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Probing Galactic Black Holes with Microlensing with Gaia and OGLE

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Abstract. As shown by recent gravitational wave detections, galaxies harbour an unknown population of black holes at high masses. In our Galaxy such dark objects can be found and studied solely via gravitational microlensing methods. This paper described our search for black-hole lenses both in archived OGLE data and among on-going microlensing events found by OGLE and *Gaia*. That combination of superb time-domain astrometry and photometry will enable us to derive masses and distances to these dark lenses uniquely, and to describe the demographics of the unseen component of the Milky Way.

Keywords. Black hole physics, surveys

1. Introduction

Black holes in the Galaxy and their mass distribution are key issues connected to understanding the late stages of the stellar evolution at its low-mass end, and – with recent detections of the very massive products of black-hole mergers via gravitational waves – at its heavy-mass end too. However, so far only a few dozen black holes are known in the Milky Way (e.g., Özel *et al.* 2010). Black holes bend space-time so that the light from distance sources travels on modified trajectories, and this method – called gravitational microlensing (Paczynski 1986) – is probably the only means of recognising more candidate black holes, either single or in binaries. To date, the total number of candidates proposed as black-hole lenses is only about five (e.g., Mao *et al.* 2002, Bennett *et al.* 2002, Wyrzykowski *et al.* 2016a). Moreover, these findings rely solely on photometric data, and therefore tend to yield rather inaccurate determinations of lens, mass and distance, and hence leave some room for non-black-hole explanations for the nature of those lenses. Additional information from sub-miliarcsecond astrometry are required in order to determine the parameters of a lens uniquely, and thus to confirm an object as a black hole. The current attempts to use the Hubble Space Telescope (Kains *et al.* 2017) or the Keck Telescope (Lu *et al.* 2016) have so far failed to identify black-hole lenses uniquely. The only successful application of the astrometric effect which led to the measurement of the mass of a white dwarf (Sahu *et al.* 2017), proves that the technique works. However, black-hole lenses are rare, so suitable astrometric data are required to enable thousands of events to be discovered. The paper presented the case that a combination of the OGLE-IV Bulge and Disk survey with *Gaia* space mission

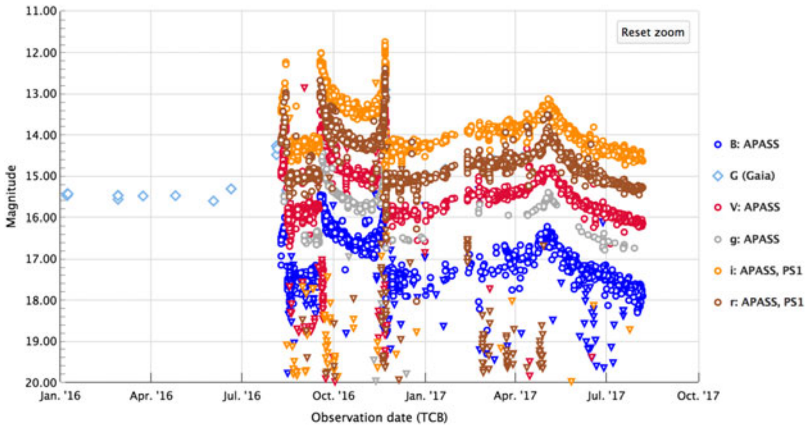

Figure 1. Light-curve of Gaia16aye from *Gaia* (diamonds) and about 30,000 follow-up observations in multiple bands from multiple observatories (circles), calibrated to the same APASS system. The data were collected by both professional astronomers and amateur observers and schools.

astrometry will provide the first robust candidates for stellar-mass black holes in the Milky Way.

2. OGLE and its 25-Years of Service for Time-Domain Astronomy

The Optical Gravitational Lensing Experiment (OGLE) began in 1992 at Las Campanas Observatory in Chile, with its pilot programme (OGLE-I) on the 1-m Swope telescope. When microlensing events started to be discovered, the project (still at Las Campanas) was upgraded in 1996 to a dedicated 1.3-m Warsaw telescope. OGLE phase II (1996–2000) used a single CCD camera; OGLE phase III (2001–2008) used an 8-chip mosaic CCD. The phase now current since 2010 (OGLE-IV) uses a mosaic CCD of 32 chips, each with 0.26 arcsec per pixel, to fill the entire field-of-view of 1.4 sq. deg. The main targets of the observations have always been the Galactic Bulge and the Magellanic Clouds, so some regions in those areas now have time-domain data spanning 25 years. OGLE primarily delivers photometry, mostly in the Kron–Cousins I-band; however, long-term imaging also yields astrometric time-series and measurements of proper motions of stars (e.g., Poleski *et al.* 2011).

3. *Gaia* and Astrometric Microlensing

Launched on December 19 2013, *Gaia* is one of the prestigious cornerstone missions of the European Space Agency. It operates in the vicinity of the Lagrangian point L2 of the Earth-Sun system. Its main goal is high-precision astrometry, and to that end it is observing the entire sky multiple times (from 40 to 250 over the nominal 5 years of the mission). As a side product it is processing daily data from more than 1000 sq. deg., and is discovering transients of various natures, primarily supernovæ but also cataclysmic variables and microlensing events (e.g., Hodgkin *et al.* 2013). One of the most spectacular binary microlensing events was discovered by *Gaia* in the Galactic Disk in the direction of Cygnus (Gaia16aye, Fig. 1; see (e.g.) Wyrzykowski *et al.* 2016b).

The main output from *Gaia* is its astrometric time-series, which will be made available for all of its billion sources down to 20 mag at the final data release in 2022. The precision of the astrometry per epoch will be better than 1 milliarcsecond, which means

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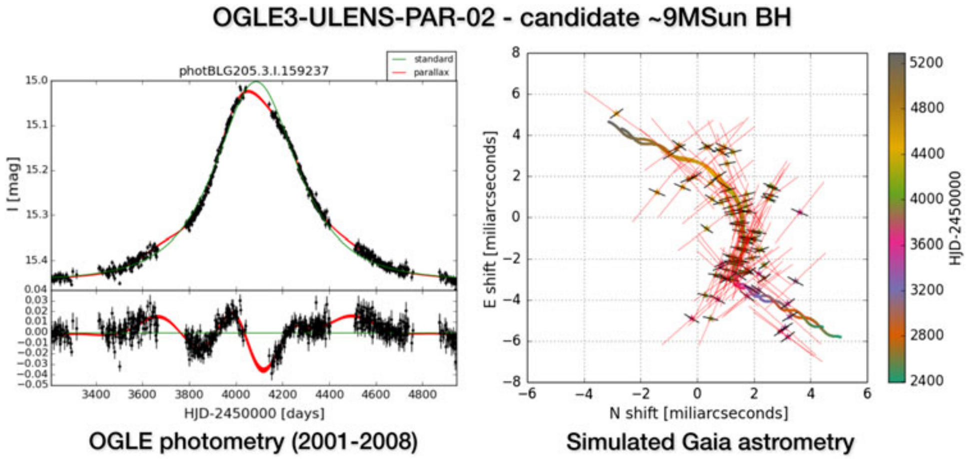

Figure 2. Combination of ground-based photometry and *Gaia*'s astrometric time-series will yield masses and distances of microlensing events, leading to confirmation of lensing black holes (Wyrzykowski *et al.* 2016a). *Left:* an example of an old microlensing event, probably caused by a 9-$M_\odot$ black hole. *Right:* a simulated *Gaia* astrometric time-series with the best-fitting model (solid line).

that – for all microlensing events which occur during the *Gaia* operation and which will have photometric coverage from ground-based surveys or follow-up programmes – the degeneracy between mass and distance will be broken (Fig. 2). Since the lensing black holes have the largest Einstein radii (proportional to $\sqrt{M}$), the black-hole lenses will be the easiest to find in such a data set (Rybicki *et al.* 2018).

4. Probing the Galactic Population of Black Holes with Microlensing

The OGLE-III data containing 150×10^6 sources in the Galactic Bulge were searched for long microlensing events exhibiting a parallax signal. A microlensing parallax is one of the crucial components for extracting the mass of the lens from a microlensing event, since $M_L = \frac{\mu_{\rm rel} t_E}{\kappa \pi_E}$, where $\kappa = 8.144\,{\rm mas}/M_\odot$, t_E is the Einstein Ring crossing time derived from the light-curve, and $\mu_{\rm rel}$ is the relative motion of the source lens. By relying on conservative assumptions about the motions of sources and lenses in the Milky Way, we were able to estimate the masses of all parallax events involving a dark lens (i.e., no extra blended light). The distribution of the 13 events shown in Fig. 3 has not been corrected for detection efficiency and may contain all sorts of dark lenses, most likely white dwarfs, neutron stars and black holes, and suggests a continuum of mass from neutron stars and black holes (Wyrzykowski *et al.* 2016a).

Measuring the masses of dark lenses is the only way to discover single stellar-mass black holes in the Milky Way and to learn about their population. This will become possible in the near future with *Gaia*'s superb astrometric time-series, plus photometry from OGLE for microlensing events detected by *Gaia*.

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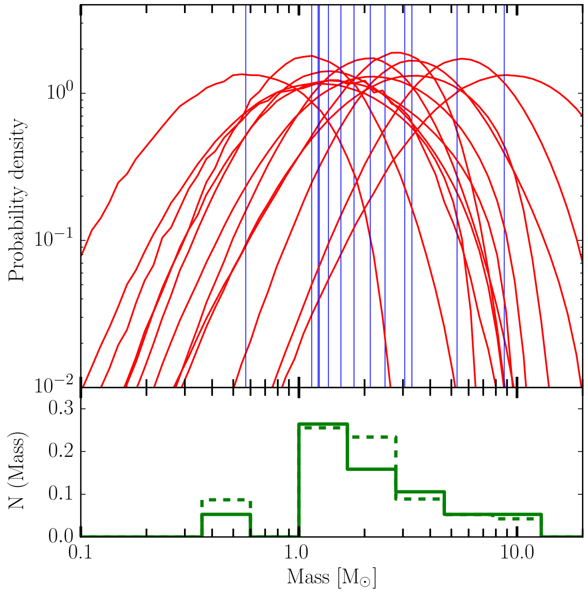

Figure 3. *Upper:* Distribution of lens mass for 13 dark-lens candidates from OGLE-III. *Lower:* The distribution of their medians, indicating a continuum of remnant masses from neutron stars to black holes. Both figures are from Wyrzykowski *et al.* 2016a.

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