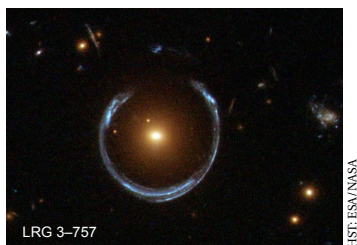


11. Astrometric microlensing

THE FIRST observations confirming ‘light bending’ as described by general relativity were made by F.W. Dyson and A.S. Eddington using the 1919 solar eclipse seen from Brazil. More compelling confirmation of light bending by the Sun included the 1973 solar eclipse, and the full-sky Hipparcos observations from 1997.

The possibility that gravitational lensing by a nearby star could result in two distinct images of a background star was pointed out by Eddington in 1920. In 1936, Einstein commented ‘Of course, there is no hope of observing this phenomenon directly. First, we shall scarcely ever approach closely enough to such a central line. Second, [the angles] will defy the resolving power of our instruments’.

Further theoretical work led to the discovery of the first case of ‘strong lensing’, a double image of the quasar QSO 0957+561 (Walsh et al., 1979). More than a hundred such galaxy-lensed systems are known today.



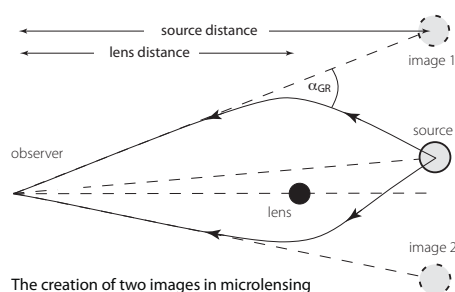
Distorted, arc-like images of galaxies were reported by Lynds & Petrosian (1986). Mainly through later Hubble Space Telescope observations, many examples are now known. A first incomplete ‘Einstein ring’, resulting from almost

perfect alignment, was reported by Hewitt et al. (1988), and dozens of more-or-less complete Einstein rings have been discovered since, including LRG 3-757.

HOW DO THESE CURIOUS structures arise? In general relativity, matter distorts spacetime, and the path of electromagnetic radiation is deflected as a result. With almost strict alignment, light rays from a distant background object (the source) are bent by the gravity of a foreground object (the lens) to create images which are distorted (and possibly multiple), and which may be highly focused and hence significantly amplified.

But these all rely on the chance alignment of a background source, an intervening lens, and an observer.

It is termed *strong lensing* if the effects are seen at an individual object level, or as *weak lensing* if it is only observed in a statistical sense.



The creation of two images in microlensing

Strong lensing can be further divided, somewhat subjectively (depending on the telescope resolution), into *macrolensing* (resulting either in multiple resolved images, or in ‘arcs’ in which the source is both sheared and magnified) and *microlensing* (in which discrete multiple images are essentially unresolved).

Relative motion between source, lens and observer leads to brightness changes, over hours or days for stellar alignments, or even over years for quasars. At peak amplification, the brightness of a background star might increase by several magnitudes over a few days.

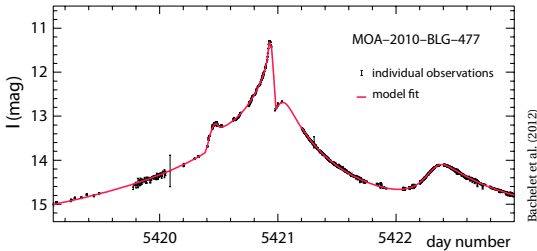
If the foreground lensing object is itself of complex structure, whether a cluster of galaxies, or a star orbited by one or more planets, then the background source may show a more complex light curve resulting from the time-varying magnification as the alignment changes.

THE EARLIEST microlensing surveys, in the 1980s–1990s, were motivated by the search for dark matter in galaxy halos, as probed by distant quasars. The observational challenges of observing these very rare and unpredictable events are enormous. Only since 1993, when massive observing programmes surveying millions of stars got underway, was microlensing observed by the EROS, OGLE, MACHO, DUO, and MOA projects.

To date, several thousand microlensing events have now been detected in the Galaxy. By the early 2000s, these surveys had excluded the possibility that the dark matter of our Galaxy’s halo contained a significant contribution from massive objects of stellar mass.

WITH THE CONSTRAINTS on dark matter largely resolved, observations turned to the search for exoplanets. The first, a planet three times the mass of Jupiter, was reported in 2004, and one just five times the mass of Earth was discovered in 2006. A two-planet system, in which orbital motion was measured during the lensing event, was observed in 2008.

By the end of 2020, more than 100 exoplanets had been discovered from the amplified light during the chance alignment of the system with a distant star.



Gaia is contributing to the study of microlensing events in fundamentally new ways. One is by providing the proper motion of the foreground object in these lensing events, which can be used to characterise the lens star.

A very different application is to use the proper motions of stars in the vicinity of a rapidly moving star, to predict which might pass close to it on the sky months or years in advance, and to prepare for such lensed and magnified events in the future. Here, a number of papers have been published, using the Gaia DR2 data.

IN ADDITION TO THIS *photometric* manifestation of microlensing, time-varying magnification of the unresolved microlensed images should also lead to a small time-varying shift of their photocentre, of up to around 1 milliarcsec. This tiny movement of a star image would be undetectable from the ground, but should be observable by Gaia, leading to mass estimates of the lens star accurate to 1%. Many studies of the effect and its detectability were made before the launch of Gaia.

The shift was first measured by Sahu et al. (2017), with Hubble. They measured a 2 milli-arcsec shift in the position of a background star as the nearby (52 pc) white dwarf Stein 2051B passed in front. Models yielded a white dwarf of 0.67 ± 0.05 solar mass – and further confirmation of the physics of degenerate matter.

THE GAIA DR2 data was used by Klüter et al. (2018) to predict astrometric microlensing events by foreground stars with high proper motions, which will pass by a background star in the coming years. From a list of 148 000 stars with proper motions larger than 150 mas yr^{-1} , they searched for background stars close to their paths, calculating the dates and separations of closest approaches, and calculating the expected astrometric shifts and magnifications of the predicted events.

They detected ongoing events by two high proper motion stars. Luyten 143–23 had a predicted closest separation of 108 mas in July 2018 with a shift of 1.7 mas. It will pass by another star in March 2021 with

a closest separation of 280 mas, and an expected shift of 0.7 mas. Ross 322 had a predicted separation of 125 mas in August 2018, and an expected shift of 0.7 mas.

Although the first of the Luyten fly-bys was not observed as part of the Gaia sky scanning, the other two were. Results are awaited!

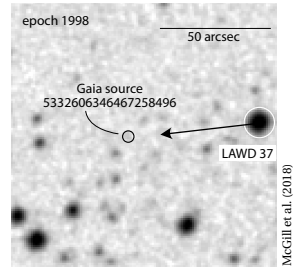
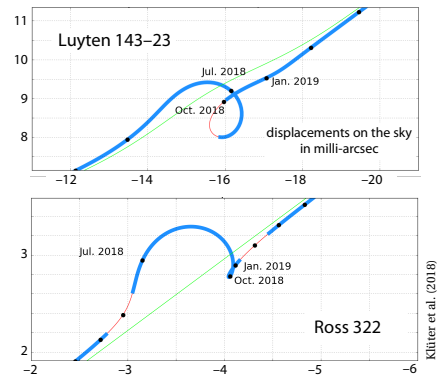
Mustill et al. (2018) searched for potential lenses within 100 pc, using parallaxes and proper motions of the lenses and background sources, then calculating peak magnifications and displacements. They found seven possible events that will occur before 2035. Of particular interest is a 14.9 mag star, which will lens a 13.9 mag background star in early 2030.

All 1.7 billion stars in GDR2 were searched by Bramich (2018), who predicted 76 microlensing events between July 2014 and July 2026. Nine of these will be caused by the white dwarf LAW2 37, and another five by the white dwarf Stein 2051 B (measured by Sahu with the Hubble Space Telescope, and also predicted by McGill et al. 2018). Other estimates have been made by McGill et al. (2020).

IT IS TOO EARLY to estimate how many events will finally be measurable by Gaia. Meanwhile the method also has applicability to more exotic lens types.

Ofek (2018) identified two candidate events of Gaia DR2 stars involving lensing by a foreground pulsar (with known proper motion) in which the shift of the background star will exceed 10 micro-arcsec.

Rybicki et al. (2018) investigated the impact of combining Gaia astrometry from space with precise, high cadence OGLE photometry from the ground. For the archival event OGLE3-ULENS-PAR-02, which is likely a black hole, they predict that at the end of the nominal 5 yr of the Gaia mission, for the events brighter than 15.5 mag at the baseline, caused by objects heavier than 10 solar masses, it will be possible to derive lens masses with accuracies of around 10%.



The motion of LAW2 37