LETTER

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

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Most known extrasolar planets (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 studies find that around 17–30% (refs 4, 5) of solar-like stars host a planet. Gravitational microlensing[6–9], 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 was discovered by microlensing[10]. These planets are at least as numerous as the stars in the Milky Way[10]. Here we report a statistical analysis of microlensing data (gathered in 2002–07) that reveals the fraction of bound planets 0.5–10 AU (Sun–Earth distance) from their stars. We find that $17^{+6}_{-9}\%$ of stars host Jupiter-mass planets (0.3–10 M_J, where $M_J = 318\,M_\oplus$ and $M_\oplus$ is Earth's mass). Cool Neptunes (10–30 $M_\oplus$) and super-Earths (5–10 $M_\oplus$) are even more common: their respective abundances per star are $52^{+22}_{-29}\%$ and $62^{+35}_{-37}\%$. We conclude that stars are orbited by planets as a rule, rather than the exception.

Gravitational microlensing is very rare: fewer than one star per million undergoes 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 the Optical Gravitational Lensing Experiment (OGLE; ref. 11) and Microlensing Observations in Astrophysics (MOA; ref. 12) 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; ref. 13) and the Microlensing Follow-Up Network (µFUN; refs 14, 15) monitor selected candidates at a very high rate to search for very short-lived light curve anomalies, using global networks of telescopes.

To ease the detection-efficiency calculation, the observing strategy should remain homogeneous for the time span considered in the analysis. As detailed in the Supplementary Information, this condition is fulfilled for microlensing events identified by OGLE and followed up by PLANET in the six-year time span 2002−07. Although a number of microlensing planets were detected by the various collaborations between 2002 and 2007 (Fig. 1), only a subset of them are consistent

with the PLANET 2002–07 strategy. This leaves us with three compatible detections: OGLE 2005-BLG-071Lb (refs 16, 17) a Jupiter-like planet of mass $M \approx 3.8\,M_J$ and semi-major axis $a \approx 3.6$ AU; OGLE 2007-BLG-349Lb (ref. 18), a Neptune-like planet ($M \approx 0.2\,M_J$, $a \approx 3$ AU); and the
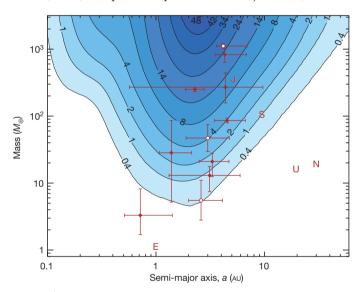

Figure 1 | Survey-sensitivity diagram. Blue contours, expected number of detections from our survey if all lens stars have exactly one planet with orbit size a and mass M. Red points, all microlensing planet detections in the time span 2002–07, with error bars (s.d.) reported from the literature. White 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.

super-Earth planet OGLE 2005-BLG-390Lb (refs 19, 20; $M \approx 5.5\,M_\oplus$, $a \approx 2.6$ 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[21], as explained in the Supplementary Information. 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; ref. 22). The efficiency was then transformed[23] 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. Among the 98 events monitored, 43 met 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 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. This is described in the Supplementary Information, and illustrated in Supplementary Fig. 2. 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 ten times the mass of 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–$1.0\,M_\odot$ (see Supplementary Fig. 3).

To derive the actual abundance of exoplanets from our survey, we proceeded as follows. Let the planetary mass function, $f(\log a, \log M) \equiv dN/(\mathrm{d}\log a \times \mathrm{d}\log M)$, where N is the average number of planets per star. 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.

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: $f = f_0\,(M/M_0)^\alpha$, 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[18,25–27] 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[18] f_0 (0.36 ± 0.15) and an estimate of the slope[25] α (-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
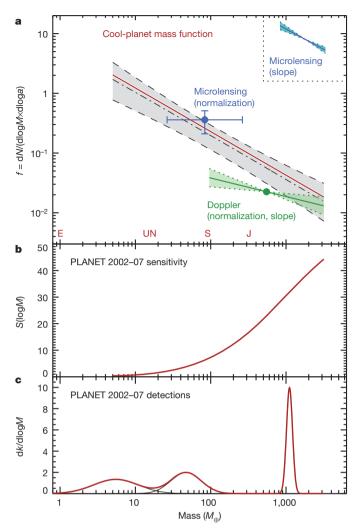

Figure 2 | Cool-planet mass function. a, The cool-planet mass function, f, for the orbital range 0.5–10 AU as derived by microlensing. Red solid line, best fit for this study, based on combining the results from PLANET 2002–07 and previous microlensing estimates[18,25] for slope (blue line; error, light-blue shaded area, s.d.) and normalization (blue point; error bars, s.d.). We find $dN/(\mathrm{d}\log a\,\mathrm{d}\log M) = 10^{-0.62 \pm 0.22}\,(M/M_{\mathrm{Sat}})^{0.73 \pm 0.17}$, 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 ($M_{\mathrm{Sat}} = 95\,M_\oplus$). The grey shaded area is the 68% confidence interval around the median (dash-dotted black line). For comparison, the constraint from Doppler measurements[27] (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.

10 planet detections. We obtained $f = 10^{-0.62 \pm 0.22}\,(M/M_0)^{-0.73 \pm 0.17}$ (red line in Fig. 2a) with a pivot point at $M_0 \approx 95\,M_\oplus$; 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[28]. The first microlensing study of the abundances of cool gas

giants[21] found that fewer than 33% of M dwarfs have a Jupiter-like planet between $1.5-4\,\mathrm{AU}$, 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 $0.5-10\,\mathrm{AU}$ (that is, for a wider range of orbital separations than previous studies), on average $17^{+6}_{-9}\%$ of stars host a 'Jupiter' $(0.3-10\,M_\mathrm{J})$ 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 $(0.5-10\,\mathrm{AU},\ 5\,M_\oplus$ to $10\,M_\mathrm{J})$, 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–$10\,\mathrm{AU}$. Planets around stars in our Galaxy thus seem to be the rule rather than the exception.

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Author Contributions A.Ca. led the analysis and conducted the modelling and statistical analyses. A.Ca. and D.K. selected light curves from 2002–07 PLANET/OGLE microlensing seasons, analysed the data and wrote the Letter and Supplement. D.K. computed the magnification maps used for the detection-efficiency calculations. J.-P.B. and Ch.C. wrote the software for online data reduction at the telescopes. 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 online 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.Ho. and A.Ca. 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 Mount Canopus (1 m) in Hobart. J.W. wrote the original magnification maps software, discussed the main implications and edited the manuscript. J.M., A.W. and U.G.J. respectively managed telescope operations in South Africa (South African Astronomical Observatory 1 m), Australia (Perth 0.61 m) and La Silla (Danish 1.54 m). A.U. led the OGLE campaign and provided the final OGLE photometry. D.P.B, V.B., S.B., J.A.R.C., A.Co., K.H.C., S.D., D.D.P., J.D., P.F., K.Hi., N.K., S.K., J.-B.M., R.M., K.R.P., K.C.S., C.V., D.W., B.W. and M.Z. were involved in the PLANET observing strategy and/or PLANET data acquisition, reduction, real-time analysis and/or commented on the manuscript. T.S. commented on the manuscript. M.K.S., M.K., R.P., I.S., K.U., G.P. and Ł.W. contributed to OGLE data.

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