Formation, Detection, and Characterization of Extrasolar Habitable Planets
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Microlensing Constraints on the Abundance of Extrasolar Planets

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Abstract. Galactic gravitational microlensing is a powerful technique to detect extrasolar planets at large orbital distances from their stars, from giant down to Earth-mass planets. We report a statistical analysis (Cassan *et al.* 2012) that combines six years of microlensing observations gathered between 2002 to 2007 by the PLANET and OGLE collaborations. From these data, we estimate the frequency of cool extrasolar planets, with masses ranging from 5 Earths to 10 Jupiters and orbits between 0.5 to 10 Astronomical Units. We find that in average, one in six stars has a Jupiter-like gas giant as companion planet, that about half the stars are orbited by a Neptune-like giant, and two-thirds are associated to super-Earths. Our study also suggests that planets should be ubiquitous throughout the Galaxy. Current deployment of wide-field imagers and possible space-based observations onboard ESA spacecraft EUCLID will soon allow a large increase of the number of monitored microlensing events. These new observatories should provide in a near future a more detailed view on planet abundance as a function of mass.

Keywords. Gravitational lensing, planetary systems, methods: statistical

1. Introduction

Since the discovery of the first extrasolar planet orbiting a main-sequence star (Mayor & Queloz 1995), the search for new worlds outside of our Solar System has undergone significant progress, counting now more than 800 exoplanets. While most of those planets are massive gas giants, already a few telluric exoplanets with masses of only a few times that of the Earth have been found.

The technique of gravitational microlensing (Mao & Paczynski 1991) is ideally suited to obtain a sample of planets below ten Earth masses at several astronomical units from their parent stars (0.5–10 AU), a region of planet parameter space that is hardly accessible by other technique. The planets found by microlensing are preferentially orbiting stars located at 1–8 kpc, *i.e.* far beyond the Solar neighbourhood and thus affording an unmatched probe of the population of extrasolar planets across the Galaxy. Moreover, the technique has very little bias on host star masses. Microlensing is thus mainly probing planetary systems around the most common stars of the Galaxy (M-K dwarfs), but solar or more massive host stars are also part of the sample.

Gravitational microlensing is very rare: fewer than one star per million undergoes a microlensing effect at any time. Until now, the planet-search strategy has been mainly split into two levels. First, wide-field survey campaigns such as the Optical Gravitational Lensing Experiment (OGLE, Udalski *et al.* 2003) and Microlensing Observations in Astrophysics (MOA, Bond *et al.* 2001) cover millions of stars every clear night to identify and alert the community to newly discovered stellar microlensing events as early as possible. Then, follow-up collaborations such as the Probing Lensing Anomalies Network

(PLANET, Albrow *et al.* 1998), the Microlensing Follow-Up Network (μFUN), RoboNet or MiNDSTEp monitor selected candidates at a very high rate to search for very short-lived light curve anomalies, using global networks of telescopes. Since its pilot season in 1995, the PLANET collaboration has been active in monitoring Galactic microlensing events, with the ambition to obtain a detailed picture of planets beyond the snow-line around all stars over the full mass range from massive gas giants to terrestrial planets.

Here, we report a statistical analysis of microlensing data (gathered in 2002-07) that reveals the fraction of bound planets 0.5–10 AU from their stars (Cassan *et al.* 2012).

2. Planet abundance analysis from 2002-07 microlensing data

Originally, the main reason for establishing follow-up collaborations was based on the fact that the observing cadence of a large microlensing survey was too low and therefore not sufficient to unambiguously establish the planetary nature of a light curve deviation. Hence, running survey observations alone would severely restrict establishing reliable planet abundance statistics, especially related to low-mass planets. To address this problem, Gould & Loeb (1992) pressed for a strategy of intense monitoring of a sub-sample of events chosen from microlensing alerts issued by survey group, in particular OGLE.

In 2002-2007, the observing strategy adopted by PLANET consisted of following up a selection of OGLE III events with high cadence and round-the-clock sampling with a global network of telescopes. The sampling rate was increased with the magnification rising towards the peak of the light curve, or in response to the real-time anomaly alerts (including alerts from OGLE). Since PLANET applied the same selection criteria and follow-up rules regardless of whether the lens harbours a planet or not, the sample can be regarded as homogeneous both for detections and non-detections, provided that planetary anomalies can be detected with the adopted strategy. In fact, Gaudi *et al.* (2002) already based their estimation of upper limits on planet abundance on such homogeneous samples, although the strategy adopted for the range of time considered (1995-2000) was different.

While microlensing survey light curves alone already provide a significant detection efficiency to giant planets, statistics from low-mass planets can only arise from events that are more densely sampled (since short-lived planetary signals can more easily fit in gaps of the data coverage). The ensemble of events we use in the present study has much more sensitivity than these previous studies, especially for low-mass planets. In fact, our sample includes many more very well-covered events with a range of peak magnifications, which thus probe more efficiently the parameter space where planet signals reside.

Following Gaudi & Sackett (2000), we use the non-detections to compute the detection efficiency of PLANET 2002-2007 observations. The OGLE Collaboration respectively alerted 389, 462, 608, 597, 581 and 610 events for 2002-2007, from which PLANET monitored (with a range of data quality and sampling) 40, 51, 98, 83, 96 and 72 light curves. The ratio between the events monitored by PLANET and OGLE alerts ranges from $\sim 10 - 16\%$ with a mean around 13%.

A crucial point is that, the observing strategy should remain homogeneous for the time span considered in the analysis. When starting its new operations in 2002, OGLE III dramatically increased its number of issued alerts (389 alerts in 2002 compared to 78 alerts in 2000 with OGLE II), which had a strong impact on the PLANET strategy. From 2002 to 2007, PLANET then operated with the same consistent strategy, but after that, was much more influenced by other teams, in particular for very high-magnification events. Hence, this condition of homogeneous strategy is fulfilled for microlensing events

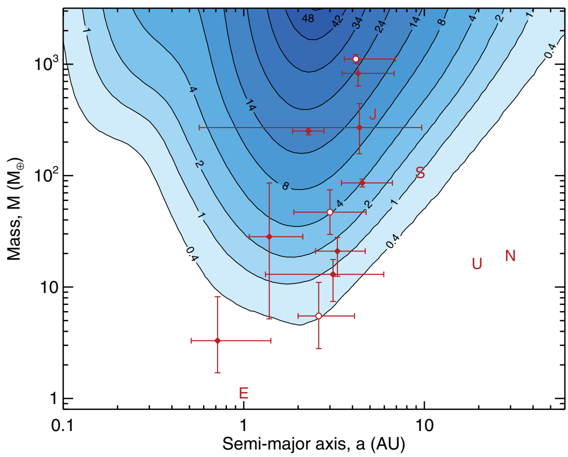

Figure 1. Survey-sensitivity diagram. Blue contours, expected number of detections from our survey if all lens stars have exactly one planet with orbit size a and mass M. Red points, all microlensing planet detections in the time span 2002–07, with error bars (s.d.) reported from the literature. White points, planets consistent with PLANET observing strategy. Red letters, planets of our Solar System, marked for comparison: E, Earth; J, Jupiter; S, Saturn; U, Uranus; N, Neptune. This diagram shows that the sensitivity of our survey extends roughly from 0.5 AU to 10 AU for planetary orbits, and from 5 $M_\oplus$ to 10 M_J. The majority of all detected planets have masses below that of Saturn, although the sensitivity of the survey is much lower for such planets than for more massive, Jupiter-like planets. Low-mass planets are thus found to be much more common than giant planets. From Cassan *et al.* (2012).

identified by OGLE and followed up by PLANET in the six-year time span 2002-07, as shown in Fig. 1 (although a number of microlensing planets were detected by the various collaborations between 2002 and 2007). This leaves us with three compatible detections: OGLE 2005-BLG-071Lb (Udalski *et al.* 2005, Dong *et al.* 2009) a Jupiter-like planet of mass $M \simeq 3.8\ M_J$ and semi-major axis $a \simeq 3.6$ AU; OGLE 2007-BLG-349Lb (Gould *et al.* 2010), a Neptune-like planet ($M \simeq 0.2\ M_J$, $a \simeq 3$ AU); and the super-Earth planet OGLE 2005-BLG-390Lb (Beaulieu *et al.* 2006, Kubas *et al.* 2008; $M \simeq 5.5\ M_\oplus$, $a \simeq 2.6$ AU).

To compute the detection efficiency for the 2002-07 PLANET seasons, we selected a catalogue of unperturbed (that is, single-lens-like) microlensing events using a standard procedure (Gaudi *et al.* 2002). For each light curve, we defined the planet-detection efficiency $\varepsilon\,(\log d, \log q)$ as the probability that a detectable planet signal would arise if the lens star had one companion planet, with mass ratio q and projected orbital separation d in Einstein-ring radius units (Einstein 1936). The efficiency was then transformed (Dominik 2006) to $\varepsilon\,(\log a, \log M)$. The survey sensitivity $S(\log a, \log M)$ was obtained by summing the detection efficiencies over all individual microlensing events. It provided the number of planets that our survey would expect to detect if all lens stars had exactly one planet of mass M and semi-major axis a.

We used 2004 as a representative season from the PLANET survey. Since the precision of the detection efficiency calculation depends on the quality of the data, not all light curves can be processed. We therefore adopt the same light curve selection criteria (e.g., no clear light curve deviation from a single lens, more than 20 PLANET data, and maximal relative errors on single-lens parameters), and same data reduction and cleaning procedures to build a catalogue of suitable events.

Among the 98 events monitored, 43 met our quality-control criteria and were processed (Cassan 2008). Most of the efficiency comes from the 26 most densely covered light curves, which provide a representative and reliable sub-sample of events. We then computed the survey sensitivity for the whole time span 2002-07 by weighting each observing season relative to 2004, according to the number of events observed by PLANET for different ranges of peak magnification. The resulting planet sensitivity is plotted in blue in Fig. 1, where the labelled contours show the corresponding expected number of detections. The figure shows that the core sensitivity covers 0.5-10 AU for masses between those of Uranus/Neptune and Jupiter, and extends (with limited sensitivity) down to about 5 $M_\oplus$. As inherent to the microlensing technique, our sample of event-host stars probes the natural mass distribution of stars in the Milky Way (K–M dwarfs), in the typical mass range of 0.14-1.0 $M_\odot$.

To derive the actual abundance of exoplanets from our survey, we proceeded as follows. Let the planetary mass function, $f(\log a, \log M) \equiv \mathrm{d}N/(\mathrm{d}\log a \; \mathrm{d}\log M)$, where N is the average number of planets per star. We then integrate the product $f \times S$ over $\log a$ and $\log M$. This gives $E(f)$, the number of detections we can expect from our survey. For k (fractional) detections, the model then predicts a Poisson probability distribution $P(k|E) = e^{-E} E^k/k!$. A Bayesian analysis assuming an uninformative uniform prior $P(\log f) \equiv 1$ finally yields the probability distribution $P(\log f|k)$ that is used to constrain the planetary mass function.

3. Results

Although our derived planet-detection sensitivity extends over almost three orders of magnitude of planet masses (roughly 5 $M_\oplus$ to 10 M_J), it covers fewer than 1.5 orders of magnitude in orbit sizes (0.5–10 AU), thus providing little information about the dependence of f on a. Within these limits, however, we find that the mass function is approximately consistent with a flat distribution in $\log a$ (that is, f does not explicitly depend on a). The planet-detection sensitivity integrated over $\log a$, or $S(\log M)$, is displayed in Fig. 2b. The distribution probabilities of the mass for the three detections (computed according to the mass-error bars reported in the literature) are plotted in Fig. 2c (black curves), as is their sum (red curve).

To study the dependence of f on mass, we assume that to the first order, f is well-approximated by a power-law model: $f_0 \; (M/M_0)^\alpha$, where f_0 (the normalization factor) and α (the slope of the power-law) are the parameters to be derived and M_0 a fiducial mass (in practice, the pivot point of the mass function). Previous works on planet frequency have demonstrated that a power law provides a fair description of the global behaviour of f with planetary mass. Apart from the constraint based on our PLANET data, we also made use in our analysis of the previous constraints obtained by microlensing: an estimate of the normalization (Gould *et al.* 2010) f_0 (0.36 ± 0.15) and an estimate of the slope (Sumi *et al.* 2010) of -0.68 ± 0.2, displayed respectively as the blue point and the blue lines in Fig. 2. The new constraint presented here therefore relies on 10 planet detections. We obtained $10^{-0.62\pm0.22} \; (M/M_0)^{-0.73\pm0.17}$ (red line in Fig. 2a) with a pivot point at $M_0 \simeq 95 \; M_\oplus$; that is, at Saturn's mass. The median of f and the 68% confidence interval around the median are marked by the dashed lines and the grey area.

Hence, microlensing delivers a determination of the full planetary mass function of cool planets in the separation range 0.5–10 AU. Our measurements confirm that low-mass planets are very common, and that the number of planets increases with decreasing planet mass, in agreement with the predictions of the core-accretion theory of planet formation. The first microlensing study of the abundances of cool gas giants (Gaudi *et al.* 2002) found that fewer than 33% of M dwarfs have a Jupiter-like planet between 1.5–4 AU, and even lower limits of 18% have been reported (Tsapras *et al.* 2003, Snodgrass *et al.*

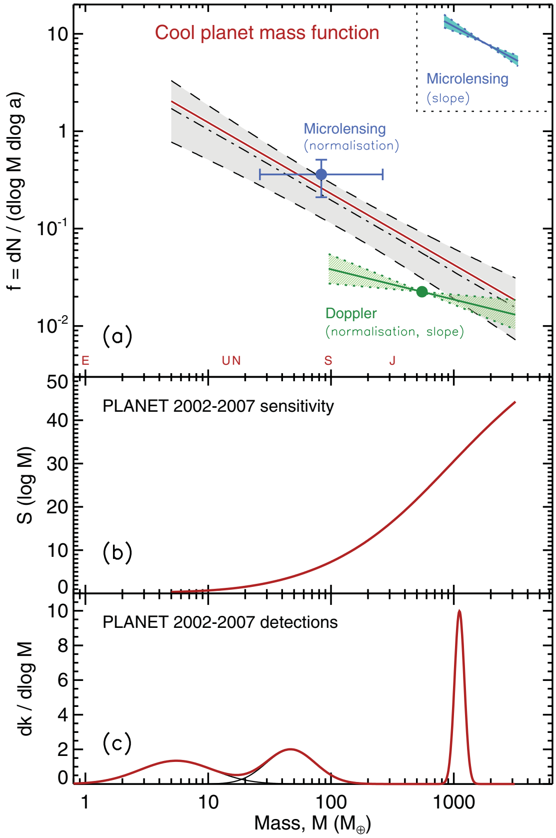

Figure 2. Cool-planet mass function. a, The cool-planet mass function, f, for the orbital range 0.5–10 AU as derived by microlensing. Red solid line, best fit for this study, based on combining the results from PLANET 2002–07 and previous microlensing estimates for slope (Sumi *et al.* 2010, blue line; error, light-blue shaded area, s.d.) and normalization (Gould *et al.* 2010, blue point; error bars, s.d.). We find $\mathrm{d}N/(\mathrm{d}\log a\ \mathrm{d}\log M) = 10^{-0.62\pm0.22}(M/M_{\rm Sat})^{-0.73\pm0.17}$, where N is the average number of planets per star, a the semi-major axis and M the planet mass. The pivot point of the power-law mass function is at the mass of Saturn ($M_{\rm Sat} = 95\,M_\oplus$). Grey shaded area, 68% confidence interval around the median (dash-dotted black line). For comparison, the constraint from Doppler measurements (Cumming *et al.* 2008, green line and point; error, green shaded area, s.d.) is also displayed. Differences can arise because the Doppler technique focuses mostly on solar-like stars, whereas microlensing a priori probes all types of host stars. Moreover, microlensing planets are located further away from their stars and are cooler than Doppler planets. These two populations of planets may then follow a rather different mass function. **b,** PLANET 2002–07 sensitivity, S: the expected number of detections if all stars had exactly one planet, regardless of its orbit. **c,** PLANET 2002–07 detections, k. Thin black curves, distribution probabilities of the mass for the three detections contained in the PLANET sample; red line, the sum of these distributions. From Cassan *et al.* (2012).

2004). These limits are compatible with our measurement of 5^{+2}_{-2}% for masses ranging from Saturn to 10 times Jupiter, in the same orbit range.

From our derived planetary mass function, we estimate that within 0.5–10 AU (that is, for a wider range of orbital separations than previous studies), on average 17^{+6}_{-9}% of stars host a ‘Jupiter’ (0.3–10 $M_{\rm J}$), and 52^{+22}_{-29}% of stars host Neptune-like planets (10–30 $M_\oplus$). Taking the full range of planets that our survey can detect (0.5–10 AU, 5 $M_\oplus$ to 10 $M_{\rm J}$), we find that on average every star has $1.6^{+0.72}_{-0.89}$ planets. This result is consistent with every star of the Milky Way hosting (on average) one planet or more in an orbital-distance range of 0.5–10 AU. Planets around stars in our Galaxy thus seem to be the rule rather than the exception.

4. Prospects

Besides star-bound planets, microlensing is a very valuable tool to search for free-floating planets, those planets which are not bound to any stars (Sumi *et al.* 2011). Free-floating planet microlensing events are characterized by their very short-time scale (less than 2 days), contrary to ordinary events which usually last few weeks (eg. stars) to several months (eg. black holes). New observing strategies with very high cadence monitoring should detect many more free-floating objects, and provide unique insight into planet formation mechanisms.

New ground-based microlensing networks are currently being deployed, mainly using wide-field robotic telescopes. Koreans astronomers are building three new 1.6m telescopes within the Korean Microlensing Network (KMTNet), University of Tasmania is about to start operation with a new robotic telescope at Bisdee Tear, while instruments on current microlensing telescopes are being upgraded.

Last but not least, space-based telescopes are also proposed for microlensing observations, onboard NASA's WFIRST and ESA's Euclid. Realistic simulations (Penny *et al.* 2012) show that a 4-months microlensing campaign onboard Euclid would probe the mass function of cold planets down to the mass of Mars, and even reach the regime of habitable Earths (*i.e.* within the star's snow-line) if extended to a 10 months campaign.

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