One or more bound planets per Milky Way star from microlensing observations

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Most of the known exoplanets have been discovered using the radial velocity[1,2] or transit[3] methods. Both are biased towards planets that are relatively close to their parent stars, and recent studies find that ~17-30 per cent[4,5] of Solar-like stars host a planet. Gravitational microlensing[6,7,8,9], on the other hand, probes planets that are further away from their stars. Recently, a population of planets that are unbound or very far from their stars and at least as numerous as the stars in the Milky Way, was discovered by microlensing[10]. Here we report a statistical analysis of microlensing data (2002-2007) that bridges the gap between these results and determines the fraction of bound planets with orbital distances 0.5 to 10 Sun-Earth distances. We find that 17^{+6}_{-9} per cent of stars host Jupiter-mass planets (0.3-10 M_J, where M_J=318 $M_\oplus$ and $M_\oplus$ is the Earth's mass). Cool Neptunes (10-30 $M_\oplus$) and super-Earths (5-10 $M_\oplus$), however, are even more common: Their respective abundances per star are 52^{+22}_{-29} and 62^{+35}_{-37} per cent. We conclude that planets around stars are the rule, rather than the exception.

Gravitational microlensing is very rare: fewer stars than one per million undergo a microlensing effect at any time. Until now the planet search strategy[7] has been mainly split into two levels. First wide-field survey campaigns such as OGLE[11] and MOA[12] cover millions of stars every clear night in order to identify and alert stellar microlensing events as early as possible. Then the follow-up collaborations, e.g. PLANET[13] (Probing Lensing Anomalies NETwork) and μFUN[14,15] (Microlensing Follow-Up Network) monitor selected candidates with very high cadence (sometimes with a hundred measurements per night), using round-the-world networks of telescopes.

In order to ease the detection efficiency calculation, it is desirable that the observing strategy remains homogeneous for the time span considered in the analysis. As detailed in the Supplementary Information, this condition is fulfilled for microlensing events alerted by OGLE and followed up by PLANET in the six years time span 2002−2007. Although a number of microlensing planets were detected between 2002 and 2007 (Figure 1), only a subset of them are consistent with the PLANET 2002-2007 strategy. This left us with three compatible detections: OGLE 2005-BLG-071Lb[16,17], a Jupiter-like planet (of mass *M*~3.8 M_J and semi-major axis *a*~3.6 Astronomical Unit or AU, the Sun-Earth distance), OGLE 2007-BLG-349Lb[18], a Neptune-like planet (*M*~0.2 M_J, *a*~3 AU), and the super-Earth planet OGLE 2005-BLG-390Lb[19,20] (*M*~5.5 $M_\oplus$ and *a*~2.6 AU).

In order to compute the detection efficiency for the 2002-2007 PLANET seasons, we selected a catalog of unperturbed (*i.e.* single-lens-like) microlensing events using a standard procedure[21] as explained in the Supplementary Information. For each light curve, we define the planet detection efficiency $\varepsilon(\log d, \log q)$ as the probability that a detectable planet signal would arise if the lens star has one companion with mass ratio *q* and projected orbital separation *d* in Einstein ring radius units[22]. The efficiency is then transformed[23] to $\varepsilon(\log a, \log M)$, with *M* the planet's mass and *a* its semi-major axis. The survey sensitivity $S(\log a, \log M)$ is finally obtained by summing up the detection efficiencies over all individual microlensing events. It provides the expected number of planets that our survey would detect if all lens stars had exactly one planet of mass *M* and semi-major axis *a*.

We first used 2004 as a representative season from the PLANET survey. Amongst the 98 events monitored, 43 passed our quality control criteria and were processed[24]. 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 compute the survey sensitivity for the whole time span 2002-2007 by weighting each observing season relative to 2004 according to the number of events observed by PLANET for different ranges of peak magnification. This aspect is described in the Supplementary Information, and illustrated in Supplementary Figure S2. The resulting planet sensitivity is plotted in blue in Figure 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 Uranus/Neptune to Jupiter masses, while it extends (though 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 Solar masses (see Supplementary Figure S3).

In order to derive the actual abundance of exoplanets from our survey, we proceed as follows. Let $f(\log a, \log M) \equiv dN/(d\log a \; d\log M)$ be the planetary mass function. We then integrate the product $f(\log a, \log M) S(\log a, \log M)$ 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.

While our derived planet detection sensitivity extends over almost three decades of masses (~5 $M_\oplus$ to 10 M_J), it covers less than 1.5 decades in orbit sizes (0.5−10 AU), thus providing less information on the dependence of f upon a. Within these limits, however, we find that the mass function is approximately consistent with a flat distribution in $\log a$ (*i.e.* f does not explicitly depend on a). The planet detection sensitivity integrated over $\log a$, or S (log$M$), is displayed in panel (b) of Figure 2. The distribution probabilities of the mass for the three detections (computed according to the mass error bars reported in the literature) are plotted in panel (c) of Figure 2 (black curves), as well as their sum (red curve).

To study the dependence of the planetary mass function f with mass, we assume that to first order, f is well-approximated by a power-law model: $f = f_0\ (M/M_0)^{\alpha}$, where f_0 (the normalisation 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[18,25,26,27] on planet frequency have demonstrated that a power law provides a fair description of the global behaviour of f with planetary mass. Besides the constraint based on our PLANET data, we also made use in our analysis of the previous constraints obtained by microlensing so far: an estimate of the normalisation[18] f_0 (0.36±0.15) as well as an estimate of the slope[25] α (-0.68±0.2), displayed respectively as the blue point and the blue lines in Figure 2. The new constraint presented here therefore relies on 10 planet detections. We obtained $f = 10^{-0.62\pm0.22}\ (M/M_0)^{-0.73\pm0.17}$ (red line in panel (a) of Figure 2) with a pivot point at $M_0 \approx 95\ M_{\oplus}$, *i.e.* 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, for the first time microlensing delivers a determination of the full planetary mass function of cool planets in the separation range 0.5−10 AU. Our measurements thus 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 scenario of planet formation[28]. The first microlensing study of the abundances of cool gas giants[21] found that less than 33% of M dwarfs have a Jupiter-like planet between 1.5−4 AU, and even lower limits of 18% have been reported[29,30]. 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 (*i.e.* for a wider range of orbital separations than previous studies), on average 17^{+6}_{-9} % of stars host a "Jupiter" (0.3−10 M_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 $M_\oplus$ −10 M_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 to 10 Sun-Earth distances. Planets around stars in our Galaxy thus appear to be the rule rather than the exception.

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Author contributions

A.C. led the analysis and conducted the modeling and statistical analyses. A.C. and D.K. selected light curves from 2002-2007 PLANET/OGLE microlensing seasons, analyzed the data and wrote the Letter and Supplement. D.K. computed the magnification maps used for the detection efficiency calculations. J.-P.B. wrote the software for on-line data reduction at the telescopes with Ch.C.. J.-P.B. led the PLANET collaboration, with M.D., J.G., J.M. and A.W.. P.F. and M.D.A. contributed to on-line and offline data reduction. M.D. contributed to the conversion of the detection efficiencies to physical parameter space and developed the PLANET real time display system with A.W., M.D.A. and Ch.C.. K.H. and A.C. developed and tested the Bayesian formulation for fitting the two-parameter power-law mass function. J.G. edited the manuscript, conducted the main data cleaning and managed telescope operations at Mt Canopus (1m) in Hobart. J.W. wrote the original magnification maps software, discussed the main implications and edited the manuscript. J.M., A.W., U.G.J. respectively managed telescope operations in South Africa (SAAO 1m), Australia (Perth 0.61m) and La Silla (Danish 1.54m). A.U. led the OGLE campaign and provided the final OGLE photometry. Most authors were involved in the observing strategy and/or data acquisition, real-time analysis and commented on the manuscript.

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Figure 1. Survey sensitivity diagram. The blue contours display the expected number of detections from our survey if all lens stars have exactly one planet with orbit size *a* and mass *M*. The red points mark all microlensing planet detections in the time span 2002 to 2007, with error bars (s.d.) reported from the literature. The three white points show the three planets consistent with PLANET observing strategy, that can be combined with the detection sensitivity displayed in blue. The red letters (E, J, S, U, N) mark for comparison planets of our Solar System − Earth, Jupiter, Saturn, Uranus and Neptune. This diagram shows that the sensitivity of our survey approximately extends from 0.5 to 10 Earth-Sun distances for planetary orbits, and from 5 Earth masses to 10 Jupiter masses. The majority of all detected planets have masses below that of Saturn, although the sensitivity at these masses is much lower than for more massive, Jupiter-like planets. Low-mass planets are thus found to be much more common than giant planets.

Figure 2. Cool planet mass function. Panel (a) shows the cool planet mass function for the orbital range 0.5−10 AU as derived by microlensing. The best fit (red solid line, this study) is based upon combining the results from PLANET 2002-2007 and previous microlensing estimates[18,25] (in blue, s.d.) for slope and normalisation. We find $dN/(d\log a \, d\log M) = 10^{-0.62\pm0.22} (M/M_{Sat})^{-0.73\pm0.17}$, 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_{Sat}=95 $M_{\oplus}$). The grey shaded area shows the 68% confidence interval around the median (dash-dotted black line). For comparison, the constraint from Doppler measurements[27] (in green, s.d.) is also displayed. Differences can arise from the fact that the Doppler technique is focusing mostly on solar-like stars, while 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. Panel (b) displays PLANET 2002−2007 sensitivity, which is the expected number of detections if all stars had exactly one planet, regardless of its orbit. Panel (c) shows the distribution probabilities of the mass for the three detections contained in the PLANET sample (thin black curves), while the red line is the sum of these distributions.