

## PLANET II: A Microlensing and Transit Search for Extrasolar Planets

Penny D. Sackett

*Research School of Astronomy and Astrophysics, ANU, Mt. Stromlo  
Observatory, Cotter Road, Weston Creek ACT 2611, Australia*

M.D. Albrow<sup>1</sup>, J.-P. Beaulieu<sup>2</sup>, J.A.R. Caldwell<sup>3</sup>, C. Coutures<sup>4</sup>,  
M. Dominik, J. Greenhill<sup>5</sup>, K. Hill<sup>5</sup>, K. Horne<sup>6</sup>, U.-G. Jorgensen<sup>7</sup>,  
S. Kane<sup>6</sup>, D. Kubas<sup>8</sup>, R. Martin<sup>9</sup>, J.W. Menzies<sup>10</sup>, K.R. Pollard<sup>1</sup>,  
K.C. Sahu<sup>3</sup>, J. Wambsganss<sup>8</sup>, R. Watson<sup>5</sup>, A. Williams<sup>9</sup>  
(The PLANET Collaboration)

<sup>1</sup>*University of Canterbury, Christchurch, New Zealand*

<sup>2</sup>*Institut d'Astrophysique de Paris, Paris, France*

<sup>3</sup>*Space Telescope Science Institute, Baltimore, Maryland, USA*

<sup>4</sup>*European Southern Observatory, LaSilla, Chile*

<sup>5</sup>*University of Tasmania, Hobart, Australia*

<sup>6</sup>*St. Andrews University, St. Andrews, Scotland*

<sup>7</sup>*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*

<sup>8</sup>*University of Potsdam, Potsdam, Germany*

<sup>9</sup>*Perth Observatory, Bickley, Australia*

<sup>10</sup>*South African Astronomical Observatory, Cape Town, South Africa*

**Abstract.** Due to their extremely small luminosity compared to the stars they orbit, planets outside our own Solar System are extraordinarily difficult to detect directly in optical light. Careful photometric monitoring of distant stars, however, can reveal the presence of exoplanets via the microlensing or eclipsing effects they induce. The international PLANET collaboration is performing such monitoring using a cadre of semi-dedicated telescopes around the world. Their results constrain the number of gas giants orbiting 1–7 AU from the most typical stars in the Galaxy. Upgrades in the program are opening regions of “exoplanet discovery space” – toward smaller masses and larger orbital radii – that are inaccessible to the Doppler velocity technique.

### 1. Looking for Exoplanets through the Lens of Gravity

The Doppler velocity technique, which measures the small to and from motion induced in a parent star by an orbiting planet, has clearly demonstrated that several percent of solar-type stars have planets very *unlike* those in the Solar System (Marcy, Cochran, & Mayor 2000). Known extrasolar planets are plotted with the nine Solar System planets in Fig. 1. With the exception of the few bodies orbiting dead stellar cores known as pulsars, exoplanets discovered to

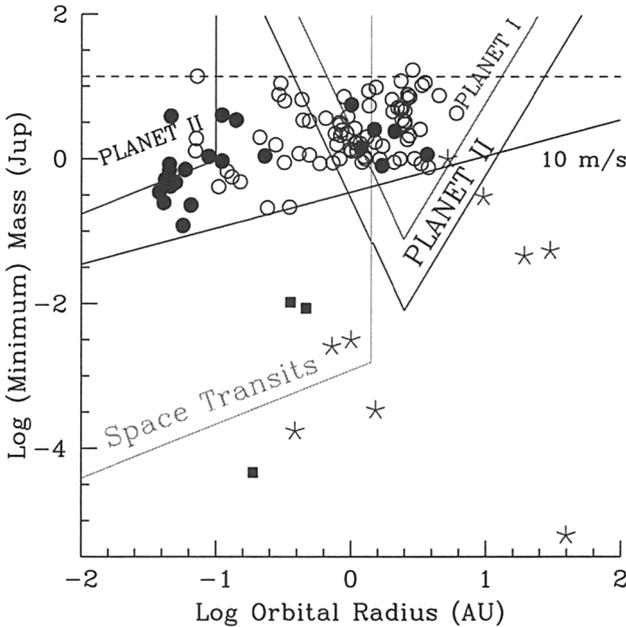


Figure 1. Solar system planets (stars) are shown on a log-log plot of mass (Jupiter masses) vs semi-major axis (AU), with known exoplanets orbiting pulsars (squares) and main sequence stars (dots). Open circles indicate exoplanets with orbits considerably more elongated than those in the Solar System. Planets creating a 10 m/s Doppler signal would lie on the indicated solid line. Discovery spaces for PLANET I, PLANET II, and future space transit missions are sketched.

date populate a portion of mass-orbit parameter space that barely overlaps that of Solar System planets. This is due to selection effects of the Doppler method which is sensitive to high-mass planets orbiting close to their parent bodies. The best Doppler searches have velocity precisions of 3 to 10 m/s, just below that needed to detect a Jovian analog in the most favorable orientation. A suite of search techniques is thus required to explore the range of masses and orbital characteristics exhibited by Solar System planets. We describe a combined microlensing and transit search (PLANET II) for extrasolar gas giants that begins this wider exploration. A general review of microlensing and transit exoplanet searches is given by Sackett (1999).

Gravitational microlensing occurs when a massive compact object (such as a star) passes very near the line-of-sight to a background luminous source (such as another star). The gravitational field of the foreground “lens” bends the light rays from the background “light bulb”, resulting in more light reaching the observer’s telescope. Significant lensing requires precise source-lens alignment, comparable to the angular radius of the so-called Einstein ring, defined as  $\theta_E \equiv [4GM(1-x)/(c^2 D_L)]^{1/2}$ , where  $x \equiv D_L/D_S$ , and  $M$ ,  $D_L$ , and  $D_S$  are the lens mass, lens distance, and source star distance, respectively. For typical Galactic microlensing,  $\theta_E \approx 1$  mas, corresponding to separations of 1 – 5 AU

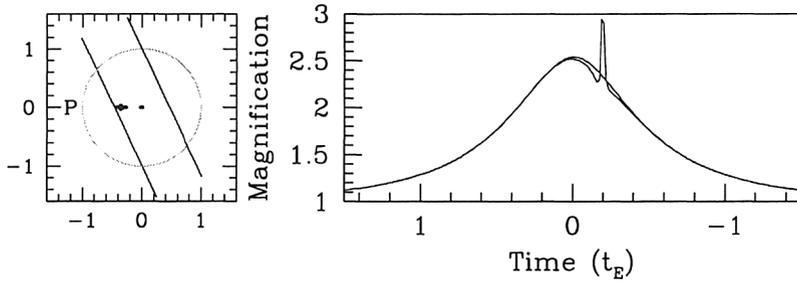


Figure 2. *Left:* The position of a Jovian  $q = 10^{-3}$  planet is marked with “P” just outside the Einstein ring radius of its primary at  $b = 1.2$ . The gravitational field of the primary lens is disturbed, creating small “caustics.” *Right:* The resulting light curves from two possible source trajectories shown at left. Only the light curve associated with the path passing near a caustic betrays the presence of the planet.

at the position of the lenses. Thus, when these rare precise alignments occur, planetary orbits comparable in size to those of Earth and Jupiter are detectable.

As an isolated lens, source, and observer move relative to one another, different portions of the lens magnification pattern are traversed by the source, resulting in a symmetric rising and falling light curve. If the lens is orbited by another star or a planet, however, more complicated magnification patterns are formed; the shape of the resulting light curve then depends on the precise source trajectory (Fig. 2), as described by Mao & Paczyński (1991). If the source passes near a defect – or “caustic” – in the lensing pattern caused by the companion, an anomalous light curve will result that deviates from the smooth, symmetric light curves of isolated lenses. Precise characterization of the anomaly allows the mass ratio  $q \equiv m_p/M$  and projected separation  $b$  of the lens and companion (in units of  $\theta_E$ ) to be determined. The size of caustics (and thus the probability that a random background star will pass near one) decreases slowly with mass ratio  $q$  (Dominik 1999), making microlensing an attractive method to search for low-mass planets.

The precise alignment required for microlensing and the vast emptiness of space conspire to reduce the probability of microlensing for background Galactic stars at any given time to  $\sim 10^{-6}$ . International groups such as OGLE (Udalski et al. 1994) and MOA team (Bond et al. 2001) monitor millions of stars nightly in search of these needles in a haystack, issuing real-time electronic alerts when they find them. The Probing Lensing Anomalies NETwork (PLANET) then performs the intensive and sensitive photometric measurements necessary to detect low-mass lensing companions. Because planetary light curve anomalies are short-lived (several hours to few days) and rare, PLANET uses a network of semi-dedicated telescopes longitudinally distributed around the Southern Hemisphere for round-the-clock monitoring (Albrow et al. 1998).

Over its first five years, PLANET monitored 43 microlensing events intensely, but found no light curve anomalies attributed to low-mass companions. (Stellar binary systems, with  $q > 0.2$  were sometimes observed.) By computing the detection efficiency of each light curve to planets with given  $b$  and  $q$  (Gaudi

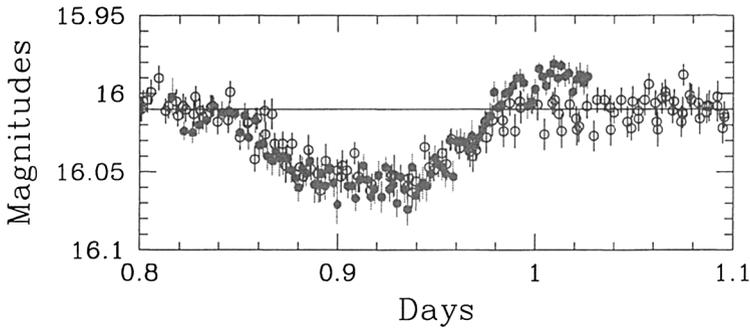


Figure 3. OGLE (open circles, Udalski et al. 2001) and PLANET (filled dots, unpublished) data for the transiting system OGLE-TR-18 ( $0.01\text{mag} \approx 1\%$ ). The companion has a period of 2.228 days and is believed to have a radius twice that of Jupiter. OGLE data were taken over six separate transits and then phase-wrapped; PLANET data were taken with the ESO/Danish 1.5m telescope during a single night.

& Sackett 2000), these null results were translated into upper limits on the frequency of gas giants orbiting the most typical stars (ie., the lenses) in the Galaxy (Albrow et al. 2001; Gaudi et al. 2002). No more than 50% of the lenses can have planets with parameters falling anywhere above the indicated PLANET I line sketched in Fig. 1. Specifically, less than 50% of  $\sim 0.3 M_{\odot}$  stars have Saturnian-mass companions with semi-major axes in the range  $1.5 \text{ AU} < a < 4 \text{ AU}$ .

## 2. Expanding Discovery Space: PLANET II

The increased number of alerts now issued by OGLE and MOA allow PLANET to select and monitor events that have particularly high sensitivity to the presence of planets. The overall planet detection efficiency is expected to increase by a factor of five, resulting in substantial sensitivity to Saturnian-mass planets throughout the range  $1 \text{ AU} < a < 10 \text{ AU}$  in orbital radius (Fig. 1). The expanded program, PLANET II, includes access to the ESO 2.2m telescope; its wide field of view ( $> 0.5$  degree on a side), enables a simultaneous search for transiting gas giants orbiting Solar-type F and G stars in the same fields. The size of the planet is determined from the depth of the partial eclipse, the orbital period is given by the time between successive transits.

The larger the orbit, the smaller the geometric probability of transiting. So-called “hot Jupiters,” with periods of 3–5 days, have  $\sim 10\%$  chance of transiting solar-type parent stars, producing photometric dips lasting 1–3 hours with an amplitude of  $\sim 1\%$ . About 1% of solar neighborhood stars searched for Doppler signals have such planets. If hot Jupiters are equally prevalent around inner Galaxy stars, simulations suggest that up to 100 planets could be found per year by searching for partial eclipses in wide-field surveys of the Galaxy. OGLE III has already found tens of transit candidates (Udalski et al. 2001); recent test results that the image subtraction technique employed by PLANET can generate comparable photometry (Fig. 3). PLANET II will sample fewer fields much more frequently and with higher signal-to-noise when using the ESO 2.2m telescope.

Transit and microlensing searches probe two important regimes of the angular momentum exchanging migration process (Trilling et al. 1998, and references therein) thought to be responsible for hot Jupiters. Microlensing can detect cool gas giants at the separations (several AU from the parent star) where they are believed to have formed; transit photometry is sensitive to hot gas giants that have migrated during their infancy from these birthplaces to small, inner orbits. Proper statistical analysis of the results of both searches would place constraints on the numbers of Jovians that migrate, and thus on the physical process itself.

Both microlensing and transit photometry have the ability to push the discovery space for extrasolar planets into smaller mass regimes than can be probed by the Doppler technique, over a wider range of orbital radii. Uranus- and Neptune-mass planets orbiting several AU from their parent stars can be detected with microlensing. Less massive planets have caustics so small that light curves probing them will be rare and suffer from finite source size effects that dilute the signal, unless smaller (and thus fainter) background stars can be monitored (Bennett & Rhie 1996; Gaudi & Sackett 2000). The best ground-based transit photometry ( $\sim 0.001$  mag) is sensitive to planets with radii one-third that of Jupiter, i.e., planets similar to Uranus and Neptune. Unless ground-based efforts considerably more substantial and precise can be undertaken, the sensitivity to terrestrial-mass planets promised by both techniques will await proposed space missions such as COROT, Eddington, Kepler, MONS, MOST and GEST. (For the latest status of these and other exoplanet projects, see <http://www.obspm.fr/planets>.)

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Penny Sackett (*photo: Seth Shostak*)