# 252. The Great Wave

TO A FIRST APPROXIMATION, our Galaxy comprises a flattened rotating disk of normal (baryonic) matter, embedded in a roughly spherical halo of dark matter. As has been known for some decades, the disk is better described as comprising a thin disk (of younger stars, gas, and dust) and a thick disk (of older stars). It hosts spiral arms, a central bulge, and an elongated central bar.

That the disk is slightly warped was first inferred from 21-cm H I observations (Burke, 1957; Kerr et al., 1957; Westerhout, 1957; Oort et al., 1958). Even at that time, it was hypothesised that the warp was possibly due to tidal interactions with the Magellanic Clouds.

I have described the progress in characterising the *stellar* warp in essay 72: from the proper motions of 2000 young stars by Miyamoto et al. (1993), and from the spatial and kinematic distributions of OB stars from Hipparcos (Smart et al., 1998; Drimmel et al., 2000). Deeper morphological and kinematic complexities, including evidence for disk 'flaring' (e.g. Sun et al., 2024), are being drawn from the successive Gaia data releases.

Very broadly, the warp starts to appear at Galactocentric radii larger than 10–12 kpc, i.e. beyond the Sun's Galactic orbit, and it appears to be precessing (Poggio et al., 2017; Schönrich & Dehnen, 2018; Poggio et al., 2018; Romero-Gómez et al., 2019; Skowron et al., 2019; Li et al., 2019; Wang et al., 2020; Li et al., 2020; Cheng et al., 2020; Poggio et al., 2020; Chrobáková & López-Corredoira, 2021; Li et al., 2023; Sun et al., 2025).

THE DIRECTION AND MAGNITUDE of the warp's precession, and its consistency across stellar age groups, appears to favour it being the result of a recent or ongoing (gravitationally induced) encounter with a satellite galaxy, rather than it being the dynamical relic of the ancient assembly history of the Galaxy.

Interpreted in a cosmological setting, our picture is then of a Galactic disk which continuously experiences gravitational torques and perturbations from a variety of sources, perhaps including a tilted triaxial halo, which causes the disk to wobble, to flare and to warp, in the process conveying important information on its formation history and mass distribution.

THESE GAIA studies often pointed out that their models needed to separate out smaller ripples in vertical and radial velocities which are superposed on the main warp trend. Quoting from Sun et al. (2025): *'Some studies also reveal that the outer disk is likely more complex than a simple warp, most of those point to a wave-like pattern (e.g. Khanna et al., 2019; Friske & Schönrich, 2019; Antoja et al., 2022), with amplitudes that can exceed 1 kpc.* This complexity was also hinted at pre-Gaia (e.g. Xu et al., 2015; Price-Whelan et al., 2015).

In parallel with these studies of the disk warp, and utilising the accurate 6D phase-space distributions (positions and space motions) of vast numbers of stars within a few kpc from the Sun, Gaia has indeed revealed that the Galactic disk is both deeply structured and strongly perturbed (e.g. Antoja et al., 2018; Gaia Collaboration et al., 2018; Kawata et al., 2018; Bland-Hawthorn et al., 2019; Clarke & Gerhard, 2022).

These rich morphological and kinematic structures are being interpreted in terms of complex rotational resonances, for example with the bar and the spiral arms (essays 115–116), and ancient stellar streams resulting from smaller tidally captured galaxies of the Local Group over our Galaxy's 10–12 Gyr history (essay 156).

AMONGST THESE features is the Gaia 'phase-space spiral' discovery by Antoja et al. (2018). This very distinct kinematic feature is evident in a graph of vertical motion in the Galaxy versus vertical position, i.e. in (the phase plane) $Z$ versus $V_Z$. This discovery, which I have described in essay 117, was based on more than 930 000 stars located in a local Galactic cylindrical ring, $R = 8.24 - 8.44$ kpc, for which their median errors in $V_R$, $V_\phi$, $V_Z$ are 0.5, 0.8, and 0.6 km s$^{-1}$ respectively.

This kind of 'phase-wrapping' had been predicted to occur after a passage of a satellite galaxy (e.g. Minchev et al., 2009; Gómez et al., 2012; de la Vega et al., 2015). Indeed, from numerical modelling, Antoja et al. (2018) inferred that the Milky Way disk was likely perturbed 300–900 Myr ago, consistent with estimates of the last pericentric passage of the Sagittarius dwarf galaxy (e.g. Purcell et al., 2011; Laporte et al., 2018; Antoja et al., 2022).

One of the next major morphological and kinematic features to be identified in the Galaxy's disk is the so-called Radcliffe Wave, discovered from the Gaia DR2 data, and which I described in essay 127.

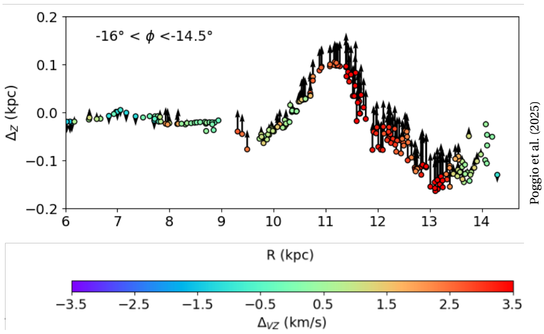
Inferring that the renowned Gould Belt is just the arbitrary celestial projection of a number of nearby star-forming regions, Alves et al. (2020) used the distances of nearby molecular cloud complexes (inferred from foreground and background stars) to establish their true 3D structure. They found a narrow and coherent 2.7-kpc arrangement of dense gas in the solar neighbourhood, at an angle of 30° to the Galactic $y$-axis, running along a significant length of the local (Orion) arm (see their Figure 2). Termed the Radcliffe Wave, it comprises the majority of nearby star-forming regions, has an aspect ratio of 1:20, and contains about $3 \times 10^6 M_\odot$ of gas.

The wave-like structure has since been confirmed, both in vertical positions and vertical velocities, by several subsequent studies, and in different stellar populations (e.g. Donada & Figueras, 2021; Thulasidharan et al., 2022; Bobylev et al., 2022a; 2022b; Li & Chen, 2022; Swiggum et al., 2022; Martinez-Medina et al., 2025).

Its origin remains uncertain. It may be caused by the Kelvin–Helmholtz instability, appearing at the interface between the Galactic disk and the halo rotating at different velocities (Fleck, 2020), or indeed some other manifestation of turbulence (Bobylev et al., 2025b; Goldman, 2025). It may be associated with the impact of shock waves from supernova explosions (Bobylev et al., 2025a). But most studies interpret the wave as arising from a gravitational perturbation of the Galactic disk, due to an external impactor such as a dwarf satellite galaxy of the Milky Way (Bobylev et al., 2022b).

Another unexpected feature has been revealed in the Gaia DR3 data, which Poggio et al. (2025) have termed 'The Great Wave', and which they conclude provides evidence for a large-scale vertical corrugation propagating outwards in the Galactic disk. They analysed the 3D structure and kinematics of two samples of young stars in the Galactic disk, one containing young giants (17 000 stars out to heliocentric distances of 7 kpc) and the other comprising classical Cepheids (3400 stars out to heliocentric distances of 15 kpc). The vertical structure of the two samples exhibit a consistent shape of the Milky Way's warp, whose amplitude reaches ~700 pc at a Galactocentric radius $R \sim 14$ kpc.

In addition, and superimposed on the warp, both samples show evidence of a large-scale vertical corrugation with a vertical height of 150–200 pc, extending over a large portion of the Galactic disk between Galactocentric radii $R \sim 10 - 12$ kpc in the third Galactic quadrant ($l = 180 - 270°$) and 12–14 kpc in the second Galactic quadrant ($l = 90 - 180°$). Its total length is at least 10 kpc, and perhaps as much as 20 kpc.




The constituent stars exhibit both radial and vertical systematic motions, with Galactocentric radial velocities of 10–15 km s$^{-1}$ directed towards the outer disk. In the vertical motions, once the warp signature is subtracted, the residuals show a large-scale feature of systematically positive vertical velocities, which is shifted to slightly larger Galactocentric radii with respect to the spatial vertical corrugation (with a phase difference of roughly $\pi/2$), indicating an oscillatory behaviour. A simple model suggests that the corrugation can be interpreted as a wave propagating towards the outer disk.

I include just one of their figures above (their Figure 16), an edge-on view of the detected corrugation using their young giant sample, in this case showing the vertical spatial residuals $\Delta Z$ as a function of Galactocentric radius $R$ for a specific slice in Galactic azimuth $\phi$. Points are colour-coded by the residuals in the vertical velocity $\Delta V_Z$. Black arrows show the direction and magnitude of the median residual vertical velocity $\Delta V_Z$.

Let me summarise. The warp spans the entire disk, some 30 kpc in extent, one side of the disk bending 'up', and the other 'down'. The Great Wave is a ripple superimposed on the warp, primarily affecting the outer disk, with the wave 'pushing' stars up and down as it ripples outward. As a result, young stars, including Cepheids, reside above or below the warped plane.

The Radcliffe wave is a massive sinuous ribbon of gas and dust that acts as a 'backbone' of our local (Orion) spiral arm, a much smaller and more local filament, affecting both dense gas and star clusters, and which may or may not be part of the same wave system. All of these features are most likely attributable to an external impactor such as a dwarf satellite galaxy. As ESA's press release descibed it: *'Like a rock thrown into a pond, making waves ripple outwards, this Galactic wave of stars spans a large portion of the Milky Way's outer disk.'*

Various studies target a synthesised picture of these perturbations (e.g. Asano et al., 2025; Cabrera-Gadea et al., 2025; Hunt & Vasiliev, 2025; Yamsiri et al., 2026; Kawata et al., 2026). Amongst various large-scale simulations see, for example, §3.1 of Asano et al. (2025).