126. Our Sun's height above the disk

For over a century it has been considered that the Sun does not lie exactly in the mid-plane of the Galactic disk, irrespective of the tracers used to define it. Already Shapley (1918), in his study of globular clusters, concluded that the Sun is '*…some 20 parsecs north of the plane*'. The table (over) lists estimates of the Sun's height above the mid-plane, $Z_\odot$, that have been made since.

Out of some 30 estimates in the past 20 years, values still range from as small as $Z_\odot = 5.2 \pm 4.7$ pc based on A/F stars (van Leeuwen, 2007) to as large (and precise!) as $Z_\odot = 34.56 \pm 0.56$ pc using 93 106 solar neighbourhood stars with a range of spectral types (Branham 2003). Both these extremes were based on the Hipparcos data! Let me note already here that positive values of Z are towards the North Galactic Pole, i.e. *above* the plane.

In a pre-Gaia review of the Milky Way, Bland-Hawthorn & Gerhard (2016) found that their most plausible estimates were between 20–30 pc, while Karim & Mamajek (2017) noted that their own determination, 17 ± 5 pc, was consistent with '*…the median of 55 previous estimates published over the past century,* 17 ± 2 *pc*'.

Since distances are crucial in deriving such a linear quantity, it would be natural to expect that Gaia is providing a more definitive answer. As we will see, it has certainly compounded the question's complexity.

The height of the Sun above the disk mid-plane is important because it affects the interpretation of numerous observations of our Galaxy's disk, such as studies of asymmetries in star counts or dust emission.

The Sun's location, and its motion with respect to the Local Standard of Rest, also has consequences for comprehending our solar system's habitability, including the Galactic radiation environment, and the Sun's vertical oscillations and passages through the spiral arms.

In the Galactic coordinate system adopted by the IAU in 1958, the equatorial plane, $b = 0°$, passes through the Sun (Gum et al., 1960; Blaauw et al., 1960). If the Sun were exactly in the mid-plane, the Galactic coordinate system's origin should coincide with the Galactic centre.

The Sun's location has also become more relevant as improved observations focus the need for a more operational definition of the Galactic coordinate system (e.g. Anderson et al., 2019). This is itself linked to whether the black hole at the Galactic centre, Sgr A*, precisely coincides with its dynamical centre (e.g. Leung et al., 2022).

Attempts to define Z_0 should be based on objects expected to trace the Galactic disk (e.g. Karim & Mamajek, 2017). In this spirit, the (still current) IAU 1958 definition was based on the distribution of H I gas, which has the advantage of tracing mass at large distances, and demonstrates a high degree of flatness in the plane.

Other suitable tracers are young stellar objects and open clusters (which typically lie within a few hundred parsec of the plane); infrared dark clouds (a particular class of molecular cloud known to be the sites of the earliest stages of star formation); H II regions and H I shells (especially prominent in the radio and infrared); asymptotic giant branch stars (luminous evolved stars that are known to trace the radial and vertical structure of the Galactic disk); and supernovae remnants.

Examples of pre-Hipparcos estimates of Z_0 range from 10 pc from interstellar dust measurements, 10–12 pc from several thousand OB stars within 4 kpc; 15 pc from IRAS source counts and COBE data; 20 pc from star counts at the Galactic poles; 27 pc from the Sloan Digital Sky Survey; 37 pc from Cepheids; to as much as 42 pc from some classical star counts.

Effects of the warp, the Gould Belt, and extinction, were often noted as complications.

Amongst many new determinations with Hipparcos were 22.8 ± 3.3 pc from open clusters, 24.2 ± 1.7 pc from O–B5 stars, and 34.56 ± 0.56 pc from more than 90 000 parallaxes with a range of spectral types.

That there was no clear consensus from Hipparcos is, today, hardly a surprise. Gaia has since confirmed numerous morphological complexities and, more particularly, various non-equilibrium dynamical features (e.g. Antoja et al., 2018; Bennett & Bovy, 2019) making their use as accurate disk tracers more questionable.

AMONGST THE MORE recent work *not* using Gaia, two papers have focussed on very young high-mass tracers, with both finding significantly smaller values, $Z_0 \simeq 5-6$ pc, than the past century's median.

Reid et al. (2019) analysed the distances and motions of 200 molecular masers associated with very young high-mass stars. They found that the orientation of the associated plane is consistent with the IAU 1958 definition to within $\pm0.^\circ1$, and that the Sun is offset toward the north Galactic pole, with $Z_\odot = 5.5 \pm 5.8$ pc. Accounting for this offset also then places the central supermassive black hole, Sgr A*, in the mid-plane of the Galaxy.

Anderson et al. (2019) used the WISE Catalogue of Galactic H II Regions to define a 'high-mass star formation mid-plane', finding a similar value, $Z_\odot = 5.6 \pm 2.6$ pc. They showed that this plane is not significantly tilted or rolled with respect to the IAU mid-plane, and that the Sun is therefore near to this mid-plane. They attribute the inconsistency with many previous *stellar* studies as arising from asymmetries in the stellar distribution near the Sun.

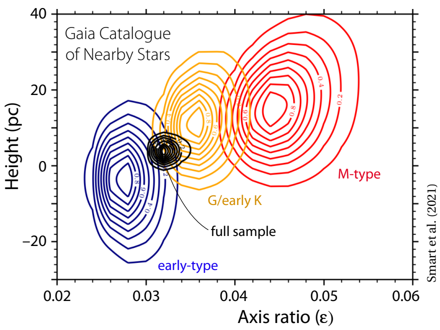
AND SO TO the early Gaia results. The first three here follow the principles of the classical K_z problem in Galactic dynamics, which aims to quantify the force law perpendicular to the Galactic plane, and which requires a tracer population whose number density, and vertical velocities, can be determined as a function of height.

Using DR1, Widmark & Monari (2019) used stars out to 160 pc and, in addition to estimating the local matter density, found $Z_\odot = 15.3 \pm 2.2$ pc. Using DR2, Widmark (2019) found $Z_\odot = 4.76 \pm 2.27$ pc.

Bennett & Bovy (2019) made a similar dynamical analysis using DR2. As well as identifying a wave-like oscillation in vertical velocity, they made the '*... most precise and accurate determination of the Sun's height above the local Galactic mid-plane*', $Z_\odot = 20.8 \pm 0.3$ pc.

From Gaia EDR3, and using the Gaia Catalogue of Nearby Stars, Smart et al. (2021) found $Z_\odot$ varying from -4 pc to 15 pc for young to older stellar populations, and a tilt between the Galactic and $Z = 0$ plane of only $0.^\circ1$.

MORE CLARITY will surely follow. Watch this space!



Reference	Description	$z_\odot$ (pc)
Shapley 1918	Globular clusters	20*
Kreiken 1926	Local stellar system	250
Gerasimovic 1927	Cepheids, O-, B-, etc	33±3
vanTulder 1942	Cepheids, planetary neb.	13.5±1.7
vanRhijn 1955	A-type stars	18
vanRhijn 1956	K-type stars	5
Gum 1960	H I gas	4±12
Blaauw 1960	OB-type stars & Cepheids	22±2
Kraft 1963	Cepheids	35±5
Elvius 1965	AFGK-type stars	10
Fernie 1968	Cepheids	45±15
deVaucouleurs 1969	Galactic absorbing layer	11
Stothers 1974	OB-type stars	24±3
Stenholm 1975	WR stars	31±10
Toller 1981	Pioneer 10 starlight	12.2±2.1
Lynga 1982	Open clusters	20
Magnani 1985	Molecular gas	30
Stobie 1987	*UBV* star counts	42±13
Caldwell 1987	Cepheids	35±9
Pandey 1987	Interstellar matter	10±4
Pandey 1988	Open clusters	28±5
Ratnatunga 1989	Yale Bright Star Catalogue	7
Conti 1990	Wolf-Rayet stars	15±3
Toller 1990	Background light/dust	12.8±2.9
Yamagata 1992	*UBV* star-count	40±3
Brand 1993	Local molecular clouds	13±7
Hammersley 1995	2MASS, IRAS and COBE	15.5±3
Cohen 1995	IRAS point source, FAUST	15.5±0.5
Humphreys 1995	Optical star counts	20.5±3.5
Ng 1997	Star counts & colours	15
Binney 1997	COBE all-sky survey	14±4
Reed 1997	OB-type stars	9.5 ± 3.5
Freudenreich 1998	Diffuse infrared background	16.2
Mendez 1998	Interstellar dust	27±1
Chen 1999	COBE & IRAS reddening	27.5±6.0
Maiz-Apellaniz 2001	OB-type stars	24.2±1.7
Chen 2001	SDSS star counts	27±4
Branham 2003	Hipparcos except OB stars	34.56±0.56
Paladini 2003	H II regions	9.3±2
Joshi 2005	Reddening of open clusters	22.8±3.3
Reed 2006	OB-type stars	19.6±2.1
Piskunov 2006	Open clusters	22±4
Elias 2006	OB-type stars	12±12
Bonatto 2006	Open clusters	14.8±2.4
van Leeuwen 2007	Hipparcos A-/F-type stars	5.2±4.7
Joshi 2007	Young open clusters & OB	17±3
Kong 2008	OB-type, horizontal branch	7.6±4.3
Juric 2008	SDSS stellar density	25±5
Majaess 2009	Cepheids	26±3
Liu 2011	Open clusters	16±4
Buckner 2014	Open clusters	18.5±1.2
Olausen 2014	Magnetar (and candidates)	17.5 ± 4.5
Bobylev 2016a	OB-, Wolf-Rayet, Cepheids	16±2
Bobylev 2016b	H II, masers, mol. clouds	8±2
Joshi 2016	Open clusters	6.2±1.1
Karim 2017	Sgr A* offset from plane	17.1±5.0
Later results*:		
Skowron 2019	classical Cepheids	14.5±3.0
Yao 2017	pulsars	13.4±4.4
Anderson 2019	high-mass/H II	5.6±2.6
Reid 2019	high-mass/molecular masers	5.5±5.8
Gaia based*:		
Widmark 2019a	dynamical model (DR1)	15.3±2.2
Widmark 2019b	dynamical model (DR2)	4.76±2.27
Bennett 2019	vertical waves (DR2)	20.8±0.3
Smart 2021	nearby stars (EDR3)	−4 → 15

This compilation is based on Karim & Mamajek (2017, Table 3)
Modifications or additions are shown *