UNCOVERING GALACTIC AND EXTRAGALACTIC PLANETS
BY GRAVITATIONAL MICROLENSING

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With its planet detection efficiency reaching a maximum for orbital radii between 1 and 10 AU, microlensing provides a unique sensitivity to planetary systems similar to our own around galactic and even extragalactic stars acting as lenses on observed background stars, and in particular can detect terrestrial planets in the habitable zone. The absence of planetary signals in the 1995–1999 PLANET data implies that less than 1/3 of galactic M-dwarfs harbour jupiters at orbital radii between 1.5 and 4 AU. If a fraction $f_p$ of stars is surrounded by a planet, annual detections of 15–25 $f_p$ jupiters and 2–3 $f_p$ earths around galactic stars would result from PLANET, a space-based campaign would yield 1200 $f_p$ jupiters and 30 $f_p$ earths, and a northern microlensing network could detect 15–35 $f_p$ jupiters and 4–10 $f_p$ saturns around M31 stars.

1. Planet detection by microlensing

An unseen planet of mass $m$ at a projected orbital radius $r_p$ around an unseen lens star of mass $M$ distorts the gravitational field of its parent star, so that deviations of 1–20% (lasting hours for earths to days for jupiters) to the lightcurve of a background star undergoing a microlensing event (lasting $\sim$1 month) can occur. The probability for a planet to cause an observable signal (detection efficiency) is roughly proportional to $\sqrt{q}$ and reaches a maximum near $r_p \sim r_E$, where $r_E = \sqrt{2R_S D}$ is the Einstein radius of the lens star, with $R_S = (2GM)/c^2$ being its Schwarzschild radius, $D = D_L(D_S - D_L)/D_S$, and $D_S$ and $D_L$ the source or lens distance.

By achieving a galactic length scale $D \sim 2.5$ kpc $[r_E/(2.5$ AU$)]^2$ for typical lens stars, namely M-dwarfs ($M \sim 0.3 M_\odot$), microlensing becomes sensitive to planetary systems similar to our own. This condition is met not only for observations of galactic bulge stars being lensed by stars in both the galactic disk or the bulge itself ($D_S \sim 8.5$ kpc, $D_L \sim 6$ kpc), but also for observations of stars in other galaxies such as M31 lensed by stars in the same galaxy ($D_S \gg D_S - D_L$, $D \approx D_L$).

For a specific mass ratio, the source star radius sets an upper limit for the planetary deviation. With a photometric precision of 1–2% from the ground and $\sim$0.3% from space, microlensing can detect planets with masses as low as Earth (ground) or even Mars (space). With individual stars not being resolved in M31 observations, only events with high peak magnifications on bright source stars (giants) can be
observed at more moderate photometric precision, so that only planets with masses larger than Saturn can be detected.

With its signal not depending on the orbital period, microlensing provides $d = r_p/r_E$ as the only orbital information and is blind to inclination and eccentricity.

## 2. Microlensing campaigns on the hunt for planets

From daily observations of $\sim 10^7$ galactic bulge stars, OGLE\textsuperscript{13} currently announces $\sim 500$ and MOA\textsuperscript{12} an additional $\sim 50$ microlensing events per year. Detection and characterization of planetary deviations requires dense round-the-clock high-precision monitoring of events selected in order to maximize the total planet detection efficiency which can be achieved by southern telescope networks as PLANET\textsuperscript{17}, MPS\textsuperscript{11} or MicroFUN, supplemented by increased sampling by OGLE and MOA.

A dedicated 1.5m space telescope (GEST\textsuperscript{11}) would be capable of dense monitoring of $\sim 10^8$ galactic bulge stars providing $\sim 5000$ microlensing events per year.

Daily observations of M31 from at least four 2m-class northern telescopes\textsuperscript{6} including sites used by MEGA\textsuperscript{5} or AGAPE\textsuperscript{23,10} can provide a sampling of up to 400 events per year every $\sim 6$ h and more frequently on ongoing anomalies.

Table\textsuperscript{1} lists and compares the capabilities of the different microlensing campaigns (PLANET, GEST, M31 northern network).

| Table 1. Capabilities of different microlensing campaigns. |
|-----------------------------------------------------------|
|               | ground | galactic bulge | space | M31 |
| number of source stars | $\sim 10^7$ | $\sim 10^8$ | $\sim 10^{10}$ |
| resolution of source stars | resolved/crowded | well-resolved | unresolved |
| telescope time | dedicated | dedicated | 0.5–2.5 h per night |
| field of view [sq deg] | 0.004–0.03 | 2 | 0.01–1 |
| number of fields monitored during night | $\sim 20$ | 1 | 1–8 |
| mean sampling interval | 1.5–2.5 h | 10–15 min | 4–6 h |
| total event rate [yr$^{-1}$] | $\sim 300$–$600$ | $\sim 5000$ | $\sim 150$–400 |
| useful types of source stars | main-sequence stars | giants |
| useful peak magnifications | $A_0 \gtrsim 2$ | $A_0 \gtrsim 1.05$ |
| rate of useful events [yr$^{-1}$] | $\sim 75$ | $\sim 5000$ | $\sim 35$–100 |
| planet detection efficiency (lensing zone average) | $\sim 20$% (jupiters) | $\sim 25$% (jupiters) | $\sim 35$% (jupiters) |
| planet probing rate [yr$^{-1}$] | $\sim 1.5$% (earth) | $\sim 1$% (earth) | $\sim 10$% (saturns) |
| upper limit on planetary abundance within 3 years | $\sim 4$% (earth) | $\sim 4$% (earth) | $\sim 10$–30% (saturns) |
| location of parent stars | galactic disk | galactic bulge | M31 |
| extraction of planet parameters | fair in many cases | good |
| identification of parent stars | no | for $\sim 33$% of the events |
| isolated and wide-orbit planets | no | yes | no |
3. First results and future prospects

The absence of planetary signals in the 1995–1999 PLANET data, corresponding to probing effectively 9 stars, yields the upper abundance limits \( f_p(d,q) \) shown in Fig. 1. For jupiters (\( q \approx 0.003 \)), \( f_p \lesssim 33 \% \) for \( 0.6 \leq d \leq 1.6 \) (lensing zone), corresponding to orbital radii of 1.5–4 AU, while a narrower region around \( d \approx 1 \) remains sensitive to \( q \lesssim 10^{-4} \). Current and future campaigns will discover many extra-solar planets within a few years, drastically reduce their upper abundance limit, or yield a combination of these two scenarios (see Table I).

References

1. D.P. Bennett and S.H. Rhie, *Astrophys. J.* **574**, 985 (2002).
2. V. Bozza et al., *Mem. Soc. Astron. Ital.* **71**, 1113 (2001).
3. S. Calchi Novati et al., *Astron. & Astrophys.* **381**, 848 (2002).
4. G. Covone, R. de Ritis, M. Dominik and A.A. Marino, *Astron. & Astrophys.* **357**, 816 (2000).
5. A.P.S. Crotts, R. Uglesich, G. Gyuk and A.B. Tomaney in *Gravitational Lensing: Recent Progress and Future Goals*, ed. T.G. Brainerd and C.S. Kochanek (ASP, San Francisco, 2001).
6. M. Dominik in *General Relativity, Cosmology and Gravitational Lensing*, ed. G. Marmo, C. Rubano and P. Scudellaro (Bibliopolis, Napoli, 2001).
7. M. Dominik et al, *Planetary & Space Science* **50**, 229 (2002).
8. B.S. Gaudi et al., *Astrophys. J.*, **566**, 463 (2002).
9. A. Gould and A. Loeb, *Astrophys. J.* **396**, 104 (1992).
10. E. Kerins et al., *Mon. Not. Roy. Astron. Soc.* **323**, 13 (2001).
11. S.H. Rhie et al., *Astrophys. J.* **522**, 1037 (1999).
12. T. Sumi et al., *Astrophys. J.* **591**, 204 (2003).
13. P.R. Woźniak et al., *Acta Astron.* **51**, 175 (2001).