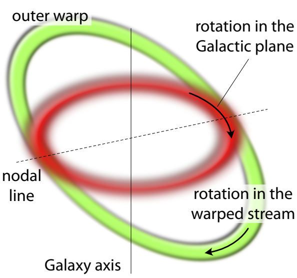
72. The warp of our Galaxy

A WARPED GALAXY is one with an outer disk component which is twisted upward at one side, and down at the other. Many galaxies display such a warped structure, including our own, with at least half of all spirals warped both in gas (H I) and in stars.



Various explanations have been proposed, including infall of intergalactic material, or tidal forcing through a close encounter with a companion galaxy (in our case, perhaps the Magellanic Clouds or the Sagittarius dwarf).

But the existence of many *isolated* warped galaxies may signify some general misalignment of the symmetry axes of the disk and its dark matter halo. In such cases, gas in the outer disk would settle into the symmetry plane of the halo, rather than of the disk. And, importantly, such a tilted disk, embedded in a massive halo, would precess.

PRE-HIPPARCOS STUDIES of our Galaxy's warp mainly focused on its spatial structure (using bright young objects such as Cepheids and OB stars), because its kinematic signature is most evident in the velocities *tangent* to the line-of-sight when viewed from in the plane.

A warping motion, based on the proper motions of 2000 young stars out to 0.5–3 kpc, had already been detected by Miyamoto et al. (1993). They used the 3d Ogorodnikov–Milne formulation to detect shear and rotation around two orthogonal axes in the plane, in addition to the classical (Oort) components. They concluded that young stars are streaming around the Galactic centre in a tilted sheet with a velocity of 225 km s^{-1}, and that the sheet is also rotating around the nodal line of the warp with an angular velocity of 4 km s^{-1} per kpc.

But in his dedicated review, Binney (1992) concluded that the detailed dynamical nature of warps, and their driving mechanism, remained uncertain; a conclusion largely unchanged 25 years later by Poggio et al. (2017).

THE HIPPARCOS DATA nevertheless provided proper motions with systematic and zonal errors significantly smaller than the expected warp signature.

Amongst the Hipparcos results, Smart et al. (1998) focused on 2422 distant OB stars (beyond 500 parsec) towards the Galactic anti-centre. Their choice of young stars assumes that they trace the motions of the gaseous component from which they were born, and thus more likely to trace the warp. They found that the disk is flat to approximately the solar radius, then turns up to the north in the direction of Cygnus at $l \simeq 90°$, and south in the direction of Vela at $l \simeq 270°$.

But while the spatial distribution of stars was consistent with studies based on neutral hydrogen, the velocity distribution was of opposite sign to that expected. Thus the stellar kinematics did not follow the signature of a long-lived warp, whether precessing or not.

Drimmel et al. (2000) confirmed these results using an enlarged Hipparcos sample of 4538 OB stars (also beyond 500 parsec) covering all Galactic longitudes, and using distances derived from both trigonometric and photometric estimates. They concluded that either the warp evolves on a time-scale of the Galactic rotation period or shorter (possibly originating from an impulsive interaction with the Sagittarius dwarf galaxy), or that other large but unidentified systematic motions (such as vertical oscillations) are present within the disk.

A PARTIAL EXPLANATION for these results was put forward by Ideta et al. (2000). They found that kinematic warps in oblate halos 'wind up', and disappear, within a few dynamical times. In prolate halos, in contrast, warps persist with continued alignment of the line of nodes, due to the fact that the precession rate of the outer disk increases when the precession of the outer disk recedes from that of the inner disk, and vice versa.

Meanwhile, cosmological CDM (cold dark matter) simulations suggest not only that dark matter halos surrounding individual galaxies are highly triaxial, but also that the fraction of prolate and oblate halos is roughly equal (Dubinski & Carlberg, 1991).

BEFORE TURNING to the new insights that have come from Gaia, I should open a parenthesis. Further complicating our Galaxy's disk structure are the discoveries of the Monoceros Ring (Newberg et al., 2002), and the Triangulum–Andromeda streams (Majewski et al., 2004). These are ring-like stellar density enhancements of the disk, at around twice the solar radius. Provisionally attributed to a Sagittarius-like impact, simulations suggest that the resulting interactions between the disk and halo can lead to a tightly wound spiral pattern of vertical density oscillations (e.g. Binney et al., 1998).

Other similar overdense regions, like Canis Major, are being further characterised by Gaia, and continue to complicate the picture (Carballo-Bello et al., 2021).

WITH GAIA DR1, Poggio et al. (2017) selected 758 OB stars, also measured by Hipparcos, with distances between 0.5–3 kpc. They found that the proper motions of nearby stars are consistent with a kinematic warp, while stars beyond 1 kpc are not. They concluded that the systematic vertical motions observed in the disk cannot be explained by a stable long-lived warp, and that it is either a transient feature, or that additional forces are causing systematic vertical motions that are masking the expected warp signal.

Schönrich et al. (2018) also used the early Gaia–TGAS distances and proper motions to estimate the vertical and azimuthal velocities in the Galactic centre and anti-centre directions. The mean vertical motions show a linear increase with distance, consistent with the known Galactic warp. But they also reveal a previously unknown wave-like pattern, with an amplitude of 1 km s^{-1} and a wavelength of 2.5 kpc, in both directions. They attributed this to a bending wave, most likely related to the Monoceros and Tri–And overdensities.

NUMEROUS STUDIES followed with the release of Gaia DR2 in 2018. Poggio et al. (2018) extended these kinematic studies out to a distance of 7 kpc from the Sun. Combining Gaia DR2 and 2-Micron All Sky Survey photometry, they identified nearly 600 00 upper main sequence stars and more than 12 million giant stars.

The spatial distribution of the former clearly shows segments of the nearest spiral arms. The large-scale kinematics of both populations show a clear signature of the Galaxy warp, apparent as a gradient of 5–6 km s^{-1} in the vertical velocities from 8–14 kpc in Galactic radius. They argued that the presence of the warp signal in both samples, which have different typical ages, suggests that the warp is a gravitationally induced phenomenon.

Romero-Gómez et al. (2019) used DR2 to examine the vertical motions of two populations up to Galactocentric distances of 16 kpc: a young bright sample mainly comprising OB stars, and an older one of red giant branch stars. They confirmed the age dependency of the warp, both in position and kinematics, its height being around 0.2 kpc for the OB sample and 1 kpc for the older sample at a Galactocentric distance of 14 kpc, with an onset radius of the warp at 12–13 kpc for the former, and 10–11 kpc for the latter. But they also confirmed a high degree of complexity in both position and velocity, including a prominent wave-like pattern of a bending mode, different in the two samples.

A study based on 2431 Cepheids from DR2 reveals asymmetric warp-like large-scale vertical motions with amplitudes of 10–20 km s^{-1} (Skowron et al., 2019). Similar features are found in a sample of 250 000 OB stars, where the flat inner disk begins to warp at about 9 kpc from the Galactic centre (Li et al., 2019), and in a study of nearly 140 000 red clump stars from LAMOST DR4 and Gaia DR2 (Wang et al., 2020; Li et al., 2020).

AMONGST THE LATEST models of the global trends in vertical velocity, Cheng et al. (2020) derived a starting radius for the flare at about 8.9 ± 0.1 kpc, and a precession rate of 13.6 ± 0.2 km s^{-1} per kpc in the direction of Galactic rotation.

From their 12 million giant stars in DR2, Poggio et al. (2020) found a similar precession of 10.86 ± 0.03 km s^{-1} per kpc, i.e. about one-third the angular rotation velocity at the Sun's Galactocentric distance of 8 kpc.

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

But here again, the model assumptions, and these conclusions, are still contested (Cheng et al., 2021).

CURRENT WARP MODELS attempt to separate out the smaller ripples in vertical and radial velocity which are superposed on the main trend.

The present picture, interpreted in a cosmological setting, is of a galaxy disk which continuously experiences gravitational torques and perturbations from a variety of sources, which can cause the disk to wobble, to flare and to warp, in the process revealing important information on the formation history of galaxies, and on the mass distribution of their halos.

Greatly augmented by Gaia's results, our Galaxy evidently presents a unique case study due to our detailed knowledge of its stellar distribution and kinematics.

Nonetheless, a clear and consistent picture of the dynamical nature of our Galaxy's warp, and its driving mechanism, remains elusive. Hopefully, future Gaia data releases will clarify our understanding.

Meanwhile, this nice animation of our Galaxy's warp, created by Stefan Payne-Wardenaar, MPIA Heidelberg, is based on the model by Chen et al. (2019).