The PLANET microlensing follow-up network: Results and prospects for the detection of extra-solar planets

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Abstract. Among various techniques to search for extrasolar planets, microlensing has some unique characteristics. Contrary to all other methods which favour nearby objects, microlensing is sensitive to planets around stars at distances of several kpc. These stars act as gravitational lenses leading to a brightening of observed luminous source stars. The lens stars that are tested for the presence of planets are not generally seen themselves. The largest sensitivity is obtained for planets at orbital separations of 1–10 AU offering the view on an extremely interesting range with regard to our own solar system and in particular to the position of Jupiter. The microlensing signal of a jupiter-mass planet lasts typically a few days. This means that a planet reveals its existence by producing a short signal at its quasi-instantaneous position, so that planets can be detected without the need to observe a significant fraction of the orbital period. Relying on the microlensing alerts issued by several survey groups that observe ∼10^7 stars in the Galactic bulge, PLANET (Probing Lensing Anomalies NETwork) performs precise and frequent measurements on ongoing microlensing events in order to detect deviations from a light curve produced by a single point-like object. These measurements allow constraints to be put on the abundance of planets. From 42 well-sampled events between 1995 and 1999, we infer that less than 1/3 of M-dwarfs in the Galactic bulge have jupiter-mass companions at separations between 1 and 4 AU from their parent star, and that less than 45 % have 3-jupiter-mass companions between 1 and 7 AU.

1 Introduction

All of our knowledge about objects outside our own solar system is based on observations of electromagnetic radiation with different wavelengths: infrared, optical, ultraviolet, radio, X-ray, γ-ray. In any case, planets are not strong emitters and orbit stars that are much stronger emitters. For optical wavelengths, most of the light coming from the planet is reflected light originating between light from a star and reflected light from a planet is about 10^-3 to 10^-10. For infrared wavelengths, this ratio becomes much smaller due to the thermal emission of the planet, but it is still 10^-4 to 10^-6. Therefore, the direct detection of planets from the emitted or reflected radiation is rather difficult.

For this reason, one has to think about how the presence of the planets yields observable signals in other objects that are easier to detect.

Since both planets and their parent stars move around their common center-of-mass, one can try to detect the small motion of the luminous parent star rather than observing the dark planet. Two techniques make use of this effect: The radial velocity technique observing the one-dimensional radial motion of the star by determining its velocity via Doppler-shift measurements, and the astrometric technique observing the two-dimensional transverse motion by position measurements.

The microlensing technique described here is even more indirect. Its basic concept is the observation of a large number of luminous source stars to wait for their brightening caused by the gravitational bending of light by intervening compact massive objects that pass close to the line-of-sight and act as so-called gravitational lenses. If these lens objects are surrounded by planets, there is some chance that their gravitational field causes additional variations in the observed brightness of the source stars. This means that microlensing can detect unseen planets orbiting unseen stars. Planets orbiting the source stars and passing in front of them would not yield to a microlensing signature resulting in a brightening of the observed stars, but to an occultation resulting in a dimming. Such signals can also be used to detect planets.

Among the different techniques, microlensing has some unique characteristics. Since microlensing relies on a chance alignment between source stars and lens objects, there is no opportunity to select the parent stars to be tested for the existence of planets, contrary to the methods relying on obser-
vations of luminous parent stars. Contrary to radial-velocity or astrometric searches, there is no need to wait for the orbital period of the planet. The passage of the star close to the line-of-sight yields a signal that lasts a few months, while the signal due to the planet is even shorter, a few days for a jupiter-mass planet. The favourite range for the detection of planets by microlensing is an orbital separation of 1–10 AU, i.e. a range comparable to our own solar system, extending roughly from Earth to Saturn with the most massive planet Jupiter being near its center, whereas radial velocity searches favour small separations or short orbital periods (related to Jupiter being near its center, whereas radial velocity searches roughly from Earth to Saturn with the most massive planet i.e. a range comparable to our own solar system, extending planets by microlensing is an orbital separation of 1–10 AU, source star, i.e. parent stars at several kpc distance, and is favouring objects halfway between the observer and the ods on luminous stars that favour nearby objects, microlensing fore solar systems that are unlike our own. Contrary to meth-sions by Kepler's 3rd law), and astrometric searches for the signal due to the planet is even shorter, a few days for a jupiter-mass planet. The favourite range for the detection of planets by microlensing is an orbital separation of 1–10 AU, i.e. a range comparable to our own solar system, extending roughly from Earth to Saturn with the most massive planet Jupiter being near its center, whereas radial velocity searches favour small separations or short orbital periods (related to the separations by Kepler’s 3rd law), and astrometric searches favour large separations or large orbital periods, and therefore solar systems that are unlike our own. Contrary to methods on luminous stars that favour nearby objects, microlensing favours objects halfway between the observer and the source star, i.e. parent stars at several kpc distance, and is therefore a unique method to determine the abundance of planets around such distant stars. Here we discuss the prospects of planet detection by microlensing and in particular the prospects and recent results of our ongoing PLANET experiment.

2 Microlensing surveys

As pointed out by Paczyński (1986, 1991) and Kiraga and Paczyński (1994), the probability for an alignment of mas-sive compact foreground objects with luminous source stars in our Galaxy that yields a significant brightening (30 %) at a given time is of the order of $10^{-6}$. One must therefore observe a large number of stars in order to see a significant number of ongoing ‘microlensing events’. Therefore, fields on the sky with a large number of stars, such as the Galactic bulge, are of special interest. About $\sim 10^5$ stars in the Galactic bulge are currently sampled (weather permitting) by the 3 collaborations OGLE (Udalski et al., 1997), EROS (Palanque-Delabrouille et al., 1998), and MOA (Bond et al., 2001). From 1995 to 1999, such a survey has also been carried out by the MACHO collaboration (Alcock et al., 1996, 1997). These surveys have been equipped with on-line data-reduction systems so that microlensing events can be caught in real-time. Issuing alerts on suspected microlensing events by e-mail and or via designated alert pages on the web\(^1\) allows follow-up observations of these events to be undertaken. The number of publicly issued alerts in the recent years is shown in Table 1.

3 The PLANET experiment

The aim of PLANET (Probing Lensing Anomalies NETwork) is to perform precise and frequent multi-band observations of ongoing microlensing events in order to study departures from the expected baseline magnitudes $V_0 \leq 20.5$ (MACHO and EROS), $I_0 \leq 19$ (OGLE), or $R_0 \leq 19.5$ (MOA), where alerts that show obvious anomalies such as caused by binary lenses or sources, have been eliminated. As additional cri-terion, high-magnification alerts fulfill the condition $A_0 \geq 10$ and alerts on bright stars fulfill $V_0 \leq 17.5$ (MACHO and EROS), $I_0 \leq 16$ (OGLE), or $R_0 \leq 16.5$ (MOA). The entry ‘—’ means that the survey was not operational, while the entry ‘0’ means that no such alerts have been issued.

| Year | OGLE | MACHO | EROS | MOA | Total |
|------|------|-------|------|-----|-------|
| 1994 | 1    | 2     | 0    | 0   | 3     |
| 1995 | 3    | 2     | 1    | 0   | 6     |
| 1996 | 2    | 0     | 3    | 1   | 6     |
| 1997 | 2    | 0     | 1    | 1   | 4     |
| 1998 | 5    | 0     | 0    | 0   | 5     |
| 1999 | 4    | 0     | 0    | 0   | 4     |
| Total| 15   | 6     | 6    | 1   | 28    |

\(^1\)OGLE (1994–): http://www.astrouw.edu.pl/~ftp/ogle/ogle2/ews/ews.html
OGLE (1994–): http://www.phys.canterbury.ac.nz/~physib/alert/alert.html
EROS (1998–): http://darkstar.astro.washington.edu/
EROS (1998–): http://www-dapnia.cea.fr/Spp/Experiences/EROS/alertes.html
MOA (2000–): http://www.astrouw.edu.pl/~ftp/ogle/ogle2/ews/ews.html

Table 1. Number of public alerts issued by the 4 collaborations OGLE, MACHO, EROS, and MOA in the different observing seasons from 1994–2000. Because some alerts correspond to the same event, the number of total alerts is sometimes smaller than the sum of alerts of the different collabora-tions. Alerts are regarded as useful for peak magnifications $A_0 \geq 2$ and baseline magnitudes $V_0 \leq 20.5$ (MACHO and EROS), $I_0 \leq 19$ (OGLE), or $R_0 \leq 19.5$ (MOA), where alerts that show obvious anomalies such as caused by binary lenses or sources, have been eliminated. As additional cri-terion, high-magnification alerts fulfill the condition $A_0 \geq 10$ and alerts on bright stars fulfill $V_0 \leq 17.5$ (MACHO and EROS), $I_0 \leq 16$ (OGLE), or $R_0 \leq 16.5$ (MOA). The entry ‘—’ means that the survey was not opera-tional, while the entry ‘0’ means that no such alerts have been issued.
from a light curve that is due to lensing of a point source by a single point-like lens. The origin of these departures can be due to blending of the light of the source star by other stars (in particular the lens) or due to effects by binary lenses (including planets), binary and extended sources, or the parallax effect due to the motion of the Earth around the Sun.

With these observations, PLANET yields valuable contributions to the fields of Galactic structure and dynamics, binary stars, extra-solar planets, stellar atmospheres, and variable stars.

PLANET uses a network of four 1m-class optical telescopes in the southern hemisphere with the following detectors:

- South African Astronomical Observatory (SAAO) 1.0m at Sutherland, South Africa: camera with beam splitter and optical 2048 × 2048 CCD, infrared 1024 × 1024 CCD, both with 0.3′′ per pixel, field of view 10′ × 10′ (optical), 5′ × 5′ (infrared)
- Yale 1.0m at Cerro Tololo Inter-American Observatory (CTIO), Chile: camera with same specifications as at SAAO
- Canopus Observatory 1.0m near Hobart, Tasmania, Australia: optical camera with 512 × 512 CCD, 0.43″ per pixel, field of view 3.7′ × 3.7′
- Perth Observatory 0.6m at Bickley, Western Australia: optical camera with 512 × 512 CCD, 0.60″ per pixel, field of view 5.1′ × 5.1′

The distribution of these telescopes in longitude allows to monitor our targets in the Galactic bulge continuously during our observing season from April to September each year. Our main observing band is I, while we take images in V about half as frequently. PLANET started its observations with a one-month pilot season in 1995 (Albrow et al., 1998) and went fully operational in 1996. We have taken data on 9 bulge events in 1995, on 21 events in 1996, on 31 events in 1997, on 33 events in 1998, on 36 events in 1999, and on 20 events in 2000. During the each of the 1998 and 1999 seasons, we have collected ∼4000 I-frames and ∼2000 V-frames.

Its experimental design allowed PLANET to obtain some important results outside the field of extra-solar planets discussed here. The measurement of the relative proper motion between lens and source in a fold caustic-crossing event towards the Small Magellanic Cloud (SMC) yielded evidence that the lens is located in the SMC itself and not in the Galactic halo (Albrow et al., 1999a,b). Furthermore, PLANET has been able to measure limb-darkening coefficients for three giant stars (at several kpc distance) (Albrow et al., 1999c, 2000b, 2001a), and by combining PLANET data with those of other microlensing collaborations, for a dwarf star in the SMC (Afonso et al., 2000). By detecting motion effects in a binary lens (Albrow et al., 2000b), tight constraints for the lens mass, distance, and rotation period have been derived. During the regular PLANET observations at the SAAO 1m, the optical counterpart of a γ-ray burst has been discovered in R-band and has been followed over the next two days in R-, V-, and I-band (Sahu et al., 2000). Finally, PLANET has been able to observe variations in the Hα equivalent width during a caustic crossing event with the FORS1 spectrograph at the VLT, giving a powerful test for stellar atmosphere models of the lensed K giant (Albrow et al., 2001b).

The current status of the PLANET experiment including a list of currently monitored events and their parameters as well as recent results can be obtained from the PLANET webpage http://www.astro.rug.nl/~planet.

4 The theory behind microlensing

Microlensing uses the effect of the deflection of light due to the gravitational field of a massive compact object. If $M$ denotes the mass of this object, and $r$ denotes the separation of the light ray from it, the light ray is deflected by the angle (Einstein, 1915)

$$\dot{\alpha} = \frac{4GM}{c^2} \frac{1}{r},$$

where $G$ is the constant of gravitation, and $c$ is the speed of light. This deflection yields two possible light trajectories from the source to the observer resulting in two images of the same source object on the sky, where the observed brightness of these images differs from the intrinsic brightness of the source object. The characteristic physical dimension of microlensing is given by the angular Einstein radius

$$\theta_E = \sqrt{\frac{4GM}{c^2}} \frac{D_{LS}}{D_L D_S},$$

where $D_L$ and $D_S$ are the distances from the observer to the lens and the source, respectively, and $D_{LS}$ is the distance between lens and source. The angular Einstein radius quantifies the quality of alignment between lens and source on the sky. If $u$ denotes the angular separation between lens and source in units of $\theta_E$, the total magnification of the source, i.e. the sum of the magnifications of the two images reads

$$A(u) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}},$$

while the separations between the images is given by

$$\Delta \theta = \sqrt{u^2 + 4} \theta_E \geq 2\theta_E.$$

The smaller the separation between lens and source, the larger the total magnification $A$; for a separation of $\theta_E$, one obtains $A = 3/\sqrt{5} \approx 1.34$. For large separations, the magnification falls off as $A \simeq 1 + 2/u^4$, where the single images contribute $A_+ \simeq 1 + 1/u^4$ and $A_- \simeq 1/u^4$, so that the total magnification quickly reaches 1 and one image is strongly demagnified. To yield a significant magnification, the separation therefore cannot exceed a few $\theta_E$, corresponding to a separation of the images that does not exceed a few $\theta_E$ either. For large image separations $\Delta \theta \gg \theta_E$, the fainter image will escape detection due to its faintness.
For a source object near the Galactic center and a solar-mass lens object halfway between us and the source, one obtains $\theta_E \sim 1$ mas. This means that the images cannot be resolved with optical telescopes on the ground (typical resolution 1") and also not with the Hubble Space Telescope (resolution of 0.04"). Therefore, the only photometric observable is the total light composed of the two (unresolved) images.

The dynamics of the Galaxy determines the relative proper motion $\mu$ between lens and source. Therefore, their separation is a function of time

$$u(t) = \left| u_0^2 + \frac{(t - t_0)}{t_E} \right|^2,$$

where $t_E = \theta_E/\mu$ denotes the times in which the lens moves by $\theta_E$ relative to the source, $u_0$ denotes the smallest separation between lens and source, and $t_0$ denotes the point of time at which $u(t) = u_0$. This means that one observes characteristic light curves determined by the parameters $u_0$, $t_0$, and $t_E$, where $u_0$ determines the peak magnification of the curve, which is given by $A_0 = A(u_0)$, and $t_E$ denotes the duration of the 'microlensing event'.

For source stars in the Galactic bulge, lens objects can be stars in the Galactic bulge itself or in the Galactic disk. A typical time scale is

$$t_E \sim 40 \text{ d} \cdot \sqrt{M/M_\odot},$$

i.e. the timescale is proportional to the square-root of the lens mass, and is about one month for a solar-mass lens object, one day for a jupiter-mass object, and one hour for an earth-mass object.

### 5 Microlensing and planets

The fact that planets around lens stars cause observable effects in microlensing light curves was first pointed out by Mao and Paczyński (1991). The shape of the light curve is dominated by the effect from the star, and the effect of the planet can be treated as a perturbation.

However, the planet cannot be modelled as an isolated single lens: the tidal field of the star at the position of the planet strongly enhances the planetary perturbation by introducing an effective shear (Chang and Refsdal, 1979; Gould and Loeb, 1992; Gaudi and Gould, 1997; Dominik, 1999). The strongest effect is obtained if the angular separation $\theta_p$ of the planet from its parent star is comparable to the angular Einstein radius $\theta_E$. To quantify further a range of separations with strong effects, one can define a region called the 'lensing zone', defined by $0.618 \theta_E \leq \theta_p \leq 1.618 \theta_E$.\(^2\) This also means that the probability of seeing a planetary signal is especially large for planets in this zone compared to outside it. The detection probability also depends on the smallest angular separation $u_0$ between lens and source and therefore on the peak magnification $A_0$. The probability of detecting a distortion larger than 5% caused by a jupiter-mass planet in the lensing zone around a solar-mass star is $\sim 15\%$ if one considers all events with $A_0 \geq 1.34$ (Gould and Loeb, 1992), while it becomes $\sim 80\%$ if only events with $A_0 \geq 10$ are considered (Griest and Safizadeh, 1998). Examples for perturbations caused by jupiter-mass planets are illustrated in Fig. 1. For planetary separations $\theta_p > \theta_E$, the main effect is an increase in magnification, while for $\theta_p < \theta_E$, a decrease takes place.

For a lens star at $D_L = 4$ kpc, the angular Einstein radius corresponds to a physical size of

$$r_E \sim \sqrt{M/M_\odot} \cdot 4 \text{ AU},$$

so that microlensing has the largest sensitivity for planets in the range 1–10 AU (taking into account distributions in the mass of the parent stars and in the distance to the parent stars). If one compares this distance to our own solar system, one sees that this is quite an interesting range of orbital separations: the most massive planet Jupiter lies nearly in the middle of this region, which extends down to Earth and on the other side nearly reaches Saturn.

Contrary to the astrometry and the radial velocity methods that rely on signals that are proportional to the mass of the planet $M_p$, microlensing can yield signals of the same strength for less-massive planets; however, the probability of observing this signal decreases, but only proportionally to $\sqrt{M_p}$. Nevertheless, a principal limit is given by the

\(^2\)0.618 means $(\sqrt{5} - 1)/2$ and 1.618 means $(\sqrt{5} + 1)/2$. 

![Fig. 1. Planetary perturbations to a light curve caused by microlensing due to a star ($t_E = 40 \text{ d}, u_0 = 0.15$). The mass ratio is $q = 10^{-3}$, resembling the ratio between Jupiter and the Sun. The upper panel shows a case where the planet is outside the angular Einstein ring of the star, namely $\theta_p = 1.34 \theta_E$, while the lower panel shows a case where the planet is inside the angular Einstein ring of the star, namely at $\theta_p = 0.77 \theta_E$. While in the first case, the main effect is an increase in amplification, it is a decrease in the second case.](image-url)
finite size of the source stars. Only if the angular size of the source star is much smaller than the angular Einstein radius of the planet, the source star can be approximated as point-like. Otherwise, its finite source size leads to a reduction of the planetary signal. For $M_p \sim 10^{-6} M_\odot$, the angular Einstein radius of the planet reaches the angular size of a solar-type source star in the Galactic bulge, so that for Jupiter-mass planets, the point-source approximation is valid. For Earth-mass planets, however, the observed deviation for larger (giant) stars, there will be no observable signal at all.

6 Determining planet parameters

From a microlensing light curve involving the signal of a planet, only 3 parameters related to the nature of the planet, its parent star, and the orbit can be extracted: the event time scale $t_E$, the mass ratio between planet and star $q$, and the instantaneous projected separation $d = \theta_p/\theta_E$ between planet and star in units of Einstein radii (Gaudi and Gould, 1997). The measured time scale $t_E$ is a convolution of the mass of the star $M$, its distance $D_L$, and the relative lens-source proper motion $\mu$, which are not known separately. By assuming a mass density along the line-of-sight, a mass spectrum, and a statistical distribution for the proper motion, one can derive probability distributions for all quantities involving $M$, $D_L$, or $\mu$ for any given observed event with time scale $t_E$ (Dominik, 1998). With reasonable assumptions about the underlying statistical distributions, the projected separation of the planet from the parent star can be determined with an uncertainty factor $\sim 2$, and the mass of the planet with an uncertainty factor $\sim 5$.

Because one is only sensitive to the instantaneous projection, only a lower limit on the semimajor axis in units of Einstein radii $\rho = a/r_E$ is obtained. Therefore, the determination of the semimajor axis $a$ depends both on statistics about the orbits and on statistics about the lens population. The same is true for the orbital period $P$. About the eccentricity $\epsilon$ of the orbit and its inclination $i$, microlensing yields no information at all.

7 PLANET’s search for planets

To be able to characterize the properties of planets, we need to take data points with a photometric precision of $1–2\%$ (in order to see $5\%$ deviations) at a sampling rate of one point every 1.5–2.5 hours. Though deviations caused by Jupiters last about 1 day, about 10–15 points over such a deviation are required to be able to extract its true nature. The photometric precision determines the exposure time needed for the images and the exposure time dictates the number of events that can be followed with the needed sampling rate. Since the exposure time for a given photometric precision depends on the brightness of the source stars, the capabilities of PLANET depend on the brightness of the source stars in the alerted microlensing events. For giant stars ($V \lesssim 17.5$), exposure times are of the order of 3 min, so that 20 events can be observed at the same time, or 75 events per season. For fainter stars, the exposure time has to be lengthened to about 10–15 min, so that around 6 events can be monitored at a given time, or about 20 events per observing season. Reliable measurements can be obtained for source stars down to $I \sim 19$, roughly corresponding to $V \sim 20.5$ for our targets.

By comparing the capabilities of PLANET with the number of alerted events, as shown in Table 1, one sees that there have been up to $\sim 50$ useful alerts per year, but only 5–10 of them involved giant stars or had a peak magnification exceeding 10. Though the total event rates from the EROS and the MOA surveys are much smaller than those from OGLE and MACHO, there is a much larger fraction of alerts with high peak magnification or on bright source stars. While there have been fewer events on giant stars than can be followed by PLANET, there have been more events on fainter stars than can be followed. Therefore, among the events on fainter stars, we selected those with larger peak magnification in order to obtain the strongest possible constraint on the abundance of planets, and also observed those events with anomalous behaviour in order to achieve our science goals outside the field of extra-solar planets.

8 Results

Though we would currently expect to detect $\sim 3$ Jupiter-mass planets per year if every lens star had such a planet within its lensing zone, we have not detected any clear planetary signal in our data yet. Because of the dense sampling of many mi-
Fig. 3. Detection efficiency ε for companions to the parent lens star that has led to the event OGLE 1998-Bulge-14, for Δχ² = 100. The companion is characterized by its mass ratio q and its instantaneous projected separation d = θp/θE from the parent star in units of Einstein radii. The four regions which differ in the shade density correspond to the labelled ranges for ε.

crolensing events, constraints on the presence of planets with certain mass and orbital separation can be derived from the fact that no signals have been observed.

For each event, there is a fractional probability that a planet would have yielded a detectable signal, namely the detection efficiency ε which depends on the mass ratio q between planetary companion and parent star and the separation parameter d. Gaudi and Sackett (2000) have developed an algorithm to calculate the detection efficiency ε(d, q) using the criterion for a ‘detectable signal’ that a fit for a binary system (star with planet) yields a χ² that exceeds that of the best single lens fit by a fixed amount Δχ². If the hypothesis of the presence of a companion is rejected if no signal is observed, and accepted otherwise, the significance level of the corresponding test is α = 1 − ε.3

We started our analysis with the well-covered event OGLE 1998-Bulge-14 (Albrow et al., 2000a), i.e. the 14th event alerted by the OGLE collaboration in the 1998 season observed towards the Galactic bulge (see Fig. 2). This event has a timescale tE ∼ 40 days and an impact parameter u0 = 0.06, corresponding to a peak amplification of ∼16. PLANET has taken 470 data points in I and 139 data points in V. During the 2 months over the peak, the average sampling interval is ∼2.5 hours and the photometric precision is ∼1.5%.

Figure 3 shows the detection efficiency for this event where Δχ² = 100. The contours shown in the figure reveal the fact that the detection efficiency reaches its maximum for separations around the Einstein radius. Assuming rE ∼ 4 AU, a planet with Jupiter’s mass and a projected separation of Jupiter’s orbital separation is ruled out. The detection efficiency decreases with smaller mass ratios and drops quickly outside a narrow region around θE. Note that this diagram uses the instantaneous projected separation in units of Einstein radii. For the conversion to orbital separations, three statistical effects have to be considered: the distribution of rE, the inclination of the orbit, and its phase.

Between 1995 and 1999, PLANET has taken data on 42 well-covered events that are suitable for our analysis on the abundance of extra-solar planets. The distribution of the sampling intervals for this event sample is shown in Fig. 4.

The effective number of lens stars n_eff that are probed for the existence of companions with given characteristics d and q is given by the sum of detection efficiencies for all observed events,

\[ n_{\text{eff}}(d, q) = \sum_{i=1}^{m} \varepsilon_i(d, q). \]  (8)

With f(d, q) being the fraction of lens stars with a companion, the number of expected signals is

\[ N_s(d, q) = f(d, q) n_{\text{eff}}(d, q), \]  (9)

and the probability for not observing any signal in all of the events is given by

\[ P(d, q) = 1 - \prod_{i=1}^{m} (1 - f(d, q) \varepsilon_i(d, q)) \]  (10)

3However, α does not coincide with the probability that a companion is present in the system given that no signal has been observed.
An inexpensive pixel-lensing survey towards the Galactic Bulge which preferably selects events with high magnifications (Gould and DePoy, 1998) would yield \( \sim 50 \) alerts per observing season, among them \( \sim 25 \) alerts with \( A_0 \geq 10 \) and \( \sim 2 \) alerts with \( A_0 \geq 200 \) (Han, 2001), so that PLANET could probe effectively \( \sim 25 \) lens stars per year for jupiter-mass planets and \( \sim 3 \) lens stars per year for earth-mass planets in the lensing zone, the latter essentially coming from the few events with the largest peak magnifications.

This implies that, with three future years of observations, PLANET will have probed \( \sim 50–85 \) stars for jupiter-mass planets, either bringing the actual constraint of less than \( 1/3 \) of the lens stars being surrounded by planets to \( 3–6\% \), or leading to the detection of up to \( 8 \) jupiter-mass planets per year. Alerts from a possible pixel-lensing survey would allow PLANET also to probe \( \sim 3 \) lens stars per year for earth-mass planets, yielding a constraint that less than \( 1/3 \) of the lens stars have earth-mass planets in their lensing zone if no signals are detected.

Ground-based microlensing searches with advanced technology (and advanced budget) could effectively probe \( \sim 10 \) stars in the Galactic bulge and disk per year for earth-mass planets per year and \( \sim 200 \) stars per year for jupiter-mass planets (Peale, 1997; Sackett, 1997). Space-based searches with a dedicated satellite (GEST) will even be sensitive to mars-mass planets and could effectively probe \( \sim 40 \) stars per year for earth-mass planets and \( \sim 2000 \) stars per year for jupiter-mass planets by microlensing, while detecting a ten times larger number of jupiter-mass planets through transits (Bennett and Rhie, 2000).

While the planetary systems studied by ongoing microlensing experiments are already at much larger distances than those studied by other techniques, microlensing even offers the possibility to constrain the abundance of planets around stars in M31, effectively probing \( \sim 35 \) lens stars for jupiter-mass planets in the lensing zone with a network of \( 2\)-m-class telescopes (Covone et al., 2000; Baltz and Gondolo, 2001; Dominik, 2001).

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\[
\begin{align*}
\approx & \quad 1 - \exp \left\{ -f(d, q) n_{\text{eff}}(d, q) \right\}, \\
\text{(11)}
\end{align*}
\]

where the approximation holds for \( f_i \ll 1 \). Therefore, fractions \( f(d, q) \) with

\[
\begin{align*}
f(d, q) & \geq -\frac{\ln(1 - P)}{n_{\text{eff}}(d, q)} \\
\text{(12)}
\end{align*}
\]

can be rejected at the confidence level \( P \). In particular, for \( P = 95\% \), Eq. (12) becomes \( f(d, q) \geq 3/n_{\text{eff}}(d, q) \).

Our limits on the fractions of systems with planets from our sample of 42 events are shown in Fig. 5. By assuming ‘typical’ values \( M \sim 0.3 \, M_\odot \) (corresponding to the bulge mass function) and \( D_L \sim 6 \, \text{kpc} \), so that \( r_E \sim 2 \, \text{AU} \), furthermore assuming circular orbits, and averaging over orbital phase and inclination, we conclude that less than \( 1/3 \) of M-dwarfs in the Galactic bulge have jupiter-mass companions at separations between \( 1 \) and \( 4 \, \text{AU} \) from their parent star, and that less than \( 45\% \) have 3-jupiter-mass companions between \( 1 \) and \( 7 \, \text{AU} \) (Albrow et al., 2001; Gaudi et al., 2002).

9 The future

While the termination of the MACHO project at the end of 1999 led to a decrease in the number of useful alerts, the 3rd phase of the OGLE project starting in 2002 will yield \( 150–250 \) useful alerts per year, among these \( 25–40 \) high-magnification alerts and about the same number of alerts on bright source stars. This will bring the effective number of lens stars being probed by PLANET for jupiter-mass planets in the lensing zone to \( \sim 15–25 \) per year.

\[
\begin{align*}
\text{Projected Separation (d)}
\end{align*}
\]

\[\text{Mass Ratio (q)}\]

Fig. 5. Fractions \( f(d, q) \) of lens stars having a companion with mass ratio \( q \) at the separation parameter \( d \) which are excluded at 95% confidence level by PLANET observations on 42 well-covered events between 1995 and 1999. From the inside to the outside, the 5 contours correspond to \( f = 3/4, 2/3, 1/2, 1/3, \) and \( 1/4 \).

\[
\approx 1 - \exp \left\{ -f(d, q) n_{\text{eff}}(d, q) \right\} ,
\]

\[
f(d, q) \geq -\frac{\ln(1 - P)}{n_{\text{eff}}(d, q)}
\]

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