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Microlensing, brown dwarfs and Gaia

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Abstract. The GAIA satellite can precisely measure the masses of nearby brown dwarfs and lower main sequence stars by the microlensing effect. The scientific yield is maximised if the microlensing event is also followed with ground-based telesecopes to provide densely sampled photometry. There are two possible strategies. First, ongoing events can be triggered by photometric or astrometric alerts by GAIA. Second, events can be predicted using known high proper motion stars as lenses. This is much easier, as the location and time of an event can be forecast. Using the GAIA source density, we estimate that the sample size of high proper motion (> 300 mas yr^{-1}) brown dwarfs needed to provide predictable events during the 5 year mission lifetime is surprisingly small, only of the order of tens. This is comparable to the number of high proper motion brown dwarfs already known from the work of the UKIDSS Large Area Survey and the all-sky WISE satellite. Provided the relative parallax of the lens and the angular Einstein radius can be recovered from astrometric data, then the mass of the lens can be found. Microlensing provides the only way of measuring the masses of individual objects irrespective of their luminosity. So, microlensing with GAIA is the best way to carry out an inventory of masses in the solar neighbourhood in the brown dwarf regime.

Key words. Brown dwarfs – microlensing

1. Introduction

The GAIA satellite was successfully launched on 19th December 2013. It reached the nothingness at the L_2 Lagrange point of the Earth and Sun on 14th January 2014. After testing and commissioning, GAIA will survey the sky from this vantage point. It will observe each object on average 72 times during the five-year mission lifetime (Eyer et al. 2013). GAIA will perform multi-epoch, multi-band photometry and spectroscopy, but the uniqueness of GAIA lies in its astrometric capabilities. The astrometric precision of GAIA depends on source magnitude and allows stellar parallaxes to be measured with errors in the range 10 to 300 μas for stars with magnitude in the range 12 to 20 (de Bruijne 2012).

Microlensing occurs when an object (lens) passes close to the line of sight between observer and source. The light rays bend towards the lens and distorted images are produced whose separation is too small to be resolved by any telescope (see Evans 2003 or Mao 2012 for recent reviews). Instead, there is a brightening of the source (photometric microlensing) and displacement of the light centroid of the images (astrometric microlensing). In principle, GAIA can detect both photometric and astrometric microlensing, though the latter is a much more attractive and feasible proposition.

Many thousand microlensing events have so far been identified, primarily towards the Galactic Bulge. They have been found by ground-based photometric surveys, the most active of which in recent years are OGLE and MOA (see e.g., Sumi et al. 2013, Suzuki et al 2014, Wyrzykowski et al. 2014). To date, no microlensing event has ever been studied using both its astrometric and photometric signal, though this can substantially break parameter degeneracies. GAIA will change all this.

Microlensing is a unique technique, as it can measure the masses of objects irrespective of their luminosity, irrespective of whether they are bright or dark. It has become widely known as a tool for exoplanet detection (e.g., Perryman 2011, Sumi et al. 2011), but it has the capability to make substantial contributions to the study of all faint stellar populations, such as brown dwarfs, white dwarfs and neutron stars. It remains a technique whose time has yet to come. The GAIA satellite with its powerful astrometric capabilities will usher in the day.

2. Preliminaries

The all-sky averaged photometric microlensing optical depth is $\sim 5 \times 10^{-7}$. The typical duration of a photometric microlensing event is 1-3 months, so there are a total of 8000-10000 photometric events during the GAIA mission. GAIA's sampling law is peculiar, with objects observed in clusters of 4-5 orbits, with gaps of 30-40 days separating these groups of measurements. Most of the stars will have on average about 70 measurements, though some areas of high star density such as the Galactic Center will only have about 50 measurements. GAIA photometric data alone will therefore rarely be adequate to characterize events

Fortunately, there is also an astrometric microlensing signal accompanying any photometric event. Although the two images of a microlensed source are unresolvable, GAIA can measure the small deviation (of the order of a fraction of a mas) of the centroid of the two images. For microlensing, the increase in apparent brightness falls off like (impact parameter)$^{-4}$, but the displacement in image locations is proportional to (impact parameter)$^{-1}$. So, the cross-section for astrometric microlensing is larger, as the effect is a much more slowly declining function of impact parameter. Paczynski (1996) already and clearly makes the point that astrometric microlensing is a powerful way of measuring the masses of brown dwarfs and other nearby stars, although he envisaged using the *Hubble Space Telescope* rather than GAIA. The astrometric cross-section is proportional to the area a lens sweeps out on the sky, and so to the product of lens proper motion and angular Einstein radius, which favours nearby lenses.

Belokurov & Evans (2002) showed that the all-sky averaged astrometric optical depth is $\sim 2.5 \times 10^{-5}$. They carried out Monte Carlo simulations assuming a distribution of lenses and sources from a Galaxy model, together with the GAIA sampling algorithm. Since then, there have been some modifications to the scanning law, though the sampling properties do not change significantly. Allowing for the astrometric precision, which is a function of the source magnitude, they concluded that there are $\sim 15,000$ astrometric events in which the centroid shift is greater than 5σ during the mission lifetime. Some of these events cannot be identified, because any identification algorithm will generate too many false positives.

For the study of dwarfs, the most important events are those for which the mass of the lens is measurable. The mass is related to the angular Einstein radius $\theta_{\rm E}$ and the relative parallax between source and lens $\pi_{\rm sl}$ by (see eq. 40 of Dominik & Sahu 2000)

$$M = 0.125 M_\odot \left(\frac{\theta_{\rm E}}{\rm mas}\right)^2 \left(\frac{\pi_{\rm sl}}{\rm mas}\right)^{-1}. \qquad (1)$$

Provided the astrometric fit enables $\pi_{\rm sl}$ and $\theta_{\rm E}$ to be extracted, then the lens mass is recoverable. This favours close lenses with larger Einstein radii and hence longer timescales. Using a covariance analysis, Belokurov & Evans (2002) estimated that only for 10 % of all astrometric events can the mass of the lens can be recovered to good accuracy. This gives a sample of $\sim 1,500$ 'gold-plated' astrometric microlensing events in the GAIA database for which all the microlensing parameters are obtainable.

So far, we have assumed that GAIA data alone may be enough to characterize events. However, the number of 'gold-plated' events can be substantially increased if GAIA data are complemented with ground-based photometry. The science alerts program (Wyrzykowski & Hodgkin 2012, Wyrzykowski et al. 2014b) has built an anomaly detection pipeline which triggers on photometric brightening. GAIA observations come in pairs separated by 106.5 minutes, which provides a check on transients and a simple classifier. Tests on SDSS Stripe 82 data suggest that major types of transients – such as microlensing – can be reliably identified and triggered with two datapoints. This raises the prospect of follow-up photometry for on-going events, which will substantially increase the numbers with accurate mass measurements.

3. The local mass function

The gold-plated events are wholly due to local lenses and this suggests a natural application is to measure the local mass function. Fig. 1, taken from Belokurov & Evans (2002), shows the recovery of the mass function in two cases in which it is assumed to be falling or rising. The mass functions are reproduced accurately above $0.3 M_\odot$. Below this, the mass functions fall below the true curves. This is because astrometric microlensing events are biased towards larger masses, which of course have larger Einstein radii. Even so, the gold-plated events can distinguish between rising and falling mass functions. Of course, the bias can be corrected for by calibration against the simulations if we wish to reproduce the mass function into the brown dwarf regime.

Local populations of low mass ($\sim 0.5 M_\odot$) black holes or neutron stars could easily have eluded identification thus far. Cool halo white dwarfs are also extremely difficult to detect. Existing programs look for faint objects with high proper motions (e.g., Oppenheimer et al. 2001, Vidrih et al. 2007). Such searches miss stars with low space motions and have difficulties detecting stars with extremely high proper motions (depending on the epoch difference). Experiments reveal that mass functions with spikes due to populations of white dwarfs and neutron stars can be easily recovered. In fact, this is the regime in which GAIA's astrometric microlensing signal is most efficient, as recently confirmed by Sajadian (2014). GAIA is the first instrument to have the capabilities of detecting nearby populations of very dark objects.

4. Predictable events

The alternative to identifying events in GAIA's database is to forecast events. A very attractive feature of astrometric microlensing is that events can be predicted in advance, if the lens proper motion is known (e.g., Paczynski 1995). For a brown dwarf at distance D_d lensing a more distant source at D_s, the angular Einstein ring is

$$\left(\frac{\theta_\mathrm{E}}{\mathrm{mas}}\right) = 8\left(\frac{M}{0.08 M_\odot}\right)^{1/2}\left(\frac{10\mathrm{pc}}{D_\mathrm{d}}\right)^{1/2}\left(1-\frac{D_\mathrm{d}}{D_\mathrm{s}}\right)^{1/2} \quad (2)$$

If the proper motion of the brown dwarf is $\dot{\theta}$, then during the 5 year GAIA mission lifetime, it sweeps our an area on the sky in square arcsec of

$$A \approx 0.024\left(\frac{M}{0.08 M_\odot}\right)^{1/2}\left(\frac{10\mathrm{pc}}{D_\mathrm{d}}\right)^{1/2}\left(\frac{\dot{\theta}}{300\mathrm{masyr}^{-1}}\right) \quad (3)$$

The total number of stars detected by GAIA is not known, but it is popularly supposed that GAIA will detect at least a billion stars. If so, the source density is $\sim$ 0.002 stars per square arcsec. For comparison, the OGLE survey has a comparable limiting magnitude to GAIA. Towards the dense bulge star fields, the source density found by OGLE is $\sim$ 0.15 stars per square arcsec (Udalski et al. 1994). However, even with the most pessimistic estimates, we still expect a sample of a few tens of brown dwarfs with proper motions in excess of 300 mas yr^{-1} to yield events during the GAIA mission. Not merely are the numbers very favourable, but there are other advantages, too. First, faint stars are favoured as lenses because the light centroid shift of the source star is less affected than with a bright lens. Second, close stars are favoured, as the centroid shift is larger. So this is ideal for determining the masses of nearby brown dwarfs and M dwarfs,

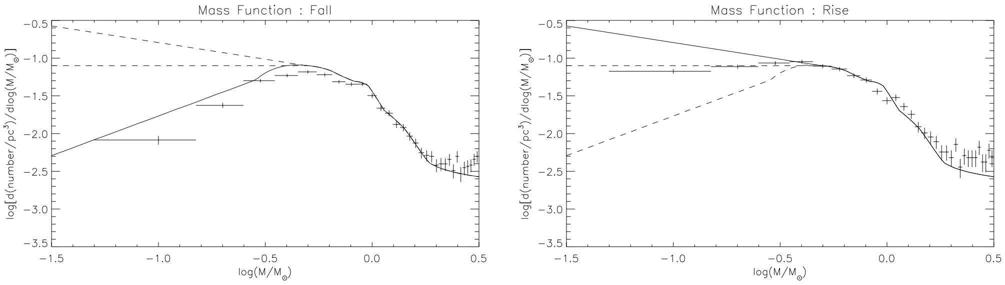

Fig. 1. Comparison of the recovered mass function from GAIA's astrometric microlensing database with the true mass function in the case that it is falling (left) and rising (right). The full line shows the mass function used in Monte Carlo simulations to provide mock GAIA datasets. The datapoints show the estimates of the mass function from the $\sim$ 1500 gold-plated events. This is discussed in more detail in Belokurov & Evans (2002).

provided we can identify enough to act as high proper motion lenses in the first place.

Compared to alerts, this is a much easier strategy to follow as the location and time of an event can be forecast ahead of time with fair accuracy. Of course, a predicted event can be followed with dense ground-based photometry with which GAIA's astrometry can be combined to yield very accurate mass measurements. Paczynski (1995) estimated that in the most propitious cases an astonishing 1 % error in the mass is obtainable. The difficulty lies in the fact that there is no reliable all-sky catalogue of faint, high proper motion stars available. Existing catalogues are partial and are often contaminated by spurious entries arising from the digitalisation of old photographic plates. Nonetheless, some interesting results have been obtained, albeit in a piecemeal manner.

Proft et al. (2011) searched though a number of proper motion catalogues – including LSPM-North of Lepine & Shara (2005) and PPMX of Roeser et al. (2008) – for possible lenses that generate events during the GAIA mission. Basically, this entails identifying background stars that lie within a certain angular distance of the future position of a high proper motion star. They identified nine candidates which have a centroid shift between 100 and 4000 μas, and argued that two of their candidates were exceptionally promising. The first is the white dwarf LSPM JO431+5858E, which has a very high proper motion of 2375 mas yr^{-1}. It lenses a faint (19.7 mag) background star with a time of closest approach of January 2014 ($\pm$1 month). The deviation remains measurable for a further 100 ($\pm$20) days. Unfortunately, given the delays in launch and in commissioning caused by stray scattered light, GAIA will now only take data well after the astrometric deviation has begun to subside. The second is the M dwarf LSPM J2004+3808 which has a proper motion of 341 mas yr^{-1}. It lenses a bright (12.7 mag) background star. The time of closest approach is July 2014 ($\pm$6 months) and the duration is 2490($\pm$1275) days. This event remains viable, and – with a predicted centroid shift of $\approx$ 1080 μas – should be easily measurable by GAIA.

Another example was identified by Sahu et al. (2014). They found that Proxima Centauri will pass close to a faint (19.5 mag) background star in February 2016, giving a centroid shift of $\approx$ 1500 μas. Their motivation, though, is somewhat different, in that they suggest that the astrometric signal may betray the presence of planets (c.f.. Di Stefano et al. 2013).

So far, this technique has not been applied to measure brown dwarf masses, yet it seems ripe for exploitation. Late-type M, L and T dwarfs with high proper motion are beginning to be known in sufficient numbers to make this feasible (e.g., Flaherty et al. 2009, Kirkpatrick et al. 2010). The UKIDSS Large Area Survey has made – and continues to make

– striking contributions to the field, For example, Table 1 of Burningham et al. (2013) contains 28 T dwarfs with high proper motion (> 300 mas yr^{-1}), whilst Table 1 of Smith et al.(2014) gives a further 41 high proper motion late-type dwarfs. Overall, scattered through the literature, there are probably already ~ 1000 known M, L and T dwarfs with high proper motion. Further, the WISE satellite provides an all-sky and multi-epoch dataset, from which color-selected brown dwarfs can be extracted with proper motions (e.g., Kirkpatrick et al. 2011). This raises the prospect of a full-sky volume-limited sample of high proper motion brown dwarfs, which would be a gold-mine for prospecting for possible lenses for GAIA.

Finally, GAIA's early data releases will provide further candidate high proper motion stars. For example, the Hundred Thousand Proper Motion Catalogue (de Bruijne & Eilers 2012) is scheduled for release 22 months after launch, and so in late 2015. These stars are in common with Hipparcos and so have decade long baselines, though admittedly only a handful are M dwarfs. The second GAIA catalogue is planned for release 28 months after launch, and will provide the full astrometric solution for all objects classified as single stars across the whole sky. This of course will substantially increase the numbers of high proper motion stars and can be used to predict events for the latter half of the mission. Although the focus is on brown dwarfs here, the masses of many classes of stars, such as bright supergiants or cool white dwarfs, are not securely established and are interesting targets in themselves.

5. Conclusions

The development of triggers for photometric microlensing has significantly extended the microlensing capabilities of the GAIA satellite (Wyrzykowski et al. 2014b). The first GAIA science alerts are expected to be released in September 2014, before this article even appears in print! Belokurov & Evans (2002) estimated that for ~ 1500 microlensing events, the mass of the lens could be deduced with good accuracy from GAIA data alone. However, follow-up photometry for alerts, combined with GAIA's astrometric signal, substantially increases the number of such 'gold-plated' events, as well as the accuracy of mass measurements. It may even be possible to alert for microlensing events on astrometry, although the false positive rate from binaries remains uncalculated and may be prohibitive.

The microlensing signal seen by GAIA is sensitive to local populations of even the dimmest of stars and darkest of objects. Astrometric microlensing favours nearby lenses with high proper motion, as then the deviation is greatest. Objects with masses around 0.5 to $1 M_\odot$, such as white dwarfs, black holes and neutron stars, are particularly cleanly detected via astrometric microlensing. Brown dwarfs have smaller Einstein radii and so the number of 'gold-plated' events is lower. The effect of this bias though is computable via simulations and so one of the major scientific contributions that GAIA can make is to determine the local mass function.

A much easier strategy than triggering events is predicting them. Proft et al. (2011) have pioneered the prediction of astrometric events for GAIA. Although one of the events that they predicted (white dwarf LSPM JO431+5858E) is no longer viable given the delay in launch and commissioning of GAIA, the other event (M dwarf LSPM J2004+3808) remains feasible. This though is a very attractive technique, and there is scope for more work. We have estimated that a few tens of high proper motion (> 300 mas yr^{-1}) brown dwarfs are enough to give astrometric lensing events during the GAIA mission. At first glance, this is a surprisingly small number, but most of the optical depth to astrometric microlensing is in nearby, fast-moving lenses. The number of high proper motion brown dwarfs has increased by leaps and bounds in recent years through surveys, such as UKIDSS. Building a high proper motion all-sky catalogue from the multi-epoch WISE dataset will yield many more brown dwarf lenses. Samples sizes of a hundred should be enough to provide many predictable events during the GAIA mission. Second, opportunities to forecast astrometric events in advance are also provided by GAIA's early data releases. As currently scheduled, 28 months after launch (that is, in April 2016), there will be a data release of the full astrometric solution for single stars, which can be mined for events in the latter half of the mission.

Of course, once the date of an event is known in advance, it can be followed from the ground or even with the *Hubble Space Telescope*. Complementing GAIA's astrometric data with photometry offers the prospect of very accurate mass determinations (to perhaps 1 % in the most propitious cases), which will be invaluable for a range of stars, not just the brown dwarfs considered in this article.

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