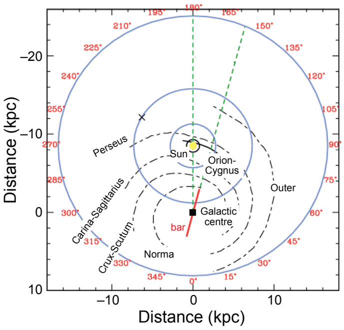
114. Our Galaxy's spiral arms

Our Milky Way is a barred spiral galaxy with a diameter of some 30 kpc, and a thin disk of thickness 220–450 pc. Our solar system lies 8.3 kpc from the Galactic centre. Beyond the central bar, the disk is organised into a series of spiral arms, delineated by a higher density of gas and dust, and more pronounced ongoing star formation. But its detailed structure is difficult to establish since our vantage point lies deep within the disk.



There are arguably considered to be four main arms: Perseus; Norma; Scutum–Centaurus and Carina–Sagittarius. There are at least two smaller arms or spurs, including the Orion–Cygnus arm which includes the Sun.

Some recent work suggests that there may be two spiral arms traced out by old stars, and four arms more defined by gas and young stars. Others have proposed that there are two different spiral patterns: the inner Sagittarius arm, and the outer more tightly wound Carina and Perseus arms with a slower rotation.

Given that other galaxies are often seen to have arms that branch, merge, and twist, with varying degrees of irregularity, it is no surprise that our Galaxy's spiral structure is complex, and that their details remain uncertain.

Observations probing the spiral-arm structure are many and varied, including H I regions at 21 cm, H_2O masers with VLBA, molecular clouds in CO, H II regions probed by pulsars, red clump stars from 2MASS and Spitzer, cluster mapping by WISE, and many others.

And there is no clear consensus on the origin and evolution of the spiral structure: it may be that they arise (along with central bars) as an inevitable consequence of stellar orbits, as I have touched on in essay #112. Others have suggested that the spiral structure is the result of collisions with the Sagittarius dwarf galaxy.

The challenge of further elucidating their structure clearly rests on knowledge of the distances and dynamics of their constituent stars. Hipparcos, restricted to the nearby Perseus and Orion arms, and using young bright OB stars and Cepheids within 2–3 kpc, allowed for some studies of their pattern speed, location of the co-rotation circle, and implications for moving groups.

Gaia's scientific case emphasised its potential role in mapping the major arms on 'our side' of the Galaxy, based on young tracer populations, and probing their kinematics and stellar population mix.

To put the following into a bigger picture, interested readers can consult the review of the overall properties of our Galaxy by Bland-Hawthorn & Gerhard (2016); a review of the Milky Way's bar and spiral arms by Shen & Zheng (2020); and a review of our knowledge of spiral arms more generally by Sellwood & Masters (2022).

The latter argue that the spontaneous development of spiral patterns in simulations of isolated disks results from a recurrent cycle of 'groove modes', being a deficiency over a narrow range of angular momentum that seeds a linear instability, itself creating new grooves (at the Lindblad resonances of the original mode), setting up a recurrent cycle. The alternative quasi-steady density-wave theory seeks to explain long-lived spiral patterns without the need for constant regeneration.

Choosing amongst these theories is most robustly done by matching the observed (spiral-driven) large-scale streaming motions to these predictive models.

One of the first of the Gaia studies made use of Data Release 1, and the distances and motions of 77 Cepheids within 1.5 kpc of the Perseus arm. Baba et al. (2018) found that both radial and rotation velocities (in Galactic coordinates) are correlated with distances from the arm, and found a dependency of their vertex deviation attributed to the spiral arm. Using N-body and hydrodynamic simulations based on these two models (transient dynamic versus a static density-wave), their results favoured a model in which the Perseus arm is in the process of disruption by a transient arm.

A MAJOR OBSERVATIONAL advance came with Gaia DR2, which provided some 6.4 million FGK stars with full 6D phase space coordinates (viz. position and velocity), parallaxes better than 20%, and precise Galactic velocities with typical uncertainties 0.9–1.4 km s^{-1}.

Katz et al. (2018) used a sub-sample of 3.2 million giant stars to map the velocity field of the Galactic disk between 5–13 kpc from the Galactic centre (the innermost region being restricted by heavy dust extinction), and up to 2 kpc above and below the plane. They also studied the distribution of 300 000 solar neighbourhood stars (within 200 pc) to examine how the over-densities evolve in more distant regions.

Their study revealed streaming motions in all three velocity components, small-amplitude fluctuations in the velocity dispersions, for example within the notorious Hercules stream, and striking ridge-like features in the stellar azimuthal velocity distribution as a function of Galactocentric radius.

The rich substructure in the phase space distribution of solar neighbourhood stars indicates that the local disk of the Milky Way is far from the settled well-mixed state invoked by Bertin & Lin (1996) for their steady-state spiral arm model. Nevertheless, Eilers et al. (2020) fitted a steady-state spiral model to estimate the arm relative amplitude of 10%, with a pitch angle of 12°.

WITH EDR3, Castro-Ginard et al. (2021) used open clusters to map the spiral arms, and to determine their pattern speed. They found a declining pattern speed with radius, along with an absence of age gradients downstream from the arms.

Uppal et al. (2022) constructed counts of red clump stars extracted from 2MASS, using EDR3 astrometry and photometry to remove foreground stars. The found an overdensity of red clump stars which traces the continuous morphology of the Outer arm from the second to the third Galactic quadrant. They also found a wave-like asymmetry above and below the Galactic plane with respect to longitude, indicating a warp-like structure.

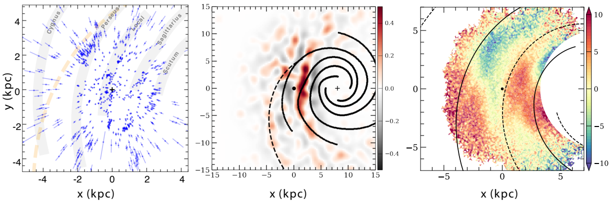
I HAVE PASSED quickly through these insights from DR1, DR2, and EDR3, because a further leap in data quantity and quality came with Gaia Data Release 3 and, with it, a major study concerning mapping of the Galaxy's asymmetric disk by Drimmel et al. (2022).

The number of sources with complete 6D phase space information (position and velocity) increased to over 33 million, along with astrophysical parameters for 470 million, and variability classification for 11 million. Using some 580 000 hot OB stars, together with 988 open clusters younger than 100 Myr, they mapped the spiral structure associated with star formation out to 4–5 kpc from the Sun. Beyond that, 2800 classical Cepheids with ages less than 200 Myr reveal spiral features in the outer disk extending to some 10 kpc from the Sun.

They also identified 8.7 million sources on the red giant branch, of which 5.7 million have line-of-sight velocities, allowing the velocity field of the Milky Way to be mapped as far as 8 kpc from the Sun.

The spiral structure revealed by the young populations shows the Local (Orion) arm to be at least 8 kpc in length, and an outer arm consistent with that seen in H I surveys, which appears to be a continuation of the Perseus arm into the third quadrant. The subset of red giant branch stars reveals the large-scale kinematic signature of the inner bar, as well as evidence of streaming motions in the outer disk that might be associated with spiral arms or bar resonances.

Evidence of streaming motions associated with spiral arms is, they conclude, much less compelling than that due to the bar. But, if present, they are consistent with the two-armed structure seen in the near-infrared.



Drimmel et al. (2022)

(a) young clusters; (b) young Cepheids; (c) red giant branch stars

A DIFFERENT MODEL for the generation of spiral arms attributes them to an interaction with the Sagittarius dwarf galaxy. Antoja et al. (2022) modelled such a tidal encounter, and found a strong similarity between the resulting kinematic signatures, in the form of ridges and waves in angular momentum, to those observed in the Gaia DR2 data. Specifically, they found that an impulsive distant tidal approach generates a perturbation in velocities that leads to a two-armed spiral structure, and a 'winding time' in the range 0.8–2.1 Gyr.

WHERE DOES all this leave us? In their review, Sellwood & Masters (2022) argue that the ubiquity of spiral patterns in the stellar disks of other galaxies appears to demand an explanation in which they largely result from self-excited disk instabilities. Other driving mechanisms, such as bars and tidal encounters, may result in spiral responses in specific cases, but such external drivers could not, they argue, account for all, or perhaps even most, spiral patterns.

But they also emphasised that we still lack compelling evidence that the recurrent cycle of 'groove modes', identified as the mechanism for spiral generation in numerical simulations, actually operates in real galaxies. Future releases of Gaia data may, they surmise, yield stronger evidence in the case of the Milky Way.

This confusing picture of the spiral structure of our own Galaxy is unfortunate, not least because it is the only case where we have a detailed 'close-up' view!