137. Occultations and stellar diameters

In essay 24, back in June 2021, I looked at some early results of stellar occultation studies which have been enabled by the Gaia positions and space motions, focusing on size measurements of Jupiter's moon Europa, as well as some remarkable insights into the atmospheric properties of Neptune's satellite Triton. Other fascinating results have been emerging in the two years since.

Let me first summarise the context. A stellar occultation occurs when a solar system object, such as an asteroid or a planetary moon, passes in front of a random star as seen from the Earth, causing a temporary drop in the observed brightness of the star.

This brightness drop can be used to determine the occulting object's position, along with its size and shape. And it can probe other properties of the occulting object, such as binarity, the presence of an atmosphere (Sicardy et al., 1990), structures such as rings or moons, or even its topographic features (Rommel et al., 2021).

Pre-Hipparcos, in 1997, the limited accuracy of the positions of both field stars and solar system bodies made it difficult to predict possible occultations with confidence, both in terms of its location on Earth, and the event time. Gaia has revolutionised the field by providing a dense grid of accurate positions of both, such that there are, today, greatly improved prospects of identifying, and predicting, a suitably bright occulting star.

Amateur observers contribute to this developing field, with one of several large efforts coordinated by the `Lucky Star project`. Various on-line databases maintain compilations of occultation results, including the `Rio group` (Braga-Ribas et al., 2019), and `NASA's Planetary Data System` (Herald et al., 2020).

Before turning to the main subject of this essay, which is the use of occultations for the measurement of stellar diameters, let me bring this topic of the occultations of outer solar system objects up-to-date.

One of the major goals in planetary science is to probe the processes of underlying the formation of our solar system. Observational constraints of its outer regions have become an important focus of ongoing research over the past few decades.

Marc Buie, the discoverer of numerous minor planets, and coordinator of the `2017 occultation campaign` of 486958 Arrokoth (aka 2014 MU_{69}, and formerly nicknamed Ultima Thule) in advance of the New Horizons flyby, has described Gaia's positional catalogue as having '*… unlocked the door to widespread studies of the outer solar system*' (Buie, 2022).

Since 2021, occultation results enabled by Gaia have included more on the shape and atmosphere of Neptune's satellite Triton (Marques Oliveira et al., 2022), and of Saturn's irregularly orbiting satellite Phoebe (Gomes-Júnior et al., 2020); of Neptune itself (Souami et al., 2022) and of Pluto (Young et al., 2022); the size, shape and various other characteristics of the trans-Neptunian objects 2002 TC_{302} (Ortiz et al., 2020), 2002 MS_4 (Rommel et al., 2021), 2003 VS_2 (Vara-Lubiano et al., 2022), Huya (Santos-Sanz et al., 2022), and Quaoar observed from space by CHEOPS (Morgado et al., 2022); and similarly for the Centaurs Chariklo and its rings (Morgado et al., 2021), the elongated 2002 GZ_{32} (Santos-Sanz et al., 2021), and (60558) Echeclus (Pereira et al., 2022); and the dwarf planet Haumea along with its satellite Hi'iaka (Fernández-Valenzuela et al., 2022).

Thermal versus occultation diameters are considered by Ortiz (2020), and an open source reduction and analysis package, SORA, by Gomes-Júnior et al. (2022).

A different application has been in the determination of star masses. Although very important in the modelling of fundamental parameters, masses can only be determined directly for certain orbital binaries by appeal to Kepler's laws. An accurate component separation at a specific epoch is a crucial ingredient.

A specific example is for the $V = 6.5$ mag K giant HIP 36189. This was originally discovered to be a binary system as a result of an occultation by (704) Interamnia in 2003 (Herald et al., 2020, Table 1). Together with the occultation-based $\rho = 13.0 \pm 0.7$ mas, with position angle $\theta = 231.9 \pm 4.0°$ (Herald et al., 2020), and the orbital period of 2.6-yr determined from Gaia DR3, yields components masses $M_1 = 3.9 \pm 2.2 M_\odot$ and $M_2 = 3.5 \pm 1.6 M_\odot$ (Arenou et al., 2022).

INTERESTINGLY, it is also possible to probe the occulted *star*, as well as the occulting solar system object, and specifically to derive *stellar* diameters.

The physical diameter of a star is a critical quantity in determining its basic properties. A star's *linear* size can be derived, in principle, from a measurement of its *angular* size combined with a knowledge of its distance (from astrometry). But the direct measurement of angular diameters is notoriously difficult because, at interstellar distances, stars are generally too small, typically below 1 milli-arcsec in diameter, to be resolved.

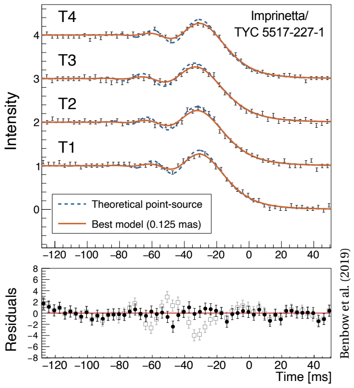
Instead, adopted methods include those based on occultations, interferometry, and eclipsing binaries. Several compilations exist, including CADARS with 7778 stars (Pasinetti et al., 2001), CHARM2 with 3243 (Richichi et al., 2005), and JMDC with some 2000 (Duvert, 2016).

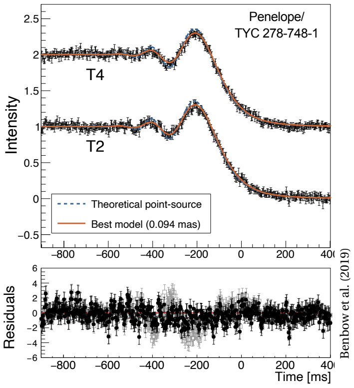
The occultation methods exploits the diffraction pattern in the shadow cast when a solar system object occults the star, and requires that the photometric uncertainty is smaller than the noise arising from atmospheric scintillation. It has long been exploited using lunar occultations, where angular diameters down to ~1 milli-arcsec have been determined (e.g., Ridgway, 1977; Sturmann, 1994), particularly toward the red end of the optical spectrum where background light from the Moon is minimised. Below 1 milli-arcsec, angular diameters have instead largely relied on interferometric measurements, exploiting the challenging techniques of either amplitude or intensity interferometry.

A MORE RECENT initiative has been to make use of the VERITAS Cherenkov telescopes, an array of four 12-m optical reflectors located at the Fred Lawrence Whipple Observatory in southern Arizona, where it is dedicated to gamma-ray astronomy in the GeV–TeV energy range. The array measures the particle showers generated in the Earth's atmosphere as a result of the high-energy gamma rays incident upon it.

Atmospheric Cherenkov telescopes used for such particle astrophysics experiments have not generally been exploited for optical astronomy due to the comparatively modest optical quality of their mirror surfaces. However, their large area makes them well-suited, as simple 'light buckets', to high time-resolution photometry including, as has recently been demonstrated, the determination of stellar angular diameters, exploiting both asteroid occultations (Benbow et al., 2019), and intensity interferometry (Abeysekara et al., 2020).

Specifically, the observation of stellar occultations by solar system objects, now routinely used to determine the properties of the *occulting* body, are consequently also capable of measuring the angular size of the *occulted* body, well below the 1 milli-arcsec limit of the lunar occultation technique. The achievable resolution also benefits from the increased distance to the occulting object compared to the distance to the Moon.





THE RESULTS of two such occultation events, using the Gaia DR2 positions in order to predict the possible observations using the VERITAS instrument, have been reported by Benbow et al. (2019), and are illustrated above. The figures show the ingress light curves of the two separate events: the asteroid (1165) Imprinetta occulting the $V = 10.2$ mag star TYC 5517–227–1 on 22 Feb 2018, and the 88-km diameter asteroid (201) Penelope occulting the $V = 9.9$ mag star TYC 278–748–1 on 22 May 2018. The diffraction patterns are clearly seen around ingress (and egress), and the figures also show the best-fit models (red lines) and corresponding residuals.

Determination of the star's angular size requires knowledge of the distance and velocity of the asteroid, and an assumed radial intensity profile of the star. From the Gaia DR2 distance for TYC 5517–227–1 of 820 ± 40 pc, their measured angular size of 0.125 ± 0.022 milli-arcsec implies a physical radius of $11.0 \pm 2.0\,R_\odot$.

For TYC 278–748–1, at a Gaia DR2 distance of 215 ± 2 pc, their measured angular size of 0.094 ± 0.01 milli-arcsec implies a physical radius of $2.17 \pm 0.22\,R_\odot$. This result is in excellent agreement with the even more precise Gaia DR2 FLAME (Final Luminosity, Age, and Mass Estimate) catalogue value of $2.173^{+0.055}_{-0.089}\,R_\odot$.

For the future, they estimate that such a (fixed) telescope capable of detecting an occultation of a 10 mag star can view 5 such occultations per year, increasing to almost one per week for occultations of 13 mag stars.