111. The distance to the Galactic centre

THE GALACTIC CENTRE is the rotational centre of our Milky Way galaxy, associated with the supermassive ($\sim 4 \times 10^6 M_\odot$) black hole, and the related compact radio source Sagittarius A* (or Sgr A*).

The distance to the Galactic centre, designated R_0, is arguably the most fundamental distance entering treatments of our Galaxy's structure and dynamics. It appears in estimates of its total mass and of its major components, its rotation, and the orbital parameters of stars characterising its chemical and dynamical evolution.

AT AROUND 7.5–8.5 kpc, the Galactic centre is too distant for trigonometric parallax determinations (at least pre-Gaia). Interstellar dust limits studies to infrared and radio wavelengths, while the large and variable extinction complicates the use of secondary distance indicators. And there are uncertainties in defining a population representative of the Galactic centre. In consequence, its distance remains not well determined.

Early estimates (e.g. Shapley 1918), were made from the space density of objects believed to be distributed symmetrically around the Galactic centre, viz. globular clusters, RR Lyrae stars and Mira variables. Others were made from H_2O masers (e.g. in Sgr B2 and W49).

From the mean of 25 determinations between 1974–86 in the range 6.7–10.5 kpc, Kerr & Lynden-Bell (1986) gave $R_0 = 8.54 \pm 1.1$ kpc, while Reid (1993) also combined different estimates to derive $R_0 = 8.0 \pm 0.5$ kpc. Based on models of Galactic rotation and the Oort constants, Olling & Merrifield (1998) gave $R_0 = 7.1 \pm 0.4$ kpc.

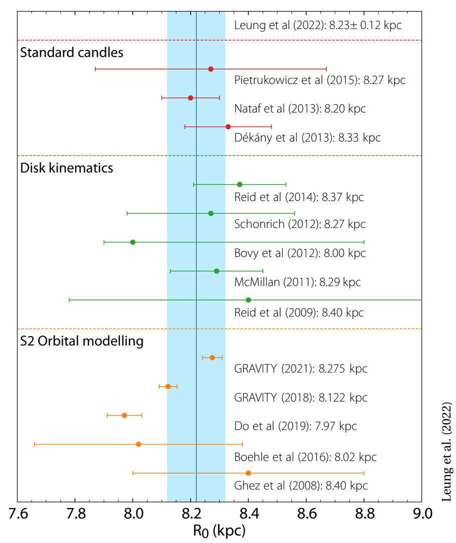
THE HIPPARCOS-based estimates were also indirect, and included $R_0 = 8.5 \pm 0.5$ kpc based on Cepheid kinematics (Feast & Whitelock 1998), $R_0 = 9.3 \pm 0.7$ kpc from a revised RR Lyrae period–luminosity relation for globular clusters (Reid 1998), and $R_0 = 8.2 \pm 0.2$ kpc from the red clump giants in Baade's window detected by OGLE (Stanek & Garnavich, 1998).

In my own review of the Hipparcos results (Perryman 2009), I concluded that *'… estimates for R_0 still lie in the rather broad range 7.5–8.5 kpc'*, with *'a value of $R_0 = 8.2$ kpc being suggested as reference'*.

FROM AROUND 2000, dynamical studies of the Galactic centre based on high-resolution adaptive optics imaging in the infrared provided more direct distance estimates. From improved proper motions and radial velocities for more than a hundred stars within the central few arcseconds of the black hole Sgr A*, Genzel et al. (2000) gave $R_0 = 7.8 - 8.2\ (\pm 0.9)$ kpc.

The orbital parallax of the Galactic centre star S2, around the black hole, based on astrometry and radial velocities, resulted in $R_0 = 7.9 \pm 0.4$ kpc from the GRAVITY collaboration (Eisenhauer et al., 2003). Two other estimates were given by Ghez et al. (2008): 8.0 ± 0.6 kpc for an unconstrained Keplerian orbit, or 8.4 ± 0.4 kpc if the black hole is considered at rest with respect to the Galactic centre (cf. Reid & Brunthaler, 2020).

The most recent estimates (figure below) have been based on standard candles, notably RR Lyrae variables (Dékány et al., 2013) and OGLE clump giants (Nataf et al., 2013); on disk kinematics (e.g. Reid et al., 2014); and on the improved orbit modelling of S2. The latest, $8.275 \pm 0.009\ (\pm 0.033)$ kpc from GRAVITY (2018; 2021), and $7.971 \pm 0.059\ (\pm 0.032)$ kpc from Keck speckle imaging (Do et al., 2019), are the most precise.

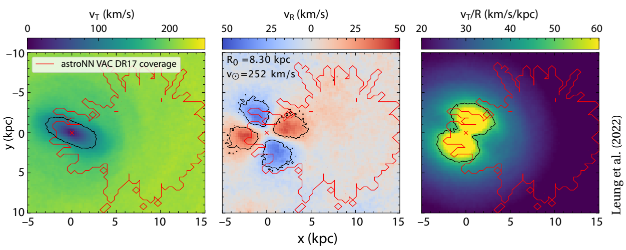


NOTWITHSTANDING THE precision in R_0 from the orbit modelling of the star S2 around Sgr A*, we are left with at least two questions: first, whether the Milky Way's barycentre, the most relevant coordinate origin for dynamical studies, indeed coincides with the location of Sgr A*, or indeed the region of highest star density. The other is the significant difference between the best estimates from the two observational teams.

It is in the context of this still uncertain history of determinations of R_0 that a new approach, making use of the Gaia data, has been made by Leung et al. (2023). It is based on the idea that the motion of stars in the central *bar* region, itself dynamically linked to the massive disk, directly defines the barycentre of the disk–bar system.

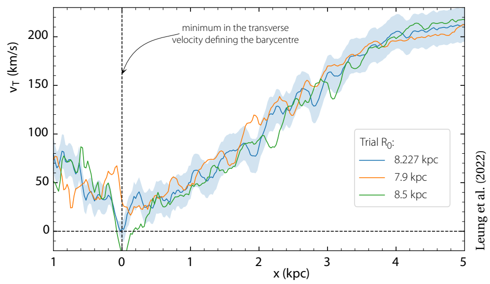
Their data set is based on the combination of the APOGEE DR17 (all-sky, high-resolution near-infrared spectroscopic survey) and Gaia EDR3, to provide a six-dimensional phase-space data set providing an unprecedented census of the Galactic bar region. It builds on previous work which used APOGEE DR16 with Gaia DR2 (Bovy et al., 2019). In practice, the spectral data provides individual radial velocities and Gaia EDR3 provides the proper motions, while the most accurate distances are extracted from a neural-network analysis, trained on Gaia parallaxes of less-distant stars.

The figure shows the spatial extent of their data (red line), projected in the Galactic $x-y$ plane, and superimposed on simulations of the disk–bar system by Kawata et al. (2017). The bar, rotating here at a pattern speed of 24.5 km s^{-1} kpc^{-1} at an angle of 25°, is seen as a density enhancement in the distribution of transverse velocities, v_T (left), as a quadrupole pattern in radial velocities (middle), and as a dipole pattern in v_T/R (right).



Their analysis searches for a minimum in the rotational velocity v_T of stars along the Sun–Galactic-centre line, and determines R_0 by associating this minimum with the Galactic centre (shown in the figure below). Their resulting estimate, $R_0 = 8.23 \pm 0.12$ kpc, is also shown as the shaded region in the figure on the previous page.

Their value would rule out the lower end of the historical measurements, as well as being inconsistent with that from the orbit modelling of the Galactic centre star S2 by Do et al. (2019). But it would be in good agreement with the consensus value $R_0 = 8.2 \pm 0.1$ kpc (which preceded the latest S2 measurements) given by Bland-Hawthorn & Gerhard (2016).



ALTHOUGH a value for R_0 does not appear in the IAU 2009 System of Astronomical Constants, the suggested value remains (I believe) that proposed by Kerr & Lynden-Bell (1986), viz. $R_0 = 8.5$ kpc. Also recommended by them were a consistent set of Galactic constants describing the Sun's motion in the Galactic disk:

* $\theta(R)$, the velocity of an object moving in a circle of radius R about the Galactic centre with centrifugal force balancing the Galaxy's gravity. The circular velocity at the Sun, $\theta_0 = \theta(R_0)$; they proposed $\theta_0 \equiv V_0 = 220$ km s^{-1};

* the Oort constants, A and B, describing the shear and vorticity of the disk rotation;

* the solar motion with respect to the Local Standard of Rest (LSR) which, by definition, moves around the Galaxy with the circular velocity θ_0.

The values of θ_0, the Oort constants at the solar radius, A_0 and B_0, and the solar motion $V_\odot$ (with components $u_\odot$, $v_\odot$, $w_\odot$) have, just like R_0, been notoriously difficult to pin down unambiguously.

THIS IMPROVED VALUE for R_0, enabled by Gaia, can be used in combination with another important result from Gaia, viz. the solar system's acceleration within the Galaxy using the apparent proper motions of quasars (Klioner et al. 2021; see essay #32).

The importance of this direct measure of the centripetal acceleration at the Sun has been described by Bovy (2020) as *'a revolutionary moment for Galactic astrophysics'*. He notes that, expressed as an acceleration

$$\frac{a_0}{c} = \frac{V_0^2}{c\,R_0} = 5.05 \pm 0.35\ \mu\text{as}\,\text{yr}^{-1}$$

which, combined with the above value for R_0, gives

$$V_0 = 243 \pm 8\ \text{km}\,\text{s}^{-1}\ .$$

The angular frequency of the circular orbit at the Sun is, similarly, $\Omega_0 = V_0/R_0 = 29.3 \pm 1.0$ km s^{-1} kpc^{-1}.

If Sgr A* is assumed to be at rest at the Galactic centre, its observed proper motion $\mu_{\rm Sgr\,A*} = -6.411 \pm 0.008$ mas yr^{-1} directly yields the Sun's peculiar velocity $\mu_{\rm Sgr\,A*} = \Omega_0 + (V_\odot/R_0)$, and hence $V_\odot = 8.0 \pm 8.4$ km s^{-1}.

BOVY (2020) goes further, but my key point here is to emphasise how Gaia is transforming our ability to characterise stellar motions across the Galaxy.