Ground-based Microlensing Surveys

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1. Overview

Microlensing is a proven extrasolar planet search method that has already yielded the detection of four exoplanets. These detections have changed our understanding of planet formation “beyond the snowline” by demonstrating that Neptune-mass planets with separations of several AU are common. Microlensing is sensitive to planets that are generally inaccessible to other methods, in particular cool planets at or beyond the snowline, very low-mass (i.e. terrestrial) planets, planets orbiting low-mass stars, free-floating planets, and even planets in external galaxies. Such planets can provide critical constraints on models of planet formation, and therefore the next generation of extrasolar planet searches should include an aggressive and well-funded microlensing component. When combined with the results from other complementary surveys, next generation microlensing surveys can yield an accurate and complete census of the frequency and properties of planets, and in particular low-mass terrestrial planets. Such a census provides a critical input for the design of direct imaging experiments.

Microlensing planet searches can be carried out from either the ground or space. Here we focus on the former, and leave the discussion of space-based surveys for a separate paper. We review the microlensing method and its properties, and then outline the potential of next generation ground-based microlensing surveys. Detailed models of such surveys have already been carried out, and the first steps in constructing the required network of 1-2m class telescopes with wide FOV instruments are being taken. However, these steps are primarily being taken by other countries, and if the US is to remain competitive, it must commit resources to microlensing surveys in the relatively near future.

2. The Properties of Microlensing Planet Searches

If a foreground star (“lens”) becomes closely aligned with a more distant star (“source”), it bends the source light into two images. The resulting magnification is a monotonic function of the projected separation. For Galactic stars, the image sizes and separations are of order μas and mas respectively, so they are generally not resolved. Rather “microlensing events” are recognized from their time-variable magnification (Paczyński 1986), which typically occurs on timescales $t_E$ of months, although it ranges from days to years in extreme cases. Presently about 600 microlensing events are discovered each year, almost all toward the Galactic bulge.

If one of these images passes close to a planetary companion of the lens star, it further

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perturbs the image and so changes the magnification. Because the range of gravitational action scales \( \propto \sqrt{M} \), where \( M \) is the mass of the lens, the planetary perturbation typically lasts \( t_p \sim t_E \sqrt{m_p/M} \), where \( m_p \) is the planet mass. That is, \( t_p \sim 1 \) day for Jupiters and \( t_p \sim 1.5 \) hours for Earths. Hence, planets are discovered by intensive, round-the-clock photometric monitoring of ongoing microlensing events (Mao & Paczynski 1991; Gould & Loeb 1992).

2.1 Sensitivity of Microlensing

While, in principle, microlensing can detect planets of any mass and separation, orbiting stars of any mass and distance from the Sun, the characteristics of microlensing favor some regimes of parameter space.

• **Sensitivity to Low-mass Planets:** Compared to other techniques, microlensing is more sensitive to low-mass planets. This is because the amplitude of the perturbation does not decline as the planet mass declines, at least until mass goes below that of Mars (Bennett & Rhie 1996). The duration does decline as \( \sqrt{m_p} \) (so higher cadence is required for small planets) and the probability of a perturbation also declines as \( \sqrt{m_p} \) (so more stars must be monitored), but if a signal is detected, its magnitude is typically large (\( \gtrsim 10\% \)), and so easily characterized and unambiguous.

• **Sensitivity to Planets Beyond the Snowline:** Because microlensing works by perturbing images, it is most sensitive to planets that lie at projected distances where the images are the largest. This so-called “lensing zone” lies within a factor of 1.6 of the Einstein ring, \( r_E = \sqrt{(4GM/c^2)D_s x(1-x)} \), where \( x = D_l/D_s \) and \( D_l \) and \( D_s \) are the distances to the lens and source. At the Einstein ring, the equilibrium temperature is

\[
T_E = T_\oplus \left( \frac{L}{L_\odot} \right)^{1/4} \left( \frac{r_E}{\text{AU}} \right)^{-1/2} \rightarrow 70 \text{ K} \frac{M}{0.5 M_\odot} [4x(1-x)]^{1/4}
\]

where we have adopted a simple model for lens luminosity \( L \propto M^5 \), and assumed \( D_s = 8 \) kpc. Hence, microlensing is primarily sensitive to planets in temperature zones similar to Jupiter/Saturn/Neptune.

• **Sensitivity to Free Floating Planets:** Because the microlensing effect arises directly from the planet mass, the existence of a host star is not required for detection. Thus, microlensing maintains significant sensitivity at arbitrarily large separations, and in particular is the only method that is sensitive to old, free-floating planets. See § 4.

• **Sensitivity to Planets from 1 kpc to M31:** Microlensing searches require dense star fields and so are best carried out against the Galactic bulge, which is 8 kpc away. Given that the Einstein radius peaks at \( x = 1/2 \), it is most sensitive to planets that are 4 kpc away, but maintains considerable sensitivity provided the lens is at least 1 kpc from both the observer and the source. Hence, microlensing is about equally sensitive to planets in the bulge and disk of the Milky Way. However, specialized searches are also sensitive to closer planets and to planets in other galaxies, particularly M31. See § 5.

• **Sensitivity to Planets Orbiting a Wide Range of Host Stars:** Microlensing is about equally sensitive to planets independent of host luminosity, i.e., planets of stars all along the main sequence, from G to M, as well as white dwarfs and brown dwarfs. By contrast, other
techniques are generally challenged to detect planets around low-luminosity hosts.

- **Sensitivity to Multiple Planet Systems:** In general, the probability of detecting two planets (even if they are present) is the square of the probability of finding one, which means it is usually very small. However, for high-magnification events, the planet-detection probability is close to unity \(^{\text{(Griest & Safizadeh 1998)}}\), and so its square is also near unity \(^{\text{(Gaudi et al. 1998)}}\). In certain rare cases, microlensing can also detect the moon of a planet \(^{\text{(Bennett & Rhie 2002)}}\).

### 2.2 Planet and Host Star Characterization

Microlensing fits routinely return the planet/star mass ratio \(q = \frac{m_p}{M}\) and the projected separation in units of the Einstein radius \(b = \frac{r_\perp}{r_E}\) \(^{\text{(Gaudi & Gould 1997)}}\). Historically, it was believed that, for the majority of microlensing discoveries, it would be difficult to obtain additional information about the planet or the host star beyond measurements of \(q\) and \(b\). This is because of the well-known difficulty that the routinely-measured timescale \(t_E\) is a degenerate combination of \(M, D_l\), and the velocity of the lens. In this regime, individual constraints on these parameters must rely on a Bayesian analysis incorporating priors derived from a Galactic model \(^{\text{(e.g., Dong et al. 2006)}}\).

Experience with the actual detections has demonstrated that the original view was likely shortsighted, and that one can routinely expect improved constraints on the mass of the host and planet. In three of the four microlensing events yielding exoplanet detections, the effect of the angular size of the source was imprinted on the light curve, thus enabling a measurement of the angular size of the Einstein radius \(\theta_E = \frac{r_E}{D_l}\). This constrains the statistical estimate of \(M\) and \(D_l\) (and so \(m_p\) and \(r_\perp\)). In hindsight, one can expect this to be a generic outcome. Furthermore, it is now clear that for a substantial fraction of events, the lens light can be detected during and after the event, allowing photometric mass and distance estimates, and so reasonable estimates of \(m_p\) and \(r_\perp\) \(^{\text{(Bennett et al. 2007)}}\). By waiting sufficiently long (usually 2 to 20 years) one could use space telescopes or adaptive optics to see the lens separating from the source, even if the lens is faint. Such an analysis has already been used to constrain the mass of the host star of the first microlensing planet discovery \(^{\text{(Bennett et al. 2006)}}\), and similar constraints for several of the remaining discoveries are forthcoming. Finally, in special cases it may also be possible to obtain information about the three-dimensional orbits of the discovered planets.

### 3. Present-Day Microlensing Searches

Microlensing searches today still basically carry out the approach advocated by \(^{\text{Gould & Loeb 1992)}}\): Two international networks of astronomers intensively follow up ongoing microlensing events that are discovered by two other groups that search for events. The one major modification is that, following the suggestion of \(^{\text{Griest & Safizadeh 1998)}}\), they try to focus on the highest magnification events, which are the most sensitive to planets. Monitoring is done with 1m (and smaller) class telescopes. Indeed, because the most sensitive events are highly magnified, amateurs, with telescopes as small as 0.25m, play a major role.
To date, four secure planets have been detected, all with equilibrium temperatures $40 \text{K} < T < 70 \text{K}$. Two are Jupiter class planets and so are similar to the planets found by RV at these temperatures \citep{bond_04, udalski_05}. However, two are Neptune mass planets, which are an order of magnitude lighter than planets detected by RV at these temperatures \citep{beaulieu_06, gould_06}. See Figure 1. This emphasizes the main advantages that microlensing has over other methods in this parameter range. The main disadvantage is simply that relatively few planets have been detected despite a huge amount of work.

4. NextGen Microlensing Searches

Next-generation microlensing experiments will operate on completely different principles from those at present, which survey large sections of the Galactic bulge one–few times per night and then intensively monitor a handful of the events that are identified. Instead, wide-field ($\sim 4 \text{deg}^2$) cameras on 2m telescopes on 3–4 continents will monitor large ($\sim 10 \text{deg}^2$) areas of the bulge once every 10 minutes around-the-clock. The higher cadence will find 6000 events per year instead of 600. More important: all 6000 events will automatically be monitored for planetary perturbations by the search survey itself, as opposed to roughly 50 events monitored per year as at present. These two changes will yield a roughly 100-fold increase in the number of events probed and so in the number of planetary detections.

Two groups (led respectively by Scott Gaudi and Dave Bennett) have carried out detailed
Fig. 2.— Expectations from a NextGen ground-based microlensing survey. These results represent the average of two independent simulations which include very different input assumptions but differ in their predictions by only $\sim 0.3$ dex. (Left) Number of planets detected per year assuming every main-sequence (MS) star has a planet of a given mass and semi-major axis (see §4). (Right) Same as left panel, but assuming every MS has two planets distributed uniformly in $\log(a)$ between 0.4-20 AU. The arrows indicate the masses of the four microlensing exoplanet detections.

Simulations of such a survey, taking account of variable seeing and weather conditions as well as photometry systematics, and including a Galactic model that matches all known constraints. While these two independent simulations differ in detail, they come to similar conclusions. Figure 1 shows the number of planets detected assuming all main-sequence stars have a planet of a given mass and given semi-major axis. While, of course, all stars do not have planets at all these different masses, Gould et al. (2006) have shown that the two “cold Neptunes” detected by microlensing imply that roughly a third of stars have such planets in the “lensing zone”, i.e. the region most sensitive for microlensing searches.

Microlensing sensitivity does decline at separations that are larger than the Einstein radius, but then levels to a plateau, which remains constant even into the regime of free-floating planets. In this case, the timescales are similar to those of bound-planet perturbations (1 day for Jupiters, 1.5 hours for Earths) but there is no “primary event”. Again, typical amplitudes are factor of a few, which makes them easily recognizable. If every star ejected $f$ planets of mass $m_p$, the event rate would be $\Gamma = 2 \times 10^{-5} f \sqrt{m_p/M_j} \text{yr}^{-1}$ per monitored star. Since NextGen experiments will monitor 10s of millions of stars for integrated times of well over a year, this population will easily be detected unless $f$ is very small. Microlensing is the only known way of detecting (old) free-floating planets, which may be a generic outcome of
planet formation (Goldreich et al. 2004; Juric & Tremaine 2007; Ford & Rasio 2007).

### 4.1 Transition to Next Generation

Although NextGen microlensing experiments will work on completely different principles, the transition is actually taking place step by step. The Japanese/New Zealand group MOA already has a 2 deg$^2$ camera in place on their 1.8m NZ telescope and monitors about 4 deg$^2$ every 10 minutes, while covering a much wider area every hour. The OGLE team has funds from the Polish government to replace their current 0.4 deg$^2$ camera on their 1.3m telescope in Chile with a 1.7 deg$^2$ camera. When finished, they will also densely monitor several square degrees while monitoring a much larger area once per night. Astronomers in Korea and Germany have each made comprehensive proposals to their governments to build a major new telescope/camera in southern Africa, which would enable virtually round-the-clock monitoring of several square degrees. Chinese astronomers are considering a similar initiative. In the meantime, intensive followup of the currently surveyed fields is continuing.

### 5. Other Microlensing Planet Searches

While microlensing searches are most efficiently carried out toward the Galactic bulge, there are two other frontiers that microlensing can broach over the next decade or so.

- **Extragalactic Planets**: Microlensing searches of M31 are not presently sensitive to planets, but could be with relatively minor modifications. M31’s greater distance implies that only more luminous (hence physically larger) sources can give rise to detectable microlensing events. To generate substantial magnification, the planetary Einstein ring must be larger than the source, which generally implies that Jupiters are detectable, but Neptunes (or Earths) are not (Covone et al. 2000; Baltz & Gondolo 2001). Nevertheless, it is astonishing that extragalactic planets are detectable at all. To probe for M31 planets, M31 microlensing events must be detected in real time, and then must trigger intensive followup observations of the type currently carried out toward the Galactic bulge, but with larger telescopes (Chung et al. 2006). This capability is well within reach.

- **Nearby microlensing events**: In his seminal paper on microlensing, Einstein (1936) famously dismissed the possibility that it would ever be observed because the event rate for the bright stars visible in his day was too small. Nevertheless, a Japanese amateur recently discovered such a “domestic microlensing event” (DME) of a bright ($V \sim 11.4$), nearby ($\sim 1$ kpc) star, which was then intensively monitored by other amateurs (organized by Columbia professor Joe Patterson). While intensive observations began too late to detect planets, Gaudi et al. (2007) showed that more timely observations would have been sensitive to an Earth-mass planet orbiting the lens. In contrast to more distant lenses, DME lenses would usually be subject to followup observations, including RV. This would open a new domain in microlensing planet searches. Virtually all such DMEs could be found with two “fly’s eye” telescopes, one in each hemisphere, which would combine 120 10 cm cameras on a single mount to simultaneously monitor the $\pi$ steradians above airmass 2 to $V = 15$. A fly’s eye telescope would have many other applications including an all-sky search for transiting
planets and a 3-day warning system for Tunguska-type impactors. Each would cost \(\sim\$4M\).

6. Conclusion and Outlook

In our own solar system, the equilibrium-temperature range probed by microlensing (out past the “snow line”) is inhabited by four planets, two gas giants and two ice giants. All have similar-sized ice-rock cores and differ primarily in the amount of gas they have accreted. Systematic study of this region around other stars would test predictive models of planet formation (e.g. [Ida & Lin 2004]) by determining whether smaller cores (incapable of accreting gas) also form. Such a survey would give clues as to why cores that reach critical gas-grabbing size do or do not actually manage to accrete gas, and if so, how much. In the inner parts of this region, RV probes the gas giants but not the ice giants nor, of course, terrestrial planets. RV cannot make reliable measurements in the outer part of this region at all because the periods are too long. Future astrometry missions (such as SIM) could probe the inner regions down to terrestrial masses, but are also limited by their limited lifetime in the outer regions. Hence, microlensing is uniquely suited to a comprehensive study of this region.

Although microlensing searches have so far detected only a handful of planets, these have already changed our understanding of planet formation “beyond the snowline”. Next generation microlensing surveys, which would be sensitive to dozens of “cold Earths” in this region, are well advanced in design conception and are starting initial practical implementation. These surveys play an additional crucial role as proving grounds for a space-based microlensing survey, the results of which are likely to completely revolutionize our understanding of planets over a very broad range of masses, separations, and host star masses (see the Bennett et al. ExoPTF white paper).

Traditionally, US astronomers have played a major role in microlensing planet searches. For example, Bohdan Paczyński at Princeton essentially founded the entire field ([Paczyński 1986]) and co-started OGLE. Half a dozen US theorists have all contributed key ideas and led the analysis of planetary events. The Ohio State and Notre Dame groups have played key roles in inaugurating and sustaining the follow-up teams that made 3 of the 4 microlensing planet detections possible.

Nevertheless, it must be frankly stated that the field is increasingly dominated by other countries, often with GDPs that are 5–10% of the US GDP, for the simple reason that they are outspending the US by a substantial margin. There are simply no programs that would provide the $5–$10M required to be in the NextGen microlensing game. If US astronomers still are in this game at all, it is because of the strong intellectual heritage that we bring, augmented by the practical observing programs that we initiated when the entire subject was being run on a shoestring. These historical advantages will quickly disappear as the next generation of students is trained on NextGen experiments, somewhere else.
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