A Predicted Astrometric Microlensing Event by a Nearby White Dwarf

Peter McGill,1⋆ Leigh C. Smith,1,2 N. Wyn Evans,1 Vasily Belokurov,1,3 R. L. Smart2,4
1Institute of Astronomy, University of Cambridge, Madingley Rd, Cambridge CB3 0HA, UK
2School of Physics, Astronomy and Mathematics, University of Hertfordshire, College Lane, Hatfield AL10 9AB, UK
3Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, New York, NY 10010, USA
4Istituto Nazionale di Astrofisica, Osservatorio Astrofisico di Torino, Strada Osservatorio 20, 10025 Pino Torinese, Italy

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT
We used the Tycho-Gaia Astrometric Solution catalogue, part of Gaia Data Release 1, to search for candidate astrometric microlensing events expected to occur within the remaining lifetime of the Gaia satellite. Our search yielded one promising candidate. We predict that the nearby DQ type white dwarf LAWD 37 (WD 1142-645) will lens a background star and will reach closest approach on November 11th 2019 (± 4 days) with impact parameter 380 ± 10 mas. This will produce an apparent maximum deviation of the source position of 2.8 ± 0.1 mas. In the most propitious circumstance, Gaia will be able to determine the mass of LAWD 37 to ∼ 3%. This mass determination will provide an independent check on atmospheric models of white dwarfs with helium rich atmospheres, as well as tests of white dwarf mass radius relationships and evolutionary theory.

Key words: white dwarfs – gravitational lensing: micro – astrometry

1 INTRODUCTION
Einstein’s general theory of relativity predicts that light passing close to a massive object is deflected (Einstein 1916). This later led Einstein to the idea that massive objects can act as gravitational lenses and multiply image background sources (see e.g., Schneider et al. 1992, for a review). In microlensing, the multiple images are typically separated by milliarcseconds and usually cannot be fully resolved, although the photometric brightening of the source and the astrometric deviation of the light centroid can be in principle detected. Paczynski (1995) noted that microlensing events can be predicted where high proper motion objects (lenses) approach the location of background sources. High proper motion stars are generally nearby and therefore have well-determined distances, which allows the lens mass to be found with high accuracy. The advent of data from the Gaia satellite, which is providing parallaxes and proper motions for over a billion stars in the Galaxy, makes it timely to look at Paczynski’s suggestion anew (e.g., Belokurov & Evans 2002; Harding et al. 2018).

This Letter is structured as follows. In section 2, the theory of mass determination via astrometric microlensing is described. Section 3 outlines the methods we used to search for lenses in the Tycho-Gaia Astrometric Solution (TGAS) catalogue, part of Gaia Data Release 1 (DR1) (Gaia Collaboration et al. 2016a,b; Lindegren et al. 2016). Section 4 gives details of our best candidate event. Finally, in section 5, we sum up with an assessment of the feasibility of observing this event with Gaia and the Hubble Space Telescope (HST) and in section 6 summarize the outlook for, and implications of, a precision measurement of the mass of LAWD 37.

2 MASS DETERMINATION BY ASTROMETRIC MICROLENSING
Microlensing occurs when a massive point-like foreground object (lens) focuses the light from a background point-like object (source). In the case of perfect alignment between the lens, source and observer, a single Einstein ring with angular radius

\[ \Theta_E \approx 90.2 \left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{\text{pc}}{D_l} \right)^{1/2}, \]

if \( D_l \ll D_s \) (1)

is formed. Here, \( M \) is the mass of the lens and \( D_l \) and \( D_s \) are the distances to the lens and source respectively. We have assumed that the distance to the source is much greater than the distance to the lens (Paczynski 1986). When a

⋆ E-mail: pm625@cam.ac.uk, lsmith,nwe,vasily@ast.cam.ac.uk

© 2015 The Authors

arXiv:1804.07049v1 [astro-ph.GA] 19 Apr 2018
lens encounters a source at some non-zero impact parameter ($\Delta \theta_{\text{min}}$), a bright major image and faint minor image of the source are formed. The major image is located outside the Einstein radius and close to the source, whereas the minor image is located inside the Einstein radius and is close to the lens. In order, the major image, source, lens and minor image is located inside the Einstein radius and close to the source, whereas the minor image is located inside the Einstein radius and is close to the lens. In order, the major image, source, lens and minor image always lie along the same line (see Boden et al. 1998, Fig 2.). The position of the images relative to the lens are

\[
\frac{\theta_\pm}{\text{mas}} = \frac{1}{2} \left[ \pm \left( u^2 + 4 \right)^{1/2} + u \right] \Theta_E \text{mas},
\]

(2)

where we have defined the dimensionless instantaneous angular separation of the source and lens as $u = \Delta \theta / \Theta_E$. Here, and in the following eqns the positive and negative parts refer to the major and minor images respectively. At closest approach, $u = u_{\text{min}} = \Delta \theta_{\text{min}} / \Theta_E$. The amplifications of the two images are given as (Paczynski 1986)

\[
A_\pm = \frac{\mu^2 + 2}{2u (u^2 + 4)^{1/2}} \pm 1.
\]

(3)

This amplification causes an apparent brightening of the source (photometric microlensing) and an apparent displacement of the image-source light centroid (astrometric microlensing).

In the case of a luminous stellar lens and source, in which the lens, source and images cannot be resolved, the apparent centroid shift due to both the major and minor images is suppressed. This is due to light contamination from the luminous lens. The centroid shift is reduced by a factor of $(1 + f_1 / f_2)$, where $f_1$ and $f_2$ are the observed fluxes of the lens and source respectively (Dominik & Sahu 2000). This effect often reduces the astrometric signal by a factor of ~ 100, making detection difficult (e.g., Proft et al. 2011). However, for some events, the impact parameter is large enough that the source and luminous lens can be resolved. In this case, we see an apparent shift of the source centroid, caused by the presence of the major image only. The centroid shift is found by taking the difference between the apparent position of the major image and the true position of the source and is given by Sahu et al. (2017) as

\[
\frac{\Delta \theta}{\text{mas}} = \theta_+ - \theta_- = \frac{1}{2} \left( \left( u^2 + 4 \right)^{1/2} - u \right) \Theta_E \text{mas}.
\]

(4)

Here, the centroid shift direction is always towards the position of the major image. This is maximal when the lens and source are at closest approach ($u = u_{\text{min}}$). If multi-epoch shifts in the source centroid and lens source separations can be measured for an event, the mass of the lens can be determined using eqns (1) and (4), provided that the distance to the lens is known.

3 CANDIDATE EVENT PREDICTION

To search for events, a high proper motion ($> 150$ mas yr$^{-1}$) sample of 13,206 lens stars from the TGAS catalog was selected. To narrow our search, the lens sample was cross-matched with the Gaia DR1 source catalogue. Each lens was paired with all sources within a search radius of 10 times its proper motion. This produced a catalogue of ~ 4000 lens-source pairs, which we investigated further by calculating time of closest approach and estimated astrometric deflection. The parallax motion of the lens and the proper motion of the source, where available from the ‘Hot Stuff for One Year’ proper motion catalogue (HSOY) (Altmann et al. 2017), was included.

We define a candidate lensing event as a lens-source pair which has a closest approach within the remaining Gaia mission time, assumed to be between 2018 and 2022. This
left 30 candidate events. Visual inspection of the stellar field around each event removed six suspected erroneous events, which could not be confirmed to be genuine in the images available to us. Of the 24 remaining events, only one had an estimated significant maximum centroid shift in excess of 0.4 mas. It is this event that we report on here.

4 THE CANDIDATE
We predict that the known white dwarf LAWD 37 (G magnitude ∼ 11) will encounter a background source (G magnitude ∼ 18) with a closest approach of ∆θ_{min} = 380 ± 10 mas (u_{min} = 11.6 ± 0.5) on November 11th 2019 ± 4 days (2019.86 ± 0.01 Julian Years). Fig. 1 shows the stellar field around the event and the trajectory of LAWD 37 as it approaches the source. The position and proper motion data for both LAWD 37 (the lens) and background source can be found in Table 1. Errors in the event parameters were calculated using the uncertainties in source and lens position, proper motion and parallax provided by the TGAS and HSOY catalogues.

At a distance of ∼ 4.6 pc, LAWD 37 (also known as WD 1142-645) is the fourth nearest known white dwarf to the Sun (Sion et al. 2009). It is classified as spectral type DQ WD 1142-645) is the fourth nearest known white dwarf to

Using eq. (1), the mass estimate of Giammichele et al. (2012) and the TGAS parallax, we find the Einstein Radius for LAWD 37 to be θ_E = 32.8 ± 0.3 mas. We have assumed that the source is sufficiently distant such that D_s ≫ D_l. Fig. 2 shows the estimated astrometric signal and separation of the lens and source during the event. At closest approach, the maximum centroid shift is δθ_{max} = 2.8 ± 0.1 mas. Gaia’s resolution limit is a function of the orientation of the objects with respect to the focal plane and the magnitude difference of the objects. However, it is potentially ∼ 100 mas \(^1\), as shown on Fig. 2. Due to the event’s large impact parameter (u_{min} ≫ 1), the photometric signal is estimated to correspond to an apparent maximum brightening of the source of ∼ 10^{-4} mag. Therefore the photometric signal is unlikely to be detected by Gaia, so we consider constraining the mass of LAWD 37 from the astrometric signal only.

5 OBSERVATIONAL OUTLOOK
With a closest approach of ∆θ_{min} = 380 ± 10 mas, a predicted astrometric deflection of δθ_{max} = 2.8 ± 0.1 mas and

---

\(^1\) https://www.cosmos.esa.int/web/gaia/science-performance

\(^2\) https://gaia.esac.esa.int/gost/

MNRAS 000, 1–5 (2015)
The final centroiding precision of Gaia will be determined by a combination of the scan direction and the relative position of the two objects. Particularly for objects fainter than \( G=13 \), Gaia provides only binned line-spread-functions with very precise positions along scan directions, but relatively low precision in the across scan direction. For objects as bright as LAWD 37, Gaia will provide a window 2 x 1” in the across and along scan respectively (Fabricius et al. 2016). From one CCD transit, it is possible to obtain precisions of 0.06 mas for a \( G=12 \) object (Fabricius et al. 2016). However, because our primary measurement is the distance between the two objects, the floor will be set by the fainter source.

When the objects are observed in the same window, the use of gates to stop LAWD 37 saturating will lead to a significantly reduced signal-to-noise of the fainter source and a corresponding loss in precision. Even when in the same window, the higher precision along scan will remain because the pixels are rectangular and approximately 3 times larger in the across compared to the along scan direction. For the best case scenario, with both objects in the window and aligned along scan, the error on the apparent separation could be lower than 0.2 mas while in the worse case scenario, with the orientation across scan, the error could be as high as 1 mas. This precision will be improved by a factor of 3 as we have 9 independent estimates, one for each column in the focal plane. We simulated a uniform distribution of scan angles and assumed the along and across scan errors above and that the 9 observations provide independent measurements. From this, we find the per epoch median error for the apparent lens source separation is \( \sigma_{\text{ls}} = 0.24 \) mas. Current GOST results from around the event maximum indicate that there will be approximately 30 scans in which the astrometric deflection will be \( > 2 \sigma_{\text{ls}} \).

Assuming that \( \theta_{\text{ls}} = 32.8 \) for LAWD 37, we may estimate the precision at which Gaia could determine its mass. At each Gaia transit with an expected astrometric deflection \( > 2\sigma_{\text{ls}} \), we draw \( 10^6 \) samples from a Gaussian centered at the expected deflection and with variance \( \sigma_{\text{ls}}^2 \). We have assumed that the error on the true lens source separation is small compared with the error on the apparent lens source separation, so that \( \sigma_{\text{ls}} \approx \sigma_{\text{deflection}} \) since the apparent lens-source separation is the sum of the true lens-source separation and the deflection. Using these samples and inverting eqn (4) for the mass of the lens, we calculate \( 10^6 \) simulated measurements for the mass of LAWD 37 at each transit. By taking the mean and variance of the mass measurement distributions for each transit and then calculating the inverse variance weighted average across all transits, we produce a final mass measurement and error. We estimate in the best case that Gaia should be able to determine the mass of LAWD 37 to \( \sim 3 \)% precision.

### Table 1. Lens LAWD 37 (first row) and source (second row) data. Proper motions of the lens and source are from the TGAS (Gaia Collaboration et al. 2016b,a; Lindegren et al. 2016) and HSOY (Altmann et al. 2017) catalogues respectively. The coordinates (\( \alpha, \delta \)) are from the Gaia DR1 source catalogue, on the ICRF and at epoch 2015.0 Julian years. Distance to the lens \( D_l \) is obtained by inverting the lens parallax of \( 215.8 \pm 0.2 \) mas from TGAS. G is the Gaia G band magnitude.

| Gaia DR1 Source Id | \( \alpha \) [deg ± mas] | \( \delta \) [deg ± mas] | \( \mu_\alpha \cos(\delta) \) [mas/yr] | \( \mu_\delta \) [mas/yr] | \( D_l \) [pc] | G [mag] |
|-------------------|---------------------------|---------------------------|---------------------------------|---------------------------|---------------|--------|
| 5332606518269523072 | 176.4549073 ± 0.2 | –64.8295714 ± 0.2 | 2662.0 ± 0.2 | –345.2 ± 0.2 | 4.63 ± 0.03 | 11.410 ± 0.002 |
| 5332605614672584964 | 176.43630456 ± 2 | –64.83429779 ± 2 | –14 ± 3 | –2 ± 3 | - | 18.465 ± 0.005 |

![Figure 3. Blue and red dashed lines indicates LAWD 37’s and the source’s trajectory around the time of closest approach. Crosses mark the time of Gaia’s predicted observations. The vectors at the top indicate the predicted source deflection direction, the largest deflection is 2.8 mas. The arrows at the bottom indicate Gaia’s scan directions (gray arrows indicate provisional scan directions after June 2019). When the deflection arrow and Gaia’s scan direction are aligned, the measurement is along scan and they will be the most precise.](image-url)
within \emph{HST}'s capabilities. Large scale observing campaigns with \emph{HST} to constrain masses of single objects via astrometric microlensing are already underway (Kains et al. 2017). Recently, the mass of white dwarf Stein 2015 B was determined with an accuracy \(\sim 7\%\) via astrometric microlensing (Sahu et al. 2017). This event had a lens-source closest approach \(\sim 100\) mas. At the point that it was still resolvable by \emph{HST} (separation \(\sim 500\) mas), this produced a deflection of the background source position of the order of \(\sim 2\) mas. The Stein 2015 B event is a similar brightness and contrast ratio to the LAWD 37 event and still the deflection was successfully measured by \emph{HST}, providing an optimistic outlook for our event.

\section{Discussion and Conclusions}

White dwarfs are comprised mainly of degenerate matter. They are expected to obey a theoretical mass radius relationship (MRR) as they evolve and cool. Observational confirmation of the MRR is problematic, mainly due to the difficulty of determining the mass of white dwarfs. In a small number of cases when a white dwarf is found in an eclipsing or astrometric binary system (see eg. Parsons et al. 2016; Liebert et al. 2013), or with a binary main-sequence companion in wide orbit whose radial velocity can be measured, the mass of the white dwarf can be determined indirectly using parameters (translated. However, for the majority of white dwarfs, the mass of the companion in wide orbit whose radial velocity can be measured, or a binary main-sequence companion in wide orbit whose radial velocity can be measured independently (Falcon et al. 2010), its mass can be calculated. However, for the majority of white dwarfs, the mass has to be determined indirectly using parameters \(T_{\text{eff}}, \log g\) derived from astrometric models. These models are fitted using spectroscopy or broad-band photometry and require assumptions about the interior structure of white dwarfs. Specifically, the thickness of the non-degenerate hydrogen layers usually has to be prescribed, leading to poor constraints on MRRs. For example, Tremblay et al. (2017) mentions that MRRs derived from astrometric models can vary between 1-15\% depending on whether a thin or thick hydrogen layer is assumed. Additionally, white dwarfs found in eclipsing binaries are post-common envelope, meaning they have interacted with their companion and potentially evolved differently from isolated white dwarfs.

LAWD 37 is a DQ white dwarf, so it has a helium rich atmosphere. This often means thin hydrogen layers are prescribed in the astrometric models (Tremblay et al. 2017). A mass determination of LAWD 37 by astrometric microlensing is completely independent of astrophysical models. Therefore, in addition to providing an independent check of model assumptions for white dwarfs with helium rich atmospheres, it will provide an important comparison point between theoretical and observed MRRs, and white dwarf evolutionary theory.

In conclusion, we have predicted that the white dwarf LAWD 37 will lens the light from a background source, causing an apparent deflection of the source position. Maximally, this deflection will be \(2.8 \pm 0.1\) mas on the 11th of November 2019 \(\pm 4\) days. If LAWD 37 and the source are read out in the same window by \emph{Gaia}, a mass determination to \(\sim 3\%\) precision should be achieved. Recent observations with \emph{HST} of a comparable astrometric microlensing event have allowed the successful determination of the mass of white dwarf Stein 2015 B with \(\sim 7\%\) accuracy. This provides an optimistic outlook for a precision mass determination of LAWD 37 from our event with \emph{HST}.

\emph{Gaia}'s second data release (DR2) is set for 25 April 2018. In addition to providing a refined prediction of the event presented in this Letter, DR2 will likely provide us with the ability to predict a large number of astrometric microlensing events, and hence precise mass measurements of a rich variety of stars.

\section{Acknowledgments}

PM would like to thank the Science and Technologies Research Council (STFC) for studentship funding. We would like to thank Lukasz Wyrzykowski, Ummi Abbas, Stefano Casertano and Boris G"ansicke for useful discussions on this work. We would also like to thank the anonymous referee, whose suggestions improved the paper greatly. This work has made use of data from the European Space Agency (ESA) mission \emph{Gaia} (https://www.cosmos.esa.int/gaia), processed by the \emph{Gaia} Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the \emph{Gaia} Multilateral Agreement.

\section{References}

Altmann M., Roester S., Demleitner M., Bastian U., Schilbach E., 2017, \emph{A&\&A}, 600, L4
Bellini A., Anderson J., Bedin L. R., 2011, \emph{PASP}, 123, 622
Belokurov V. A., Evans N. W., 2002, \emph{MNRAS}, 331, 649
Boden A. F., Shao M., Van Buren D., 1998, \emph{ApJ}, 502, 538
Casertano S., et al., 2016, \emph{ApJ}, 825, 11
Dominik M., Sahu K. C., 2000, \emph{ApJ}, 534, 213
Dufour P., Bergeron P., Fontaine G., 2005, \emph{ApJ}, 627, 404
Einstein A., 1916, \emph{Annalen der Physik}, 354, 769
Fabricius C., et al., 2016, \emph{A&\&A}, 595, A3
Falcon R. E., Winget D. E., Montgomery M. H., Williams K. A., 2010, \emph{ApJ}, 712, 585
Gaia Collaboration et al., 2016a, \emph{A&\&A}, 595, A1
Gaia Collaboration et al., 2016b, \emph{A&\&A}, 595, A2
Giammichele N., Bergeron P., 2012, \emph{ApJ}, 754, 29
Harding A. J., Stefano R. D., Lépine S., Urama J., Pham D., Baker C., 2018, \emph{MNRAS}, 475, 79
Kains N., et al., 2017, \emph{ApJ}, 843, 145
Koester D., Weidemann V., 1982, \emph{A&\&A}, 108, 406
Liebert J., Fontaine G., Young P. A., Williams K. A., Arnett D., 2013, \emph{ApJ}, 769, 7
Lindegren L., et al., 2016, \emph{A&\&A}, 595, A4
Paczyński B., 1986, \emph{ApJ}, 304, 1
Paczyński B., 1995, \emph{Acta Astron.}, 45, 345
Parsons S. G., et al., 2016, \emph{MNRAS}, 458, 2793
Pribulla T., Dufour P., Bergeron P., Fontaine G., 2011, \emph{A&\&A}, 536, A50
Sahu K. C., et al., 2017, \emph{Science}, 356, 1046
Schlafly E. F., et al., 2017, preprint, \(\text{arXiv}:1710.01309\)
Schneider P., Ehlers J., Falco E. E., 1992, \emph{Gravitational Lenses}, \(\text{doi:10.1007/978-3-642-03758-4}\)
Sion E. M., Holberg J. B., Oswalt T. D., McCook G. P., Wasatonic R., 2009, \emph{AJ}, 138, 1681
Tremblay P.-E., et al., 2017, \emph{MNRAS}, 465, 2849

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.