GSE orbit, and distinct from the Sagittarius stream which occupies the same plane, but orbits in the opposite sense.

Their findings also match the N-body simulations of the GSE merger by Naidu et al. (2021), which consisted of a $5 \times 10^8 M_\odot$ infall, starting at $z \sim 2$, and with a tilted and retrograde orientation before rapidly 'radialising'.

Of course in giving these, and the two following, short summaries of important advances in understanding our Galaxy's structure and evolution, I have omitted many details and associated studies.

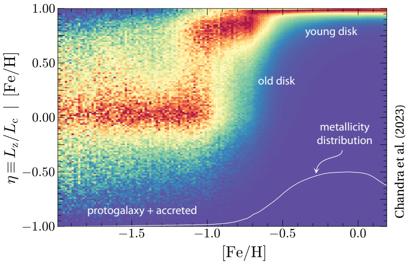
Using the Gaia DR3 astrometry and spectroscopy of 5.8 million stars, along with metallicities from Andrae et al. (2023), Malhan & Rix (2024) identified two high-contrast overdensities in the energy–angular momentum ($E - L_z$) plane of bright ($G < 16$) and metal-poor ($-2.5 < [\mathrm{M/H}] < -1.0$) stars, which they designated Shakti and Shiva. Both have $M_\star \gtrsim 10^7 M_\odot$, and both follow prograde orbits inside the solar circle. But while their orbits suggest an accreted origin, their metal abundances are more typical of an *in situ* population.

They reconciled these properties by inferring either that they may have resulted from resonant orbit trapping of the field stars by the rotating bar, along the lines described (above) by Dillamore et al. (2023). Or that they were protogalactic fragments that formed stars rapidly and coalesced early. In this case, they might be similar to those of the 'poor old heart' of the Milky Way (Rix et al., 2022, see essay 102), although not as deep in the Galactic potential, and with still discernible orbits.

Finally, Chandra et al. (2024) used the [Fe/H] and [α/Fe] for 9.9 million red giants derived by Andrae et al. (2023), to characterise their angular momentum as a function of metallicity. Taking this as a proxy for age, they identified three distinct evolutionary phases: a disordered/chaotic protogalaxy, a (kinematically) hot old disk, and a cold young disk. In their interpretation, the old high-α disk starts at $[\mathrm{Fe/H}] \simeq -1.0$, 'spinning up' from the nascent protogalaxy (as also inferred by Belokurov & Kravtsov, 2022), and then exhibiting a smooth cooling down toward more ordered and circular orbits.

The overlap between the protogalaxy and hot disk, $-1.2 \lesssim [\mathrm{Fe/H}] \lesssim -0.9$, includes stars with intermediate orbits, extending to $[\mathrm{Fe/H}] \sim -0.5$, and coinciding with a previously identified 'in-situ halo' or 'splash' population (Bonaca et al., 2017; Belokurov et al., 2020).

They also identified an analogue from the cosmological simulations TNG50, in which the protogalaxy spins up into a thin high-α disk, before being heated and torqued by a major gas-rich merger (as with the GSE merger). This adds a large amount of low-metallicity gas and angular momentum, from which the kinematically cold low-α stellar disk is subsequently born.



Chandra et al. (2023)

As the authors state, we are steadily gaining a coherent picture of our Galaxy's three-phase formation… involving spin-up, merger, and cooldown.