153. The solar motion

GAIA IS PROVIDING a major advance in understanding our Galaxy's disk and halo kinematics. Here, I will look at the specific problem of determining the 'solar motion'. To understand what this is, why it is important, and how it is determined, we need some background.

Describing the stellar kinematics of the Galactic disk has become ever more sophisticated as the quality of observations improves. Efforts started with an ellipsoidal and Gaussian model for the velocity distribution in the solar neighbourhood by Schwarzschild (1908).

But even early on it was recognised that this picture is too simple: for example, Kapteyn (1905) and others pointed out that the distribution of velocities in the solar neighbourhood is not smooth but clumpy, in particular for early-type stars, now hypothesised to be (at least in part) the fabric of associations and open clusters.

TO PROGRESS, a number of concepts are useful (see Perryman, 2009, Chapter 9 for more details):

(a) Distance of the Sun from the Galactic centre, R_0. It is a working hypothesis that the Galactic centre (defined by the black hole, Sgr A*, itself assumed to coincide with the Galaxy's barycentre) defines the origin of an inertial coordinate system.

(b) Circular velocity, $\Theta(R)$, usually measured in $\mathrm{km\,s^{-1}}$, 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. The simplest definition assumes axisymmetry.

(c) The 'solar neighbourhood' is a loose concept considered to be a volume centred on the Sun, of arbitrary size much smaller than the Galaxy, but containing a representative subset of its population. It may range, for example, from a sphere of radius 10 pc for the faint, common white dwarfs or M dwarfs, out to 1 kpc or more for the brighter and rarer O and B stars.

(d) The 'Local Standard of Rest' (LSR) is the velocity of a hypothetical group of stars in strictly circular orbits at the solar position. Its practical definition is again complicated by the wide choice of stars and stellar types that can be chosen to represent it.

(e) The 'solar motion' can then be determined with respect to a range of the Galaxy's stellar and interstellar constituents. Most frequently, it is estimated with respect to the Local Standard of Rest, $\mathbf{v}_\odot = (u_\odot, v_\odot, w_\odot)$, being the difference between the Sun's velocity and that of the reference system which, by definition, moves around the Galaxy with circular velocity $\Theta_0 \equiv \Theta(R_0)$.

DESCRIPTIONS OF the velocity field beyond the solar neighbourhood consider the Galaxy disk as being in a state of differential rotation. The rotation curve of the Galaxy has an innermost part $R \lesssim 3$ kpc in almost solid body rotation. The rotation velocity rises outwards, is roughly constant at $R \sim R_0$, and is fairly flat or with a slow decline at still larger radii, implying the presence of invisible or dark matter in the outer parts.

Description of the rotation law in terms of the classical Oort constants rests on the assumption of circular motion around the Galactic centre. Expressions for the radial and transverse velocities relative to the Sun, v_R and v_T, in particular valid for $d \ll R_0$, i.e. characterising differential Galactic rotation in the solar vicinity, can then be recast in terms of the Oort constants A and B (Mihalas & Binney, 1981, Equation 8–15,16 and 8–19,20).

The Oort 'constants' have units of frequency, and are usually expressed in $\mathrm{km\,s^{-1}\,kpc^{-1}}$. Physically, and in analogy with fluid dynamics, A describes the azimuthal shear of the velocity field, while B describes its vorticity.

If the assumptions of strictly circular motion and axisymmetry are relaxed, but are still restricted to motions in the plane, a more general expression for the velocity field can be described in terms of four 'Oort' constants, which quantify the local divergence (K), vorticity (B), and azimuthal (A) and radial (C) shear of the velocity field (Chandrasekhar, 1942; Olling & Dehnen, 2003).

In the interpretation of the Hipparcos results, some attempts were also made to quantify, and interpret, expressions for a more complete deformation tensor, i.e. including motions out of the plane. This was first described in terms of a first-order Taylor series expansion by Ogorodnikov (1932) and Milne (1935).

Solar motion with respect to the Local Standard of Rest, according to various methods, and as represented by specific stars or spectral types. A more extensive listing is given by Perryman (2009); Table 9.2. $u_\odot$ is the component toward the Galactic centre, $v_\odot$ in the direction of Galactic rotation, and $w_\odot$ toward the north Galactic pole. GCNS is the Gaia Catalogue of Nearby Stars.

Source	Reference	Stars	Solar motion wrt LSR ($\mathrm{km\,s^{-1}}$) $u_\odot$	$v_\odot$	$w_\odot$	Total $V_\odot$
Pre-Hipparcos:						
Compilation	Mihalas & Binney (1981)	various	9	12	7	16.5
APM-based	Evans & Irwin (1995)	various	7.3 ± 1.5	13.9 ± 2.3	8.8 ± 2.2	18.0
Hipparcos:						
Oort–Lindblad	Feast & Whitelock (1997)	Cepheids	9.3	11.2	7.61 ± 0.64	16.4
"	Miyamoto & Zhu (1998)	Cepheids	10.62 ± 1.20	16.06 ± 1.14	8.60 ± 1.02	21.1
Ogorodnikov–Milne	Miyamoto & Zhu (1998)	O–B5 stars	11.59 ± 0.49	13.39 ± 0.48	7.12 ± 0.44	19.1
"	Mignard (2000)	A0–A5 dwarfs	9.92 ± 0.25	10.71 ± 0.26	6.96 ± 0.21	16.2
"	"	F0–F5 dwarfs	11.46 ± 0.37	11.16 ± 0.37	7.02 ± 0.41	17.5
"	"	M0–M5 giants	7.37 ± 0.61	20.29 ± 0.63	6.85 ± 0.66	22.6
"	Branham (2000)	all Hipparcos	10.30 ± 0.06	19.13 ± 0.05	7.09 ± 0.04	22.8
Vectorial harmonics	Makarov & Murphy (2007)	non-binary	9.9 ± 0.2	15.6 ± 0.2	6.9 ± 0.2	19.7
Spiral-density wave	Mishurov & Zenina (1999)	Cepheids	7.8 ± 1.3	13.6 ± 1.4	–	–
"	Lépine et al. (2001)	Cepheids	8.8 ± 1.0	11.9 ± 1.1	–	–
Other	Dehnen & Binney (1998)	dwarfs	10.0 ± 0.36	5.25 ± 0.62	7.17 ± 0.38	13.4
"	Brosche et al. (2001)	K0–K5 giants	9.0 ± 0.5	21.0 ± 0.5	7.7 ± 0.4	24.1
"	Hogg et al. (2005)	dwarfs	10.1 ± 0.5	4.0 ± 0.8	6.7 ± 0.2	12.8
Gaia:						
GCNS (EDR3)	Smart et al. (2021)	$G < 13$ mag	11.3	6	7	14.6
"	Robin et al. (2022)	Besançon model	10.79 ± 0.56	11.06 ± 0.94	7.66 ± 0.43	17.3
"	Guo & Qi (2023)	$d < 100$ pc	10.1 ± 0.1	22.8 ± 0.1	7.8 ± 0.1	26.1
halo streams (EDR3)	Malhan et al. (2020)	$d = 3 - 30$ kpc	8.88 ± 1.21	241.91 ± 1.67	3.08 ± 1.08	–

With this background, this compilation of *some* of the pre-Hipparcos, Hipparcos, and Gaia determinations of $(u_\odot, v_\odot, w_\odot)$, should be reasonably self-explanatory. And let me stress that determination of the solar motion is important not only because it is typically determined as one part of the overall disk velocity field. Many astrophysical conclusions, not only dynamical but extending to dark matter detection experiments (e.g. Freese et al., 2013), depend on its assumed value.

The component in the direction of the Galactic rotation, $v_\odot$, is particularly uncertain. While there are good reasons why young stars might be expected to represent this component (related to the secular evolution of Galactic orbits), they are also problematic because their space motions are not yet dynamically 'relaxed'.

Of the Gaia-based determinations, three have used the Gaia Catalogue of Nearby Stars within 100 pc, itself based on Gaia EDR3 (GCNS, Smart et al., 2021). The solar motion is derived, as usual, by model fitting to the velocity distributions of representative stars.

Smart et al. (2021) based their determination on bright stars, $G < 13$ mag, while Guo & Qi (2023) employed the full sample. Robin et al. (2022) based their model fitting, largely using the GCNS sample with some deeper extensions, to adjust their (Besançon) dynamical model of the Galaxy disk to the Gaia EDR3 data.

A very different approach has been taken by Malhan et al. (2020). It circumvents the traditional route of representing the Sun's velocity with respect to the Galactic centre as the velocity of the Sun with respect to the solar neighbourhood (defined by local stellar samples) added to the velocity of the Local Standard of Rest.

Instead, they used EDR3 to measure all three components of the Sun's velocity with respect to the Galactic halo, as represented by 17 stellar streams over distances of 3–30 kpc. Their method is based on the fact that, in low-mass streams, stellar proper motions should be directed along the stream structure in a non-rotating rest frame of the Galaxy, and in which any observed deviation arises due to the Sun's own reflex motion. Their determination of the Sun's motion is also independent of a Galactic potential model.

Their $v_\odot$ component *includes* the contribution from the motion of the Local Standard of Rest itself, for which recent (Gaia-based) estimates favour values in the range $240 - 260\,\mathrm{km\,s^{-1}}$ (e.g. Hayes et al., 2018; Bovy, 2020). They argue that their determination, the first to estimate all three components of the Sun's velocity with respect to the halo, is in global agreement with past measurements by other techniques.

This suggests, in turn, that the inner Galaxy, and in particular the disk, is not moving with respect to the inertial frame defined by the halo streams.