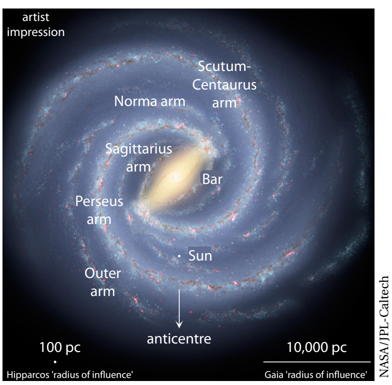
39. The Galactic anticentre

THE BROAD features of our Galaxy are today well established. Our Sun sits close to the mid-plane, and 8 000 pc out, in a rotating spiral galaxy comprising a flattened disk, a central spherical bulge and an inner bar. All are embedded in a spherical halo comprising normal matter as well as invisible dark matter of unknown form.

Our Galaxy has been shaped over its 10 billion year history by the accretion of other smaller galaxies, with evidence for major mergers in the distant past, as well as others still slowly ongoing today. Probing the details of these various populations, and understanding their history, is one of the major goals of modern astronomy. And in this, Gaia is proving to be something of a revolution.

OBSERVATIONS TOWARDS the Galactic centre probe its densest and most complex regions, with multiple populations superimposed along our line-of-sight to the centre: the thin and thick disks, star clusters, spiral arms, a bar-like inner structure, and the central bulge.



The opposite direction, 180° away on the sky, is termed the Galactic anticentre. In this direction, star densities are lower, interstellar extinction is lower (meaning that observations can more easily probe to larger distances), and stars of the disk and halo dominate.

Nonetheless, the structural and dynamical phenomena on display, including the remnants of ancient and recently disrupted stellar systems of extragalactic origin, are proving to be an important window on its dynamics and past history.

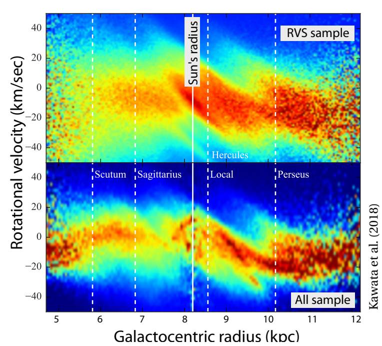
It has not been easy to understand how these various features have arisen. For example, the prominent spiral arms, seen in 60% of all galaxies, arise from some combination of density waves, and self-propagating star formation, but they remain incompletely understood.

THE BAR towards the centre of our Galaxy was recognised only in the 1960s, while the fact that the flattened disk actually comprises two separate 'populations' – a thin disk, and a thick disk – was discovered only in the 1980s. The picture has become even more confusing over the past 20 years, with various other complex structures and dynamical features still being uncovered.

Gaia is providing huge numbers of stars with well-defined distances and velocities, allowing many of these features to be mapped in much greater detail, such that better models and theories of them can be developed.

SINCE THE late 1950s, astronomers have recognised that the disk is not flat, but warped – slightly curved up on one side, and down on the other. One idea was that this resulted from an irregular-shaped dark matter halo. But velocities of 12 million giants stars, from Gaia DR2, suggest instead that it is a ripple-like effect due to the Sagittarius dwarf galaxy, which orbits the Milky Way, and which has probably ploughed through the Galaxy's disk several times in the past (Poggio et al., 2020).

Amongst other features suspected before the Gaia survey are vertical asymmetries in the star counts linked to vertical bending and breathing waves, and large-scale substructure and velocity patterns in the disk.



Gaia DR2 has already clarified many of these. From orbital velocities around the Galaxy, between 5–12 kpc from the centre, Kawata et al. (2018) found several prominent diagonal 'ridges' in two large samples: of 861 680 radial velocity stars, and 1 049 340 brighter than 15.2 mag.

In another example, Bennett & Bovy (2019) used Gaia DR2 to confirm that the local disk is undergoing a wave-like oscillation, and they established a dynamical model of this perturbed local vertical structure.

THE ASTROMETRIC MEASUREMENTS from EDR3 have allowed further progress, reported in some detail by Antoja et al. (2021). Distant regions of the Galaxy in all directions, especially in the direction of the anticentre, can now be explored using positions and velocities of unprecedented quality. We can now probe structures and motions to distances of 15 000 pc or more from the Galactic centre, out to the very outskirts of our Galaxy's disk. And spatial and velocity structures can be rigorously classified as a function of age and radius.

IN THE OUTER DISK, beyond 12 000 pc, the velocity field is seen even more prominently – and with further structure – than with Gaia DR2. Here, velocities are dominated by an upwards warping motion of $5\,\mathrm{km\,s^{-1}}$, and attributed either to the passage of the Sagittarius dwarf galaxy, or to our ancient collapsing disk that never achieved dynamical equilibrium.

The ridge-like features, already seen in the circular velocities of the Gaia DR2 data, are now detected in EDR3 up to 14 000 pc from the Galactic centre. Two additional ridges are apparent, still part of the disk's circular rotation, but now extending out to 16–18 000 pc. The precise nature and origin of all of this detailed velocity structure is not yet known.

IN THE GAIA DR2 data, two distinct populations of redder and bluer stars were evident in the Hertzsprung–Russell diagram of the subset of stars with large tangential velocities near the Sun. These high-velocity stars are nearby members of the stellar halo population.

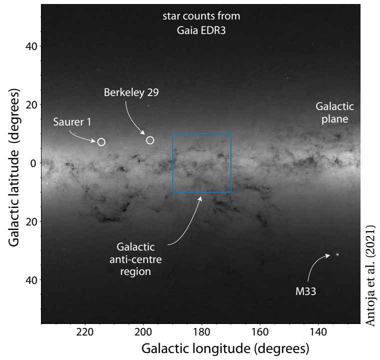
Babusiaux et al. (2018) suggested that the bluer stars are an accreted population arising from the ancient merger of the Gaia 'Enceladus' galaxy, while the redder stars are a distinct thick disk population that was present at the time of the Enceladus merger.

The Gaia EDR3 data extends the distance out to which the Gaia Enceladus debris merger can be traced, to distances of 17 000 pc or more from the Galactic centre. The new data also show that most of the (local) halo is made up of debris from this single accretion event.

OTHER DENSITY STRUCTURES are seen towards the edge of the disk in the anticentre direction. The deep Sloan Digital Sky Survey had already hinted at the existence of a 100°-wide structure in their star count maps in 2002. Now known as Monoceros, and some 10 000 pc distance from the Sun, later studies have confirmed its existence, and its large extension on the sky. Together with the Anticentre Stream, and the Triangulum–Andromeda 'overdensities', they are all part of a complex and sub-structured outer disk.

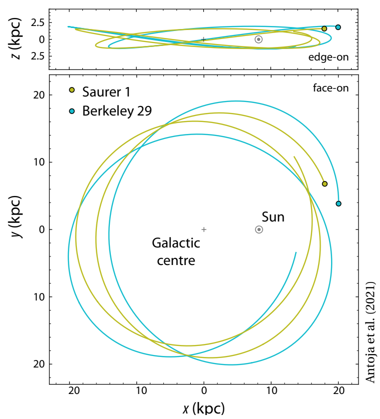
The earlier idea that these could be the remains of an accreted dwarf galaxy seem less likely today, in part because there is no obvious progenitor, and in part because their stars are so similar to the rest of the disk.

OPEN CLUSTERS can also be used to trace the global structure and evolution of the disk, and a major advance in this area already took place using Gaia DR2. Berkeley 29 and Saurer 1 both lie in the anticentre direction and, with ages of several Gyr, are among the oldest Galactic open clusters known.



Their unusual location, 20 000 pc from the centre, and more than 1000 pc above the mid-plane, led several authors to question whether they are really associated with the disk, or whether they had an extragalactic origin. The difficulty of interpretation was simply because, at these very large distances, small proper motion errors translate into very large uncertainties in space velocities.

Using the vastly better astrometry of Gaia EDR3, and the much improved ability to assign cluster membership, Antoja et al. (2021) showed that the two clusters are indeed in disk-like orbits.



Orbits of Saurer 1 and Berkeley 29

But their distant location raises questions as to their origin: does the disk really extend so far out, or were these clusters delivered there by other means, such as radial migration, interaction with a passing galaxy, or born from material expelled from the disk?

These clusters may be small in size, but they provide important clues about the nature of the outer disk.

THE TRANSFORMATION brought by Gaia is hard to overstate. Where space science of the late 20th century gave astronomers a catalogue of 120 000 stars, and a 'radius of influence' of around 100 pc, Gaia provides a census of 2 000 000 000 stars, extending this radius of influence out to the very edges of our Galaxy's disk.

As Antoja et al. (2021) expressed it: *'The Gaia EDR3 data, together with the advantage of having astrometry and photometry from the same mission, have allowed us to extend the horizon for exploration towards the very end of the disk, to travel to the past to explore its ancient components, and to detect its small constituents and phase space features with much greater resolution.'*