216. Star and exoplanet radii: an update

I DISCUSSED Gaia's early contributions to the determination of stellar and exoplanet radii in essay 21, where DR1 parallaxes were used to estimate the radii of 350 000 stars and 116 transiting exoplanets from the Kepler survey (Stassun et al., 2017; Stevens et al., 2017). I look here at more recent results on star and planet radii made possible with Gaia Data Releases DR2 and DR3.

THE MOST DIRECT method of determining stellar diameters involves measuring the star's *angular* diameter (using adaptive optics, lunar occultation, or interferometry; e.g. Baines et al., 2023), then converting the angular diameter to a *linear* diameter using knowledge of the star's distance. Angular diameters can also be determined using eclipse timings and radial velocities of detached eclipsing binaries, again requiring distances to convert them to linear measure (e.g. Torres et al., 2010).

Together, these methods have provided diameters for some 400–500 stars. These relatively few fundamental measures provide the most rigorous size constraints for models of stellar structure and evolution (e.g. Andersen, 1991; Torres et al., 2010; Stassun et al., 2014).

STELLAR RADII can also be estimated using spectroscopic indicators of surface temperature and luminosity to infer the radius using the Stefan–Boltzmann law: $L = 4\pi R^2 \sigma T_{\rm eff}^4$, where L is the bolometric luminosity, R the radius, and $T_{\rm eff}$ the effective temperature. This also requires distances to convert fluxes to luminosities.

Such estimates rest on various assumptions, different for different stellar types. For example, stars are not blackbodies and, for the hottest and coolest, much of the energy lies outside the optical region. Recent all-sky, broadband photometry from the far-UV (at 0.15 μm with GALEX) to the mid-IR (at 22 μm with WISE), has led to much improved estimates of bolometric luminosities.

But surface gravities, chemical abundances, the treatment of rotation and convection, and reddening, introduce further model dependencies. And the underlying assumptions of sphericity, and that the radius is well-defined, break down for the very largest, or for those stars that are heavily spotted.

TO PROVIDE the numerical context, I should mention that various estimates of stellar radii had been made based on Hipparcos distances, amongst them 32 early-type stars by Jerzykiewicz & Molenda-Zakowicz (2000), 1040 FGK stars by Valenti & Fischer (2005), 166 planet-hosting stars by van Belle & von Braun (2009), and 125 A–M dwarfs by Boyajian et al. (2012; 2013).

In contrast, Gaia is now providing the fundamental distances (and other data) needed for estimating stellar diameters for hundreds of millions of stars.

AS I NOTED above, the first application of Gaia distances gave estimated radii for more than 350 000 stars with DR1 parallaxes better than 10% (Stassun et al., 2017; Stevens et al., 2017). They derived bolometric luminosities, L, from fits to the spectral energy distributions (using a wide range of photometric data including Tycho, 2MASS, Galex and WISE), $T_{\rm eff}$ values from photometry and spectroscopy, and distances from Gaia DR1.

They estimated effective temperature, bolometric flux, and angular diameter uncertainties of order 1–2%, with final radius uncertainties of order 8%, slightly larger than some previous (model-dependent) estimates.

Yu et al. (2023) used the spectral energy distributions predicted by the MARCS and BOSZ models with 32 photometric bandpasses, and spectroscopic parameters from the APOGEE, GALAH, and RAVE surveys, along with distances from Gaia DR3, to estimate radii for 1.5 million stars, with an estimated accuracy of 7%.

AS EVIDENT from the additional photometric and spectroscopic data which is required for the better estimation of L and $T_{\rm eff}$, Gaia also contributes to the estimates of stellar radii by providing detailed and homogenous (albeit model-dependent) astrophysical information for each star, derived from Gaia's 3-colour photometry and its RVS (radial velocity spectrometer) spectra.

Results of the Gaia project's 'astrophysical parameters inference system' (Apsis, which I outlined in essay 89) were made available with Data Release 2 (Andrae et al., 2018), and Data Release 3 (Andrae et al., 2023). Let me summarise the parts relevant to stellar radii.

Apsis employs two 'General Stellar Parameterizer' modules. The first, GSP–Spec, uses projection and optimisation methods to best match the mean RVS spectra with a large grid of *theoretical* spectra computed using MARCS models, with a range of atmospheric parameters ($T_{\rm eff}$, log(g), metallicity [M/H], [α/Fe]) and chemical abundances, [X/Fe], spanning the full space of Galactic stellar populations (Recio-Blanco et al., 2023).

The second, GSP–Phot, estimates $T_{\rm eff}$, log(g), [M/H], absolute magnitude, radius, distance, extinctions (A_0, A_G, A_{BP} and A_{RP}), as well as the reddening $E(G_{BP}–G_{RP})$, by forward-modelling the BP/RP spectra, apparent G magnitude, and parallax using a Markov Chain Monte Carlo (MCMC) method (Andrae et al., 2023).

FLAME (Final Age and Mass Estimates) takes the output from GSP–Phot and GSP–Spec, along with astrometry and photometry, to derive the evolutionary parameters: radius, luminosity, mass, and age.

The bottom line is that, bundled with Gaia DR3, Apsis provides (model-dependent) stellar radii, along with $T_{\rm eff}$, log(g), and [M/H], for 470 million stars.

A FURTHER method used to estimate stellar radii and masses, at least for certain spectral types, is asteroseismology (essays 51 and 149). Here, Gaia distances allow for important tests of asteroseismic models.

Asteroseismic radii rely on the measured oscillation frequencies (notably the 'large frequency spacing' and the frequency of maximum oscillation power), along with more conventional stellar parameters, notably $T_{\rm eff}$, L, and [M/H] (e.g. Basu et al., 2010).

Early applications using Gaia DR2 have been described by Sahlholdt & Silva Aguirre (2018) and Bellinger et al. (2019). Other tests and comparisons based on Gaia DR3 have been described by Yu et al. (2023) and Valle et al. (2024). With due model calibration, and accurate metallicities, 'asteroseismic radii' for a few thousand stars accurate to a few percent have been derived.

ONE SPIN-OFF from the knowledge of stellar diameters is the ability to estimate the radii of transiting exoplanets, and in particular for the several thousand being discovered by NASA's Kepler and TESS missions. The radius of a transiting planet cannot be measured directly, but can be derived from the transit lightcurve, given the radius of its host star. Masses are constrained by radial velocity measures.

The planet's radius and mass yield its mean density, which in turn informs whether the planet is a gas giant (like Jupiter or Saturn), an ice giant (like Uranus or Neptune), or a rocky planet (like Earth or Mars). Combined with information about their periods and host star properties, the distribution of planetary radii is already yielding insights into the physics of planetary interiors and atmospheres, and of planet formation and evolution.

THERE ARE four main observables which characterise the profile of an exoplanet transit: the transit depth ΔF, the period, the interval between the first and fourth contacts, and between the second and third contacts.

The transit depth is determined by the planet/star radius ratio, $\Delta F = (R_{\rm p}/R_\star)^2$. But estimates of the *stellar* mass and radius require external constraints, such as its surface gravity, astroseismology, or an independent estimate of the stellar radius. Without going further into methodological details, let me summarise the results on exoplanet radii that have been obtained so far.

Using Gaia DR1 distances to derive the radii of the planet-hosting stars, Stassun et al. (2017) derived the radii of 116 exoplanets with uncertainties ~10–20%. Using DR2 parallaxes, Berger et al. (2018) gave revised radii for 177 911 Kepler stars. Their ~8% precision was a factor 4–5 improvement over previous estimates. From these stellar radii, they estimated the radius of 2123 Kepler planets (and 1922 candidates), confirming a gap in the radius distribution of close-in planets, those between Earth–Neptune size (see also Petigura, 2020).

This general picture was confirmed in a 1000 planet sample by Fulton & Petigura (2018). Their stellar radii improved from 11% to 3% precision (with good agreement with the Apsis results, their Figure 3), with planet radii improved to 5% precision. Improved stellar masses using DR2 was demonstrated by Stassun et al. (2018).

FURTHER IMPROVEMENTS in numbers and accuracies came with Gaia DR3. Berger et al. (2023) presented a homogeneous catalogue of 7993 planet-hosting stars (3248 from Kepler, 565 from K2, 4180 from TESS), and their total of 9324 transiting planets.

They used isochrone fitting and Gaia DR3 parallaxes, photometry, and metallicities to compute $T_{\rm eff}$, log(g), masses, radii, stellar densities, luminosities, ages, distances, and V-band extinctions, finding residual scatter (compared to interferometry and asteroseismology) of 2.8%, 5.6%, 5.0%, and 31% between their $T_{\rm eff}$, radii, masses, and ages and those in the literature.

They determined radii for 4281 Kepler, 676 K2, and 4367 TESS planets, with the 'planet radius gap' being less prominent in the K2 and TESS samples than in the Kepler sample alone. And they identified a clear radius inflation trend in their large sample of hot Jupiters.

In a loosely related study, Zink et al. (2023) used Gaia DR3 proper motions and radial velocities to identify a Galactic location trend: they found that stars making large vertical excursions from the Galactic plane host fewer super-Earths and sub-Neptunes.

I HAVE FOCUSED here simply on the *numbers* of new stellar and exoplanet radii being enabled by Gaia. The above references go into more details of the consequences for planet formation and evolution models.