24. Occultations of Europa and Triton

A STELLAR OCCULTATION occurs when a solar system object, such as an asteroid or a planetary moon, passes in front of a 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, often with kilometre precision. And it can probe other properties of the occulting object, such as the presence of an atmosphere, structures around it such as rings or moons, or even the measurement of its topographic features, such as mountains or valleys.

The first occultation of a star by an asteroid, Juno, was recorded in 1958. But until the Hipparcos results became available in 1997, the limited accuracy in the knowledge of star positions made it difficult to predict future occultations with any confidence. With Hipparcos positions, some 30 such events have been observed every year since. Amongst them, occultations of asteroids, satellites of asteroids, Centaurs and Kuiper Belt Objects, and even Pluto, have all been observed in this way.

OF THE FOUR Galilean moons, only a handful of occultations have ever been observed: of Ganymede (in 1911, 1972, and 2016) and of Io (in 1971), with none of Europa or Callisto. Their rarity is largely because of the difficulty in predicting potential occultations due to the uncertainties in the positions of background stars.

The first recorded occultation of one planet by another was of Jupiter by Mars in 1170 CE, observed by the monk Gervase of Canterbury in the west, and Chinese astronomers in the east. A recent computation of past and future planet–planet events, based on their accurate orbits, found two in the 19th century, none in the 20th, and five in the 21st century, all involving one of Mercury and Venus, with one of the planets beyond Earth.

Occultations of one solar system moon by another moon can also occur. Infrared imaging of an occultation of Io by Europa in 2015 yielded 2-km resolution maps of Io's volcano Loki Patera. Even triple transits of Jupiter's Galilean moons occur once or twice a decade: the crossings of Callisto, Io and Europa were observed by the Hubble Space Telescope in January 2015.

IT IS STRAIGHTFORWARD to appreciate how the results from Gaia are transforming this field. The Hipparcos catalogue contained nearly 120 000 stars distributed fairly uniformly over the sky, or about 3 stars per square degree, all brighter than about 10–11 mag. In reality, this is a rather sparse coverage of the sky, and it means that the chance of any particular target object passing in front of one of them is rather small. Planning this type of occultation observation, of course, requires predicting such an alignment weeks or months in advance.

A further complication is that since all stars are moving due to their proper motions, knowing a star position 30 years after the epoch at which the Hipparcos measurements were centred (about 1990) means that we must also have an accurate knowledge of their proper motions in order to predict their *current* positions.

The Gaia satellite is measuring every object brighter than about 20 mag, and with a much greater accuracy – in both positions and proper motions – than even Hipparcos. In particular, since relatively bright stars are required for this type of occultation measurement, Gaia is providing a catalogue of some two million or more stars brighter than about 10–12 mag, or some 50 stars per square degree on average. This dense grid of highly accurate star positions means that there are greatly improved prospects of finding – and predicting – a suitably bright occulting star.

THE FIRST OF my two examples of the use of the Gaia data for occultation measurements are for Jupiter's Galilean moons. Between 2019–2020, Jupiter was projected against a very dense star region, in the vicinity of the Galactic centre, a configuration that will not occur again until 2031. The high background star density means that the probability of a stellar occultation by the Jovian moons increases dramatically.

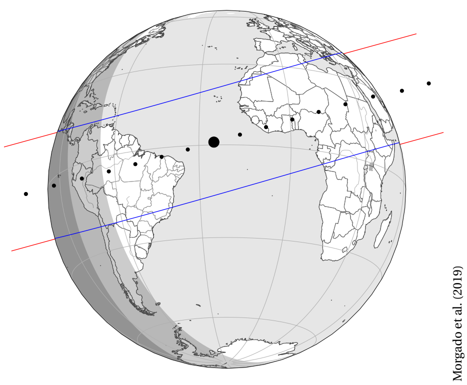
And this provides an even better opportunity to observe stellar occultations by the Galilean moons, determine their positions, improve their orbits, and measure their shapes independently of satellite probes, thus helping (for example) in the study of tides generated by gravitational forces by Jupiter itself.

In this context, it is worth emphasising that accurate orbits, of both Jupiter and its satellites, are essential to the task of preparing space missions targeting the Jovian system. In the near future, the European Space Agency's JUICE mission (the JUpiter ICy moons Explorer) is targeting launch in June 2022, and NASA's Europa Clipper mission, focusing on its moon Europa, in 2024.

ADVANCES IN THIS technique exploiting the Gaia data were reported by Morgado et al. (2019), who made the first such observation of Europa on 31 March 2017.

They predicted that Europa would occult a 9.5 magnitude star at 06:44 UTC on that day. The shadow path, several thousand km wide, would cross South America with a velocity of 17.78 km s^{-1}. The prediction was made using the state-of-the-art description of Europa's orbit, itself referred to the orbit of Jupiter, provided by the Jet Propulsion Laboratory (JPL). The star's position was obtained from the best-available Gaia catalogue (DR1) at the time, updated using its proper motion and parallax for the predicted occultation time.

Three stations in Chile and Brazil observed the occultation, and measured a brightness drop corresponding to the chord of the satellite that each observed. Taken together, they gave estimates of Europa's major and minor ellipsoidal axes, 1562.0 ± 3.6 km and 1560.4 ± 5.7 km respectively. These values, and the body's resulting oblateness, are in good agreement with those from the Galileo mission images. Topographic features of Europa are predicted to be at a level of only some hundreds of metres, below the resolution of these observations.

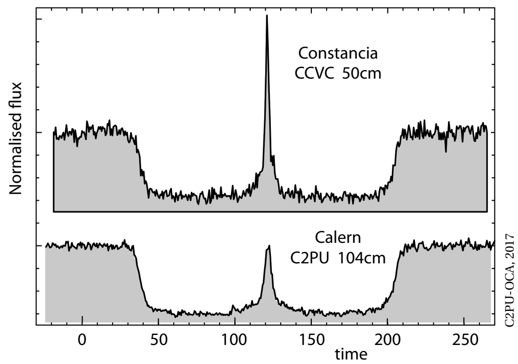


Predicted occultation of Io, on 2 April 2021

Various occultations of bright Gaia stars by Jupiter's Galilean moons have been predicted for the future. This example shows the predicted occultation by Io, of a 5.8 magnitude star, expected on 2 April 2021 10:24 UTC. The blue lines show the satellite's expected size, and the blue dashed lines correspond to an uncertainty of 20 milli-arcsec in its position. Black dots show the centre of the body's shadow at 1 minute intervals.

A FEW MONTHS AFTER these observations, on 5 October 2017, the largest of Neptune's satellites, Triton, passed in front of a 12.6 magnitude star.

A major goal of this particular event was to examine Triton's atmosphere. During the occultation of a body possessing an atmosphere, stellar rays will be refracted and focused by it, creating a flash which can be detected by an observer very close to the line of 'centrality'. This was first observed for Triton by Sicardy et al. (1990). With a width of about 100 km, this band subtends an angle of about 5 milli-arcsec at the distance of Triton.



Occultation of Triton and its central flash, 5 October 2017

To allow Triton's position on the sky to be determined accurately enough for these observations, a preparatory observational campaign was carried out at the Observatório do Pico dos Dias (Brazil), between 15–23 September 2017. This provided the positions of Triton as it completed one complete orbit around Neptune.

Together with pre-release Gaia DR2 star positions, this gave Triton's position to 3 milli-arcsec at the time of the event, corresponding to 60 km on the Earth, and to 8 seconds in the event's predicted time.

On 5 October 2017, as predicted, Triton's shadow swept across Europe and North Africa, and a few minutes later, the US East Coast. More than a hundred observing stations were ready to observe the event, which had a maximum duration of three minutes.

The event was successfully witnessed at more than 70 sites, 25 of them detecting the central flash. Its shape and spectral dependence are sensitive to the atmosphere's detailed structure, and to the presence of hazes near its surface. The data are still being analysed.

The next occultation by Triton will be by an 11 magnitude star on 6 October 2022, and will be visible from India, China and Japan.

OTHER OCCULTATIONS using the Gaia positions have since been made, amongst them a handful of trans-Neptunian objects, the Centaur Chariklo, and Saturn's irregularly orbiting satellite Phoebe. And many more of these coveted events can now be planned, for example as coordinated by the `Lucky Star project`.