Predictions of Gaia’s prize microlensing events are flawed

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ABSTRACT

Precision astrometry from the second Gaia data release has allowed astronomers to predict 5,787 microlensing events, with 528 of these having maximums within the extended Gaia mission (J2014.5 - J2026.5). Future analysis of the Gaia time-series astrometry of these events will, in some cases, lead to precise gravitational mass measurements of the lens. We find that 61% of events predicted during the extended Gaia mission with sources brighter than G = 18 are likely to be spurious, with the background source in these cases commonly being either a duplicate detection or a binary companion of the lens. We present quality cuts to identify these spurious events and a revised list of microlensing event candidates. Our findings imply that half of the predictable astrometric microlensing events during the Gaia mission have yet to be identified.

Key words: gravitational lensing: micro

1 INTRODUCTION

The astrometric signatures of microlensing events offer singular opportunities for direct gravitational probes of the fundamental properties of stars and stellar remnants, whether that be the mass of single objects (e.g Paczynski 1995; Miralda-Escude 1996; Rybicki et al. 2018; Kains et al. 2017) or characteristics of their populations (e.g Dominik & Sahu 2000; Belokurov & Evans 2002; Lam et al. 2020). Microlensing occurs when a massive object (the lens) aligns closely with a distant background source as seen by an observer. Two images of the source are formed, resulting in an apparent brightening of the source (photometric microlensing – Paczynski 1986), and apparent deflection of its position (astrometric microlensing – Hog et al. 1995; Miyamoto & Yoshii 1995; Walker 1995).

While photometric signatures of microlensing events are routinely detected by large scale monitoring surveys of the Galactic bulge (e.g the Optical Gravitational Lensing Experiment, OGLE - Mróz et al. 2019, or the Korea Microlensing Telescope Network, KMTNet - Kim et al. 2016), the detection of astrometric effects is still rare. This is due to the lack of large scale astrometric monitoring surveys which publish time-series astrometry. Despite this, astrometric microlensing events can still be found. It is possible to predict lens-source alignments ahead of time (Refsdal 1964), if the positions, proper motions, and parallaxes of both the background source and lens are known. The strength of the microlensing signal can be computed based on a mass estimate for the lens, allowing targeted follow-up campaigns to be organized to observe the event. As astrometric catalogues increased in quality and number, many searches for predicted events were carried out (Feibelman 1966; Salim & Gould 2000; Proft et al. 2011; Lépine & DiStefano 2012; Sahu et al. 2014; Harding et al. 2018; McGill et al. 2018).

To date, only two events from these predictions have been detected. Sahu et al. (2017) used the Hubble Space Telescope to measure the mass of white dwarf Stein 2051 b to 8% precision. Zurlo et al. (2018) used the Very Large Telescope to obtain a 40% precision mass measurement of Proxima Centauri. The advent of astrometric data at an unprecedented precision and volume from the second Gaia data release (GDR2 - Gaia Collaboration et al. 2018) reignited interest in predicting microlensing events. Searches by many studies resulted in precise predictions of 5,787 microlensing events occurring over the next century (Bramich 2018; Mustill et al. 2018; Klüter et al. 2018a,b; Bramich & Nielsen 2018; McGill et al. 2019a). In addition to predicting future microlensing events, events occurring over Gaia’s observation baseline were presented with the view that they could be analysed when Gaia releases time-series astrometry (e.g. Klüter et al. 2019).

Can we trust these predictions? How many of these events will Gaia observe? In this letter we examine these questions in detail.

2 THE PREDICTED EVENTS

We analyse the predicted microlensing events found by searches solely using GDR2 (Bramich 2018; Mustill et al. 2018; Klüter et al. 2018a,b; Bramich & Nielsen 2018; McGill et al. 2019a), giving us a total sample of 5,787 distinct events caused by 4,436 lenses. Although many of these studies predict some of the same events, there are key differences. Mustill et al. (2018) searched for photometric events caused by lenses within 100 pc over the next 20 years. Klüter et al. (2018a) presented two on-going astrometric events which at the time required immediate follow up. Bramich (2018) presented a catalogue of photometric and astrometric events with maximums during the extended Gaia mission (J2014.5 - J2026.5). Klüter et al. (2018b) (hereafter K18b), presented a catalogue of predicted pho-
The predicted microlensing event caused by the lens G123-61A showing that the source is not present. Arrow shows the direction of the proper motion of the lens. Annotated text gives the GDR2 G magnitudes. North is in the upwards vertical direction in both images. Left: DSS-blue image (epoch J1985.0) with positions projected to the image epoch if the source has a GDR2 proper motion, otherwise the position is at the GDR2 reference epoch of J2015.5. Right: 2MASS $K_s$-band image (epoch J2000.0) of the event with positions shown at both the GDR2 reference epoch of J2015.5 and the 2MASS image epoch.

Figure 1. Images of the region surrounding the predicted microlensing event caused by the lens G123-61A showing that the source is not present. Arrow shows the direction of the proper motion of the lens. Annotated text gives the GDR2 G magnitudes. North is in the upwards vertical direction in both images. Left: DSS-blue image (epoch J1985.0) with positions projected to the image epoch if the source has a GDR2 proper motion, otherwise the position is at the GDR2 reference epoch of J2015.5. Right: 2MASS $K_s$-band image (epoch J2000.0) of the event with positions shown at both the GDR2 reference epoch of J2015.5 and the 2MASS image epoch.

At a first glance, the predicted microlensing event by the lens G-123-61A (Gaia DR2 1543076471216523008, $G = 13.3$) looks like a promising candidate. This event, predicted by K18b, peaked on J2016.311 with a predicted maximum astrometric deflection of $\sim$0.45 mas. Klüter et al. (2019) conclude that with time series astrometry from Gaia this event should permit a mass determination of G-123-61A to 24% precision. The quality of this estimated constraint is largely due to the high apparent brightness of the source. Crucially, this would allow Gaia to obtain high precision single epoch measurements of the astrometric deflection (Rybicki et al. 2018).

While we expect cases like that of G-123-61 to be rare, the trouble does not end there. Inspection of imaging around several other events revealed further missing sources, with one example being the event caused by the lens LP 701-45 (Gaia DR2 2610954226042154624, $G = 14.8$) and the source - Gaia DR2 2610954226041533696, $G = 17.3$) predicted by K18b to peak on J2022.36 with a deflection $\sim$0.1 mas. The Gaia uncertainties on the right ascension and declination of the source are highly degenerate with a correlation of 99.8%, suggesting that the 2D astrometric pipeline was attempting to fit points lying along a line. We suspect that the source in this event is a binary companion of the lens, explaining why it does not appear in legacy DSS2 imaging. In many cases we were not able to tell by eye from the DSS2 imaging whether the source was visible at the J2015.5 position because the magnitude source is not present in the image at the GDR2 epoch of J2015.5. It is clear from Fig. 1 that a thirteenth magnitude source is not present in the image at the GDR2 epoch of J2015.5 position which was used in the event’s prediction, nor is there an unaccounted thirteenth magnitude source elsewhere in the image.
4 DIAGNOSTIC TEST FOR SPURIOUS MICROLENSING CANDIDATES

Typical predictable astrometric microlensing events are caused by nearby – and therefore bright and high proper motion – lenses and more distant – and therefore usually fainter – background sources. This is because small observer-lens distances cause larger astrometric signals (Dominik & Sahu 2000), and high proper motion objects are more likely to align with a source over a given time. In this in hand our naïve expectation of a source-lens pair is that the lens should be a bright star and that the source should be a randomly picked star in the background (and thus resemble a ‘typical’ star in GDR2). If the properties of the source are unusual or are similar to that of the lens, then we should question whether the predicted microlensing source-lens pair is real.

In Fig. 2 (left) we show the difference in colour between the source and lens versus the difference in their magnitudes. Surprisingly, there is a cluster of lens-source pairs with bright sources where the source colour is within 0.1 mag of the lens colour. Given that the most observable microlensing events are those with bright sources, we decided to investigate the astrometric properties of these sources to see if they are consistent with having genuine stars.

Stars only have reported parallaxes and proper motions in GDR2 if they satisfy the three criteria given by Lindegren et al. (2018): $G \leq 21$, $\text{VISIBILITY}_{\text{PERIODS}_{\text{USED}}} \geq 6$, and $\text{ASTROMETRIC}_{\text{SIGMA}5D_{\text{MAX}}} \leq (1.2 \text{ mas}) \times \gamma(G)$. The function $\gamma(G) = \log[1, 10^{0.2G-18}]$ is flat for $G \leq 18$ and then transitions to exponential growth. The quantity $\text{VISIBILITY}_{\text{PERIODS}_{\text{USED}}}$ is the number of time resolved clusters of detections used in the astrometric pipeline and is required to be at least six to ensure a long enough baseline for the astrometric solution. The quantity $\text{ASTROMETRIC}_{\text{SIGMA}5D_{\text{MAX}}}$ is the square root of the largest singular value of the scaled 5×5 covariance matrix of the astrometric parameters, and so is comparable to the semi-major axis of a position error ellipse (Lindegren et al. 2018). The third cut can be interpreted as requiring that the astrometric uncertainty should not be unusually large for a star of that magnitude. We define the quantity

$$\Psi = \frac{\text{ASTROMETRIC}_{\text{SIGMA}5D_{\text{MAX}}}}{(1.2 \text{ mas}) \times \gamma(G)},$$

such that if $\Psi > 1$ then the source will fail the third cut. We show $\Psi$ versus the source-lens colour difference in the middle panel of Fig. 2. The cluster of source-lens pairs with identical photometry in the left panel stands out in the middle panel, with all of these sources having $\Psi > 1$. This is highly unusual for sources brighter than $G = 16.1$. In Fig. 2 most of these sources have $\Psi < 0.1$ – and so we can conclude that these sources are atypical and thus concerning. All of the events in the cluster were identified by K18b and were predicted to have their peak prior to J2026.5. We emphasise that the left and middle panels of Fig. 2 only show the sources with colour photometry. There is a few-fold larger group of sources without colour photometry that have $G_{\text{source}} < G_{\text{lens}}$, $\Psi \geq 0.3$ and a peak prior to J2026.5, and thus the cluster in Fig. 2 is only a subset of the phenomenon. We conjecture that the reason only those sources in the extended cluster with $G_{\text{source}} \approx G_{\text{lens}}$, have colour photometry is the colour excess cut applied by DPAC, $E = (F_{\text{BP}} + F_{\text{RP}})/F_{\text{G}} < 5$. The colour photometry measured for these sources is dominated by the flux from the nearby lens and so $F_{\text{BP}}/F_{\text{RP,source}} \approx F_{\text{BP}}/F_{\text{RP,lens}}$, and thus $E_{\text{source}} \gg 5$ unless the source and lens have similar magnitudes.

In Fig. 2 (right) we show the sources with $G < 18$ and a predicted astrometric microlensing signal peak before J2026.5. Most of these sources are astrometrically-unusual compared to typical GDR2 sources, having an astrometric $\text{SIGMA}5D_{\text{MAX}}$ in the top 2% of stars at that magnitude. Those sources with extreme astro-
metric errors are mostly those without a 5D astrometric solution, while those with 5D astrometry are representative of the DR2 source catalogue. We propose that events with sources brighter than $G=18$ should only be considered reliable if the source has a published 5D astrometric solution.

Two factors determine whether a bright source will have a published 5D astrometric solution. Firstly, fewer detections will reduce the likelihood of having the requisite six visibility periods as well as making it more likely that $\Psi > 1$, because fewer measurements constraining the astrometric solution will increase the astrometric uncertainty. For each source with $G \leq 18$ and a microlensing peak prior to J2026.5, we calculated the ratio of astrometric detections $k$ (ASTROMETRIC_MATCHED_OBSERVATIONS) to the predicted number of astrometric observations $n$ computed using the scanning law of Boubert et al. (2020) and the published gaps from DPAC. The 1σ interval $k/n \in (22.9, 60.0)\%$ for the sources without 5D astrometry is significantly lower than the 1σ interval $k/n \in (65.0, 95.8)\%$ for the sources with 5D astrometry. Secondly, an increase in either the astrometric uncertainty of the centroiding of individual detections or the scatter between the centroids around the single source astrometric fit will increase the reported astrometric error. We estimated the typical centroiding uncertainty from the harmonic mean of the equatorial positional uncertainties ($\sigma_{\text{AL}} = \sqrt{v/(1/\sigma_{\alpha}^2 + 1/\sigma_{\delta}^2)}$ where $v$ is ASTROMETRIC_N_GOOD_OBS_AL), and show in Fig. 3 that the sources without a 5D astrometric solution have enhanced centroid error compared to both the predicted microlensing sources with 5D astrometry and to the bulk of Gaia DR2. We note some of the sources at magnitudes dimmer than $G = 18$ are likely to be spurious events, however these are difficult to distinguish from the main population as astrometric error increases with magnitude.

Requiring 5D astrometry resolves another troubling property of the current sample of predicted microlensing events: the microlensing rate appears to peak at present day. In Fig. 4 we show the number of microlensing events with $G_{\text{source}} < 18$ predicted per year by K18b. We restrict ourselves to K18b because it is easier to interpret the rate if we only need to consider one set of selection cuts. Our expectation is that there should be a fairly constant rate of microlensing events, but, as noted by K18b, there should be a deficit of events around the GDR2 epoch of J2015.5 because the lens and source are less likely to be resolved by Gaia at their point of closest approach. Paradoxically, the rate of predicted microlensing events peaks either side of a dip at J2015.5. This is strong evidence that these events are unlikely to be real. If we remove sources without 5D astrometry then the microlensing event rate matches our expectations, with that cut predominantly removing sources with peaks near to J2015.5. We use the number of events per year between J2034.5 and J2055.5 to infer that the Poisson rate of K18b-type astrometric microlensing events is $16.0^{+10.9}_{-9.8}$ events yr$^{-1}$, assuming the inverse-square-root Jeffrey’s prior on the rate. Marginalising over this rate, we find that there should be 191$^{+18}_{-17}$ events during the twelve year horizon of the extended Gaia mission, only 85 of which found by K18b meet our criteria for reliable identification. Over half of the astrometric microlensing events that will be detected by Gaia are yet to be identified.

Not all of the events during the Gaia mission predicted by K18b will result in useful mass measurements of the lens. Filtering events by our new astrometric cut changes the outlook for astrometric lensing events with Gaia. Of the 513 events predicted by K18b to peak between J2014.5 and J2026.5, only 260 have a source with 5D astrometry. Bright sources suffer an even higher attrition rate with only 85 of the 227 events with $G_{\text{source}} < 18$ surviving. This will impact the prospects of high-precision lens mass measurements with Gaia. Klüter et al. (2019) identified that 62 of their predicted single lens-source events could lead to mass measurements of the lens with precision better than 100%, but we find that only 28 of these are likely to occur. All seven events with an estimated precision on the mass of the lens below 10% with the full ten year Gaia data are unlikely to occur. Notably the 5.4% mass estimate of 75 Cancri is unlikely to be realised. We conclude that many of these spurious events are likely caused by the source star being a detection of a binary companion of the lens.

The reliability of K18b’s predictions increases significantly beyond J2026.5. Requiring 5D astrometry for sources with $G < 18$ only eliminates 46 of the total 3221 events. All of the events predicted by Klüter et al. (2018a), Mustill et al. (2018) and McGill et al. (2019a) survive. Only 2 of the 76 events predicted to happen L4 P. McGill et al.
events searches with results from the European Space Agency (ESA) mission Gaia for useful suggestions. This work presents where available and visual inspection described above, 2MASS lens and source IDs associated with this paper we list all of the events predicted using extended mission are yet to be identified. In the online Table Gaia that at least half of the astrometric microlensing events during the extended mission are being processed by the Gaia Data Processing and Analysis Consortium (DPAC). Funding for the DPAC is provided by national institutions, in particular the institutions participating in the Gaia MultiLateral Agreement (MLA). The Gaia mission website is https://www.cosmos.esa.int/gaia. The Gaia archive website is https://archives.esac.esa.int/gaia.

5 CONCLUSIONS

We critically analyse the fidelity of predicted microlensing events extracted from GDR2. We find that a significant portion of the bright events (G_{source} < 18) which are promising candidates for detection with Gaia are likely not genuine. This is demonstrated with a case study of G123-61, a high quality candidate for which two lenses are predicted to pass over the same source. Comparing with DSS and 2MASS observations we find that the source in both 2MASS detections. This leaves no false-positives whilst increasing the reliability of the sample of microlensing events and a published 5D astrometric solution. We demonstrate that this cut has a false positive rate of 2%. We classify as plausible 17 of the 142 events which fail the cut, implying a false negative rate of 12%. If a pure sample is required, we additionally recommend only considering events where both the source and lens have 2MASS detections. This leaves no false-positives whilst increasing the false-negative rate to 27%. We note that for the two events we eliminated from Bramich (2018), both the source and lens have 2MASS detections.

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