Wide-orbit Exoplanet Occurrence Rate

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Exoplanets that do not orbit any star, or free-floating exoplanets, are some of the most intriguing astronomical objects. Candidate free-floating exoplanets are discovered using gravitational microlensing technique as very short events that show only a single lens. In order to verify if these candidates are truly free-floating we should consider an alternative interpretation, i.e., that the event is caused by a bound exoplanet on a wide orbit and by chance the signal from the host is not detected. I will present the most recent estimate of occurrence rate of wide-orbit exoplanets (i.e., similar to Uranus and Neptune) with masses smaller than a few Jupiter masses. I will also show a method to derive the occurrence rate that takes into account the uncertainties of each object parameters.

1 Introduction

Currently, we know almost 5000 exoplanets that orbit stars other than Sun. In this sample, we find a large variety of parameters of planets, of their host stars, and of planetary orbits. Except these exoplanets we also know candidate free-floating planets (FFPs) from the direct imaging surveys (Miret-Roig et al., 2022) and the gravitational microlensing surveys. Microlensing phenomenon takes place when an object (called lens) passes very close to a line joining a background star (called source) and an observer. The light from the source is bend by the gravity of the lens and observer sees an increase in flux received (Paczyński, 1986). The mass of the lensing object is proportional to the square of the Einstein timescale of the event (e.g., Gould 2000) and the shortest timescales are caused by the least massive lenses. Unfortunately, the Einstein timescale depends also on event parameters other than the lens mass, hence, measuring the timescale gives only rough information about the lens mass. Microlensing events caused by stars have typically Einstein timescales on the order of dozens of days. The events with timescales shorter than 2 days are most likely caused by planetary-mass objects. There are extremely short events in which we see a signal of only a single lens and these are classified as candidate FFPs. The shortest detected microlensing event is OGLE-2016-BLG-1928 with a timescale of 42 minutes and mass most likely between that of Mars and Earth (Mróz et al., 2020). The ratio of the number of FFP Jupiter-mass candidates to the number of main sequence stars was first estimated to be above one (with large errorbar; Sumi et al. 2011) but more detailed study estimated this ratio to be below 0.25 (Mróz et al., 2017). The single short-lasting events are called candidate FFPs, not certain FFPs because it is possible that these planets have host stars that by chance have not passed near the line joining the source and the observer, hence, they have not produced any microlensing signal. However, we can approach the problem on deciding if planets are bound or not from other perspective: based on the occurrence rate of wide-orbit bound planets.

For planets detected using microlensing, we routinely measure two astrophysically important parameters: the planet to star mass-ratio (q) and the on-sky projected separation divided by the Einsein ring radius (s). In a typical case, $s = 1$ translates to a 2D planet-star separation of ≈ 2.5 AU. Microlensing is most sensitive to planets with s close to unity. Previous statistical studies of the bound microlensing planet occurrence rate (Gould et al., 2010; Cassan et al., 2012; Suzuki et al., 2016) had low sensitivity to planets that can mimic FFPs, i.e., $s \gtrsim 3$ and $q \lesssim 10^{-3}$.

Here we summarise our recent study of wide-orbit (i.e., $s > 2$) microlensing planet occurrence rate (Poleski et al., 2021). The results are key to statistical assessment on what fraction of FFP candidate events are caused by FFP lenses.

2 Methods

In Poleski et al. (2021) we used data from the third and fourth phases of the Optical Gravitational Lensing Experiment project (OGLE; Udalski 2003; Udalski et al. 2015). We selected well-observed microlensing events and found 3095 of them. These events were analyzed in two ways. First, we searched for signals of wide-orbit planets. We found six known planets, a few other anomalous events, and a new microlensing planet. The new planet is in the event OGLE-2017-BLG-0114 but the most likely interpretation is that the planet has $s < 1$ (Sec. 4.4 of Poleski et al. 2021), hence, does not enter our sample. Second, the selected events were analyzed to derive the survey sensitivity for wide-orbit planets $S(s, q)$, i.e., the number of planet detections expected if every star had a planet with given s and q. The survey sensitivity calculations were conducted using inject-recover method and required significant amount of computations. The results of these computations are presented in Fig. 1.

The bound planet occurrence rate is parameterized as (Suzuki et al., 2016):

$$f(s, q; A, n, m) = \frac{d^2 N_{\rm pl}}{d \log q \ \ d \log s} = A s^m \left(\frac{q}{q_{\rm br}} \right)^n , \tag{1}$$

where $q_{\rm br} = 1.7 \times 10^{-4}$ (we ignore change of n for $q < q_{\rm br}$). The parameters A, m, and n are typically estimated using Bayesian approach. For this purpose we define likelihood (for the Poisson distribution):

$$\mathcal{L}(A, n, m; \{s_i, q_i\}) = e^{-N_{\rm exp}} \prod_{i=1}^{N_{\rm obs}} f(s_i, q_i;\ A, n, m) S(s_i, q_i) , \tag{2}$$

where $\{s_i, q_i\}$ are parameters of $N_{\rm obs}$ detected planets and $N_{\rm exp}$ is the number of expected planets:

$$N_{\rm exp} = \int f(s, q;\ A, n, m)\, S(s, q)\, d \log s \ \ d \log q \, . \tag{3}$$

This approach has significant disadvantage – it ignores the fact that s and q are measured with uncertainties and $S(s, q)$ varies for varying s and q of given planet, which are still within measured uncertainties. This disadvantage can be coped with by using the hierarchical Bayesian approach. Specifically, we replace the product in Eq. 2 with numerical marginalization over measurement uncertainties. In Poleski et al. (2021) we drew K samples of (s, q) for planet i, i.e., $(s_{i,k}, q_{i,k})$. Then the

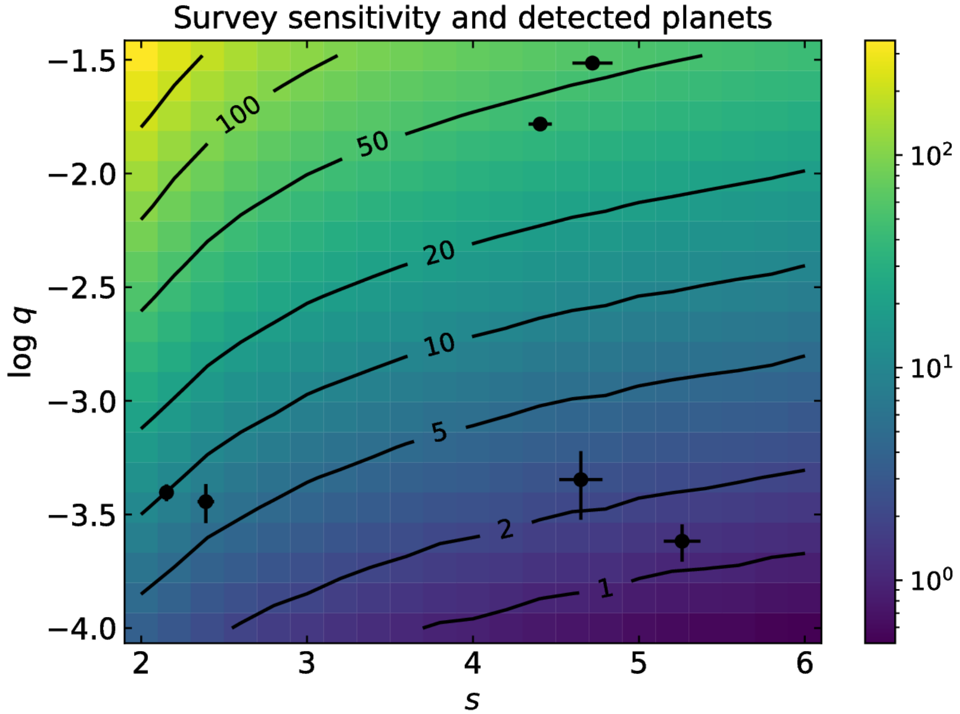

Fig. 1: Survey sensitivity and detected planets in log mass-ratio vs. separation plane. The black dots indicate planets: OGLE-2008-BLG-092LAb (Poleski et al., 2014), OGLE-2011-BLG-0173Lb (Poleski et al., 2018), MOA-2012-BLG-006Lb (Poleski et al., 2017), OGLE-2012-BLG-0838Lb (Poleski et al., 2020), MOA-2013-BLG-605Lb (Sumi et al., 2016), and OGLE-2016-BLG-0263Lb (detected only if the $\Delta\chi^2$ limit is decreased from default of 300 to 200; $s = 4.7, \log q = -1.5$; Han et al. 2017). Figure is reproduced from Poleski et al. (2021) with permission.

corrected formula for likelihood is (Foreman-Mackey et al., 2014; Sharma, 2017):

$$\mathcal{L}(A, n, m; \{s_{i,k}, q_{i,k}\}) = e^{-N_{\rm exp}} \prod_{i=1}^{N_{\rm obs}} \left(\frac{1}{K} \sum_{k=1}^{K} f(s_{i,k}, q_{i,k};\, A, n, m) S(s_{i,k}, q_{i,k}) \right). \quad (4)$$

3 Results

The parameter inference using MCMC method resulted in $A = 1.04^{+0.78}_{-0.57}$, $m = 1.09 \pm 0.64$, and $n = -1.15 \pm 0.25$. Each of these values is statistically consistent with parameters found by Suzuki et al. (2016), but our values point to a larger number of wide-orbit planets. The integral of $f(s, q)$ for q in range $(10^{-4}, 0.033)$ and s in range $(2, 6)$ results in $0.4^{+0.4}_{-0.2}$ wide orbit planets per star for Suzuki et al. (2016) occurrence rate, and $1.4^{+0.9}_{-0.6}$ for Poleski et al. (2021) occurrence rate.

Acknowledgements. This work was supported by Polish National Agency for Academic Exchange grant "Polish Returns 2019."

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