75. The local mass density

OUR SOLAR SYSTEM lies very close to (well, just a few light-years from!) the mid-plane of our Galaxy's flattened disk, and a colossal 30 000 light-years from its centre. Like all the other stars in the solar neighbourhood, the Sun (and our planetary system with it) rotates around the centre of the Galaxy, in an approximately circular orbit, once every 250 million years.

Looking out at the disk of our Galaxy, the Milky Way, stellar motions are of course not at all discernible to the naked eye. But astronomy has known for decades that, in addition to these largely circular motions, stars are 'bouncing up and down' about the Galaxy mid-plane, reaching distances of several tens of light-years above or below it, before being 'hauled' back down by the gravitational force exerted by the matter concentrated in the disk itself. The stars then fly on through the mid-plane, before continuing on their indefinite oscillatory journey.

The collective gravity of the Galactic plane results in an oscillatory motion somewhat analogous to a Focault's pendulum controlled by Earth's gravity, albeit with a somewhat longer period... of about 60–90 million years!

What is the *total* amount of matter in the solar neighbourhood determining these motions? The answer must include both visible material (mainly stars and gas, with the contribution of 'cold' gas presently being the most uncertain), along with any dark matter – mass models of the Galaxy based only on visible star counts can only be used to infer *lower* limits.

The result can be expressed in mass per unit volume, $M_\odot\,\mathrm{pc}^{-3}$ (or, for dark matter hunters, in $\mathrm{GeV\,cm}^{-3}$), or as the column density out to a given z distance from the plane, expressed in $M_\odot\,\mathrm{pc}^{-2}$. Our present understanding is that the projected mass of disk matter corresponds to roughly $70\,\mathrm{g\,m}^{-2}$, about the density of typical A4 paper, spread out across our Galaxy's mid-plane!

MEASUREMENT of the *dynamical* effects of the local mass density, from the vertical motions of stars, is potentially more robust. Analysis of the density and velocity distribution of a tracer sample of stars can provide estimates of the local density of *all* disk-like matter.

This is often referred to as the K_z problem in Galactic dynamics, where K_z is defined as the component of the Galaxy's gravitational acceleration towards the Galactic plane in the solar neighbourhood.

In a plane-stratified approximation out to a few kpc, K_z is assumed to increase monotonically with z. Studies then use some suitable 'tracer' population to estimate these forces – stars whose number density and velocities can be determined as a function of distance from the plane. Matter produces both the restoring potential (mathematically described by Poisson's equation), and is at the same time influenced by it (mathematically described by the Boltzmann or vertical Jeans' equation).

HIPPARCOS brought a number of observational advances to this problem: primarily an improved accuracy on distances and space velocities, but also an increased size of various tracer populations (such as A stars and K giants). It also provided an improved estimate of the local stellar luminosity function, such that the contribution of *visible* disk matter is better known.

Amongst the first of these studies, Crézé et al. (1998) used luminous A stars within 125 pc of the Sun – stars bright enough to be seen at meaningful distances, but not so young as to be influenced by velocity inhomogeneities as a result of recent star formation.

Crézé et al. derived a local 'dynamical' density of $0.076 \pm 0.015\,M_\odot\,\mathrm{pc}^{-3}$, and a revised assessment of the visible matter density of $0.085\,M_\odot\,\mathrm{pc}^{-3}$. These dynamical and visible estimates being broadly compatible, they argued that (with a dark massive halo still required to explain the Galaxy's rotation curve) the halo must be, to a first approximation, largely spherical.

Along with other Hipparcos-based studies, using different star samples and methodologies (e.g. Bienaymé (1999); Korchagin et al. (2003); Soubiran et al. (2003); Holmberg & Flynn (2004); Bienaymé et al. (2006)), another important consensus emerged: that dark matter is distributed largely in the form of the halo, with little if any concentrated in the disk.

The pre-Gaia status is reviewed by Read (2014).

With its huge stellar samples and accurate space motions, it is not surprising that Gaia is opening a new chapter in this sort of dynamical study.

One of the first to tackle this problem with Gaia was a study by Widmark (2019) using DR2 (a preliminary study along similar lines based on DR1 was made by Widmark & Monari, 2019). His model for the total matter density assumed that it is symmetrical, smooth, and monotonically decreasing with distance from the mid-plane. His (Bayesian) model accounts for the position and velocity of each individual star, in a joint fit of the vertical velocity distribution and stellar number density distribution.

He did this for eight separate data samples, with different limits in absolute magnitude, each containing about 25 000 stars. In all cases, he inferred a density distribution strongly peaked within 60 pc of the Galactic plane. Assuming a baryonic model and a dark matter halo of constant density, this corresponds to an excess surface density of $5-9 M_\odot$ pc^{-2}. He concluded that there is a surplus of matter close to the Galactic plane, perhaps due to an underestimated presence of cold gas.

The model also provides an estimate of the Sun's position and vertical velocity with respect to the Galactic plane, of $Z_\odot = 4.8 \pm 2.3$ pc and $W_\odot = 7.2 \pm 0.2\,\mathrm{km\,s^{-1}}$.

A similar but more extensive study using DR2 was made by Widmark et al. (2021). They repeated the analysis for 120 stellar samples in 40 spatially separate sub-regions of the solar neighbourhood. And by excluding areas of known open clusters, they aimed to quantify the sorts of spatially dependent systematic effects that have complicated this type of measurement in the past.

Their results reveal an unexpected but clear trend for all 40 spatially separated sub-regions, implying a total matter density distribution that is highly concentrated towards the Galactic mid-plane (< 60 pc), but decaying rapidly with height, and with a dependence on Galactic radius consistent with a disk scale length of a few kpc.

They suggested, in particular, that the very low matter density inferred above 300 pc is inconsistent with the observed scale height of the stellar disk, and inferred a time-varying phase-space structure that is large enough to affect all stellar samples in the same way.

Gaia is also providing new possibilities for determining the total matter density of the disk. Widmark et al. (2020) have proposed using 'stellar streams' passing through or close to the Galactic plane. They argue that the vertical component of energy for (dynamically cold) stream stars is approximately constant, such that the vertical positions and vertical velocities of their stars are related via the disk density.

This does not require the disk to be in dynamical equilibrium, and furthermore makes it possible to measure the surface density at large distances from the Sun.

Such methods that avoid assumptions of dynamical equilibrium are gaining importance as other Gaia data clearly indicate such dis-equilibrium (e.g. Salomon et al., 2020). And here we must make a short excursion.

A fascinating discovery using Gaia data has been the identification of what is called the Galaxy's 'phase-space spiral', first reported by Antoja et al. (2018) for stars that lie within 100 pc from the Sun, and subsequently confirmed to hold over a more extended volume of the Milky Way disk (e.g. Bland-Hawthorn et al., 2018). Faint spirals appear in the number density of stars projected onto the $z-v_z$ plane, which are even more prominent when characterised by their radial and azimuthal velocities.

While suggesting that our Galaxy's disk is locally out of dynamical equilibrium, the mechanism driving these phase-space spirals remains uncertain. One suggestion is that they can be (at least 'briefly') generated by a passing satellite, perhaps by a recent encounter with the Sagittarius dwarf galaxy in the case of our own.

Another is a long-lasting phenomenon which, according to N-body simulations, seems to originate spontaneously early in the life of even isolated Milky Way-type galaxies (Raha et al., 1991; Khoperskov et al., 2018): an initially axi-symmetric disk develops a prominent central bar in 2–3 rotations which, after 0.5–1 Gyr, becomes vertically unstable and buckles, breaking the symmetry with respect to the equatorial disk midplane.

First efforts in using such time-varying structures to measure the vertical gravitational potential of the Galactic disk yield a local halo dark matter density of $0.0085 \pm 0.0039 M_\odot$ pc^{-3}, and an upper limit on the surface density of any thin dark disk with a scale height < 50 pc of about $5 M_\odot$ pc^{-2} (Widmark et al., 2021). They argue that these time-varying dynamical structures '*... can also be regarded as assets containing useful information*'.

In a broader context, the Sun's distance from the disk mid-plane, and its vertical velocity and oscillation period, probably have some connection to our own solar system's habitability, for example in relation to the frequency of stellar fly-bys (and therefore cometary impacts), or the incidence of ultraviolet or X-ray radiation.

And the local dark matter density is an important quantity for dark matter detection experiments. Other estimates come from our Galaxy's rotation curve (reviewed by Sofue, 2020), and from the analyses of halo stars, also most recently from Gaia (Wegg et al., 2019).

In their review, de Salas & Widmark (2021) conclude that most local analyses coincide within a range:

$$\rho_{\mathrm{DM},\odot} = 0.4-0.6\,\mathrm{GeV\,cm^{-3}} = 0.011-0.016 M_\odot\ \mathrm{pc^{-3}}$$

while more global studies give a slightly lower range:

$$\rho_{\mathrm{DM},\odot} = 0.3-0.5\,\mathrm{GeV\,cm^{-3}} = 0.008-0.013 M_\odot\ \mathrm{pc^{-3}}$$

(where $1 M_\odot$ pc^{-3} = 37.5 GeV cm^{-3}).

Future Gaia data releases will certainly allow many more advances in these important areas.