117. The Gaia phase-space spiral

In the years before Hipparcos, understanding of the dynamical structure of the local solar neighbourhood was restricted by the accuracy of star positions and space motions determined from the ground. The framework for describing the kinematics of the Galactic disk, the Oort–Lindblad model, was quantified by the Oort constants, A and B, empirically derived parameters that characterise its local rotation. Within this picture was evidence for clusters, moving groups, and spiral arms.

The derivation of the Oort constants is based on an assumed potential with axial symmetry. Complications arise in a non-axisymmetric system, for example in the presence of spiral density waves and the central bar. In such cases, the Oort constants will vary with azimuth, and the resulting numerical values further depend on the type and distance of the tracer stars studied.

A more general analysis was formulated as a first-order Taylor-series expansion by Ogorodnikov (1932) and Milne (1935). Clube (1973), for example, showed that the local proper motions were not well described by the Oort–Lindblad model, finding a significant expansion component, which he attributed to spiral density waves and, within 300 pc, to the burst of recent star formation which gave rise to the Gould Belt.

The Hipparcos distances and proper motions provided further evidence of a more complex picture, and several analyses discussed the space velocities in terms of this more general expression for the velocity field in the vicinity of the Sun. A further development represented the global field of tangential velocities in terms of vector spherical harmonics (e.g. Makarov & Murphy, 2007), providing tantalising hints of the complex stellar velocity patterns in the solar neighbourhood.

Before continuing, let me explain the use of the term 'phase space'. In dynamical systems, a phase space is a space in which all possible states of a system are represented, with each possible state corresponding to one unique point in the phase space. For stellar systems, the 6-dimensional 'phase space' consists of the 3D position and 3D momentum variables.

By providing, for the first time, accurate 6D phase-space distributions (positions and space motions) of vast numbers of stars within a few kpc from the Sun, Gaia has revealed that the Galactic disk is both deeply structured and strongly perturbed (e.g., Katz et al., 2018; Antoja et al., 2018; Kawata et al., 2018; Bland-Hawthorn et al., 2019; Clarke & Gerhard, 2022).

Amongst these new insights are a much better understanding of the morphology and pattern speed of the bar, including evidence in the Gaia data that it is slowing down, presumably due to dynamical friction with the massive halo (Bovy et al., 2019; Sanders et al., 2019; Chiba et al., 2021; Chiba & Schönrich, 2021). And there are hints that the spiral structure is possibly transient (Baba et al., 2018; Hunt et al., 2018a; 2018b; 2019; 2022).

Within the baryonic halo, i.e. the visible stars, Gaia has shown that a significant fraction are moving on strongly radial orbits. This has been interpreted as a remnant of a large galaxy (Gaia-Sausage-Enceladus) falling into the Milky Way about 10 Gyr ago (Helmi et al., 2018; Belokurov et al., 2018; Di Matteo et al., 2019; Gallart et al., 2019). It has been suggested that this merger disrupted the proto-Galactic disk, and created the inner metal rich halo stars, which are possibly the same population as the thick disk component (Di Matteo et al., 2019; Gallart et al., 2019; Belokurov et al., 2020).

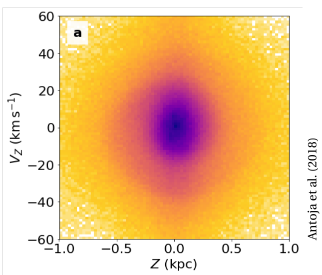
Many other streams have been discovered in the Gaia data since (see essay #71; e.g. Ibata et al., 2019; Yuan et al., 2020; Naidu et al., 2020; Myeong et al., 2019; Naidu et al., 2020; Necib et al., 2020; Malhan et al., 2022).

Within the disk itself, rich structure in the $U-V$ velocities, i.e. in the plane of the Galaxy, provides observational evidence for numerous kinematic associations, or moving groups, some of which are clearly attributed to open cluster stars 'dissolving' into the field star population, while others have a very different origin, some driven by dynamical resonances with the rotating central bar or the dissolving spiral arms. I have already covered some examples of these kinematic structures in previous essays, specifically the Hercules stream (#115), and the Arcturus and HR 1614 streams (#116).

IN ADDITION to the above has been the discovery of what is called the 'Gaia phase-space spiral', or sometimes the 'phase-plane spiral'. The description simply refers to the fact that this new, and very distinct, kinematic feature becomes evident in a graph of vertical motion in the Galaxy versus vertical position, i.e. in (the phase plane) Z versus V_Z, rather than (say) the space velocities in the plane of the Galaxy, V_R versus V_ϕ. [Elsewhere I have used the Galactic UVW coordinates, where U is in the direction of the Galactic centre, V in the direction of Galactic rotation, and W is towards the north Galactic pole. Here I use instead V_R, V_ϕ, V_Z respectively, to adhere to the notation used by the discovery authors.]

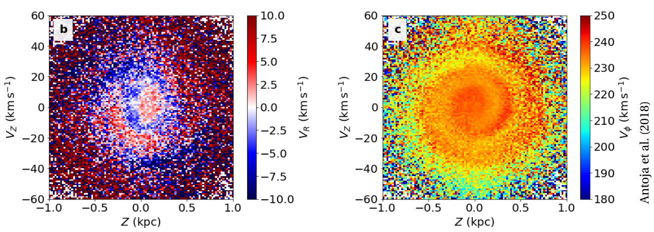
THIS PARTICULAR feature was first noticed in the Gaia DR2 data by Antoja et al. (2018), who found that certain phase space projections show substructures that were not only new, but had not even been predicted by existing models of the Galaxy.

They used Gaia DR2 sources for which the 6D phase space coordinates can be computed, i.e. all sources with available 5-parameter astrometric solution (sky positions, parallax and proper motions) and radial velocities. They selected stars with parallax errors smaller than 20%, resulting in more than 6.3 million stars. They adopted a vertical distance of the Sun above the plane of 27 pc, a distance of the Sun to the Galactic centre of 8.34 kpc, and the Sun's circular velocity of 240 km s^{-1}. They then selected the more than 930 000 stars located in a local Galactic cylindrical ring, $R = 8.24 - 8.44$ kpc, for which their median errors in V_R, V_ϕ, V_Z are 0.5, 0.8, and 0.6 km s^{-1} respectively.



This image shows their results in the vertical position–vertical velocity plane, $Z - V_Z$. The data is in bins of $\Delta Z = 0.01$ kpc and $\Delta V_Z = 0.1$ km s^{-1}, and the intensity is simply proportional to the number of counts.

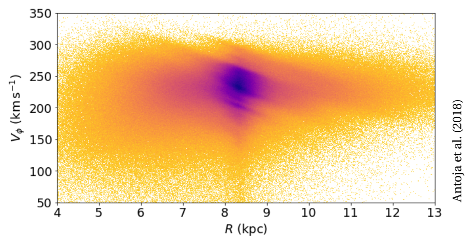
While spiral structure is evident in this image, albeit rather faintly, it becomes more prominent (in the same plane) when coloured as a function of median V_R (below left, here with bins of $\Delta Z = 0.02$ kpc and $\Delta V_Z = 1$ km s^{-1}), and even more so as a function of V_ϕ (below right).



Although this kind of 'phase-wrapping' had been predicted to occur in the disk after a passage of a satellite galaxy (e.g. Minchev et al., 2009; Gomez et al., 2012; de la Vega et al., 2015) it had not been observed previously. From numerical modelling, Antoja et al. (2018) inferred that the Milky Way disk was perturbed 300–900 Myr ago, consistent with estimates of the last pericentric passage of the Sagittarius dwarf galaxy (e.g., Laporte et al., 2018).

ANOTHER PHASE-SPACE projection that shows a *'remarkably different and stunning appearance'* with the Gaia data, also reported by Antoja et al. (2018), is the azimuthal velocity V_ϕ versus radius R. Although previously noted using early Gaia and LAMOST data (Monari et al., 2017), the extent and unprecedented precision of Gaia reveals a multitude of thin diagonal ridges.

The arches in the velocity space projection $V_R - V_\phi$ in the solar neighbourhood, previously discovered with the Gaia data by Katz et al. (2018), and described in my essays #115–116, are projections of these diagonal ridges at a fixed Galactic location.



ALTHOUGH ATTRIBUTED by Antoja et al. (2018) to a passage of the Sagittarius dwarf galaxy, subsequent studies have continued to probe its origin, studying phase mixing after a tidal perturbation by a dwarf galaxy (Binney & Schönrich, 2018; Bennett & Bovy, 2019; Laporte et al., 2019), or the result of bar buckling (Khoperskov et al., 2019; 2020), and/or a persistent dark matter wake (Grand et al., 2022).

A consensus interpretation has not yet been reached. Binney & Schönrich (2018) emphasised that the frequency at which stars oscillate vertically depends on their angular momentum about the Z-axis in addition to the amplitude of the star's vertical oscillations, such that spirals should form in both V_ϕ and V_R whenever a massive substructure, such as the Sagittarius dwarf galaxy, passes through the Galactic plane.

Laporte et al. (2019) reached similar conclusions, further arguing that since $Z - V_Z$ looks the same in all stellar population age bins, right down to the youngest ages, rules out a bar-buckling origin.

Meanwhile Hunt et al. (2022) extended the analysis, discovering a transition to two armed 'breathing spirals' in the inner Milky Way, concluding that the local data actually contain signatures of *multiple* perturbations, with the prospects of using their distinct properties to infer the properties of the interactions that caused them.