49. The rotation of our Galaxy

THE STARS making up the disk of our Galaxy rotate around the Galactic centre which, today, is generally assumed to be defined by its central massive black hole. Our Sun, about 8 kpc from the centre, participates in this general motion, moving around the Galaxy in an approximately circular orbit in about 250 million years.

It has long been known that our Galaxy, as all others like it, does not rotate like a solid body. Instead, its 'rotation curve' has an innermost region (within about 3 kpc from the centre) in almost solid-body rotation, rising to a fairly constant rotation velocity in the solar vicinity. Further out it is flat, or with a slow decline, taken to imply the presence of 'dark matter' in its outer parts.

Much about our Galaxy's origin, structure, and dynamics relies on an understanding of the detailed form of its rotation. Yet many issues complicate its measurement and interpretation, even in the vicinity of our Sun. Before looking at what Gaia has to say about Galactic rotation, we should look at these complications.

IN ANALOGY WITH THE PROBLEM faced by the ancient Greeks in comprehending the motion of the planets, we must understand how the Sun's position and velocity affect its perceived motion around the Galaxy. First, we need to know the distance to the centre of Galaxy, R_0. A difficult problem in its own right, recent results from the GRAVITY collaboration yield, for example, $R_0 = 8.12 \pm 0.03$ kpc (Abuter et al. 2018).

The 'local standard of rest' is the velocity of a hypothetical group of stars in strictly circular orbits at the solar position. Its practical definition is complicated by the wide choice of stars used to represent it, with young stars (for example) not yet being in dynamical equilibrium.

The 'solar neighbourhood' is another somewhat loose concept. It is considered to be a volume centred on the Sun much smaller than the overall size of the Galaxy, containing a statistically representative subset of its population, but with a somewhat arbitrary size dependent on the objects under investigation.

The 'solar motion' itself can be determined with respect to a range of stellar and interstellar constituents. Most frequently, this motion is estimated with respect to the local standard of rest, with $(u_\odot, v_\odot, w_\odot)$ being the difference between the Sun's velocity and that of the reference system which, by definition, moves around the Galaxy with a certain circular velocity.

This circular velocity, usually designated $\Theta(R)$, is the velocity of an object moving in a circle of radius R, in the Galactic plane and about the Galactic centre, for which centrifugal force balances the Galaxy's gravity.

OUR GALAXY'S ROTATION is often expressed in terms of the classical Oort constants, A and B, resting on the assumption of circular motion around the Galactic centre within an axisymmetric potential (the so-called Oort–Lindblad model). Physically, and in analogy with fluid dynamics, A describes the azimuthal shear of the velocity field, while B describes its vorticity.

Local values of the angular rotation rate and its local derivative can then be expressed directly in terms of local values of A and B, with its angular rotation given by $\Omega_0 = A - B$, and its local derivative by $\Omega_0' = -(A + B)$.

Complications in deriving and interpreting A and B occur if the gravitational potential is not axisymmetric, specifically in the presence of spiral density waves and the central bar, in which case the Oort constants will vary with azimuth, and the numerical values will depend on the distance of the tracers adopted.

If the assumptions of strictly circular motion and axisymmetry are relaxed, but still being restricted to motions in the plane, the velocity field can be described by an additional two (Oort) constants, namely a radial shear (C), along with a local divergence (K).

Even more generalised expressions for the velocity field in the vicinity of the Sun assume only that it can be represented by a continuous smooth flow. This was first formulated as a first-order Taylor-series expansion by Ogorodnikov (1932) and Milne (1935).

A later development dating from the 1990s describes the global set of tangential velocities in terms of vector spherical harmonics, allowing for the identification of yet more complex systematic stellar motions.

Armed with these caveats and complications, it is worth stressing that before Hipparcos, such studies could only sample a very small region around the Sun.

Hipparcos allowed many advances, including better estimates of R_0, of the Sun's local motion with respect to the local standard of rest, of the Oort constants A and B, and of the detailed form of the rotation curve, along with higher-order velocity structures.

For example, the first contribution making use of the Hipparcos Cepheid data was that by Feast & Whitelock (1977). They used 220 Cepheids, and assumed $R_0 = 8.5$ kpc, from which they estimated $(u_0, v_0, w_0) = (9.3, 11.2, 7.6)\,\mathrm{km\,s^{-1}}$, and found $A = +14.82 \pm 0.84$ and $B = -12.37 \pm 0.64$ ($\mathrm{km\,s^{-1}\,kpc^{-1}}$), from which $\Omega_0 = A - B = +27.19 \pm 0.87$ and $\Omega_0' = -(A+B) = 2.4 \pm 1.2$.

I took a first look at Gaia's contribution to studies of Cepheid variables in an earlier essay (#43), with their application to estimates of the Hubble constant (from EDR3) in #44. As I pointed out there, while the Hipparcos catalogue contained just 280 Cepheids, Gaia DR2 included 9575, of which 3767 are in the LMC, 3692 are in the SMC, and 2116 are elsewhere ('all-sky').

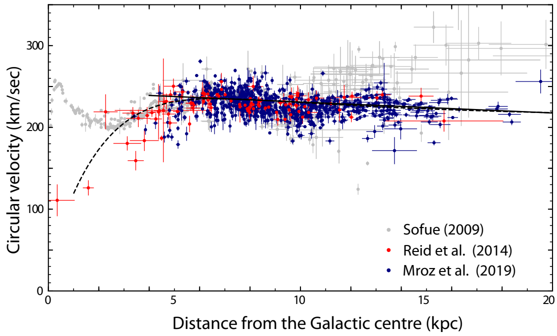
Given that Cepheids can be seen to large distances, and that they reflect the Galaxy's young population, they also provide an important tracer of Galactic rotation, as well as its spiral arms (and indeed its warp).

An examination of the rotation curve from Gaia DR1 was made by Bovy (2017). He used 304 267 main-sequence stars from the Tycho–Gaia Astrometric Solution to examine its structure out to 230 pc from the Sun. The pattern of proper motions clearly displays the effects of differential rotation. Along with the Oort constants $A = 15.3 \pm 0.4$ and $B = -11.9 \pm 0.4$, significant (non-zero) values of $C = -3.2 \pm 0.4$ and $K = -3.3 \pm 0.6$ (all in $\mathrm{km\,s^{-1}\,kpc^{-1}}$), demonstrate the importance of non-axisymmetry for the velocity field of local stars.

A number of papers have already focused on the rotation curve based exclusively on Cepheids.

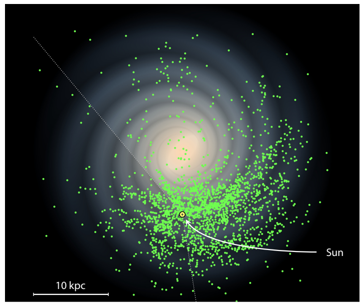
Bobylev (2017) used 260 Cepheids from DR1 to give the Sun's velocity as $(u_\odot, v_\odot, w_\odot) = (7.90, 11.73, 7.39) \pm (0.65, 0.77, 0.62)\,\mathrm{km\,s^{-1}}$, with the rotation curve (for $R_0 = 8$ kpc) described by $\Omega_0 = 28.84 \pm 0.33\,\mathrm{km\,s^{-1}\,kpc^{-1}}$, $\Omega_0' = -4.05 \pm 0.10\,\mathrm{km\,s^{-1}\,kpc^{-2}}$, and yielding a linear rotation velocity of the local standard of rest of $231 \pm 6\,\mathrm{km\,s^{-1}}$.

Mroz et al. (2019) used 773 Cepheids from Gaia DR2 to measure the rotation curve out to 20 kpc from the Galactic centre. Assuming $R_0 = 8.122 \pm 0.031$ kpc (from the GRAVITY Collaboration), they estimated the rotation speed of the Sun as $\Theta_0 = 233.6 \pm 2.8\,\mathrm{km\,s^{-1}}$. From this accurate Galactic rotation curve at distances $R > 12$ kpc, they showed that the rotation curve at Galactocentric distances $R = 4 - 20$ kpc is nearly flat, with a small decreasing gradient of $-1.34 \pm 0.21\,\mathrm{km\,s^{-1}\,kpc^{-1}}$.



Mroz et al. (2019)

Kawata et al. (2019) found reasonable agreement of the local centrifugal speed derived from 218 Galactic Cepheids in DR2 based on both an axisymmetric model, and from a simulation of a Milky Way-like galaxy containing a bar and spiral arms.



Skowron et al. (2019)

2431 Cepheids in a 4-arm spiral model

Skowron et al. (2019) constructed a three-dimensional map of our Galaxy's young stellar population, based on the positions and distances of 2431 Cepheids from the Optical Gravitational Lensing Experiment (OGLE–IV), supplemented by distances and velocities from Gaia DR2. Their simple model of star formation in spiral arms successfully reproduces the observed Cepheid distribution.

Ablimit et al. (2020) examined 3500 Cepheids from OGLE, Gaia, and other surveys with the goal of measuring the rotation curve over Galactocentric distances of 4–19 kpc. Their analysis yields a gently declining rotation curve with a gradient of $(-1.33 \pm 0.1)\,\mathrm{km\,s^{-1}\,kpc^{-1}}$, in agreement with the findings of Mroz et al. (2019).

What does this all mean? Interpreting this rotation in the framework of the Navarro–Frenk–White (NFW) model of galaxy formation, they estimate our Galaxy's (virial) mass as $(0.822 \pm 0.052) \times 10^{12} M_\odot$ within the corresponding (virial) radius of 191.84 ± 4.12 kpc, and a predicted local dark matter density of $0.33 \pm 0.03\,\mathrm{GeV\,cm^{-3}}$. They also conclude that the dark matter halo is the main contributor to the form of the Galactic rotation curve beyond distances of about 12.5–14.5 kpc.

In addition to this information being extracted on the rotation curve of our Galaxy, the Gaia Cepheid data is also being used to trace out the pattern of our Galaxy's warped disk structure, as well as of its spiral arms. I will look separately at these two topics.