REVIEW

Studying planet populations with Einstein’s blip

BY MARTIN DOMINIK*

School of Physics & Astronomy, SUPA, University of St Andrews, North Haugh, St Andrews KY16 9SS, UK

Although Einstein originally judged that ‘there is no great chance of observing this phenomenon’, the ‘most curious effect’ of the bending of starlight by the gravity of intervening foreground stars—now commonly referred to as ‘gravitational microlensing’—has become one of the successfully applied techniques to detect planets orbiting stars other than the Sun, while being quite unlike any other. With more than 400 extra-solar planets known altogether, the discovery of a true sibling of our home planet seems to have become simply a question of time. However, in order to properly understand the origin of Earth, carrying all its various life forms, models of planet formation and orbital evolution need to be brought into agreement with the statistics of the full variety of planets like Earth and unlike Earth. Given the complementarity of the currently applied planet detection techniques, a comprehensive picture will only arise from a combination of their respective findings. Gravitational microlensing favours a range of orbital separations that covers planets whose orbital periods are too long to allow detection by other indirect techniques, but which are still too close to their host star to be detected by means of their emitted or reflected light. Rather than being limited to the Solar neighbourhood, a unique opportunity is provided for inferring a census of planets orbiting stars belonging to two distinct populations within the Milky Way, with a sensitivity not only reaching down to Earth mass, but even below, with ground-based observations. The capabilities of gravitational microlensing extend even to obtaining evidence of a planet orbiting a star in another galaxy.

Keywords: general relativity; gravitational lensing; extra-solar planets; extra-terrestrial life

1. The gravitational bending of light

(a) Testing Einstein’s prediction(s)

Based on a calculation that focused on fundamental principles rather than strict mathematical rigour, Einstein (1911) concluded that gravity should cause light to bend around massive bodies. Even more importantly, he found that the deflection of light by the Sun should be observable, and explicitly encouraged astronomers

*md35@st-andrews.ac.uk

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to try to measure it. Around 1919, Einstein remarked that ‘the first among fellow-scientists who has taken the pains to put the theory to the test’ was Erwin (Finlay-)Freundlich\(^1\) (e.g. *The Times*, 8 August 1964). The measurement of stellar positions near the Solar limb requires light from the Sun to be blocked out, so he embarked on a Solar eclipse expedition to the Crimea in 1914. His efforts, however, were impaired by both the outbreak of the First World War and bad weather. The failure of several further attempts gave Einstein the opportunity to revise his prediction of the deflection angle with the application of the fully developed Theory of General Relativity to twice the value found earlier (Einstein 1915), before a measurement had been made. With the Hyades cluster, the densest population of bright stars in the ecliptic plane, being behind the Sun, the eclipse of 29 May 1919 (e.g. Ellis *et al.* 2009) could hardly have been more fortuitous. The observations resulting from the British expeditions to Sobral (Brazil) and the Island of Principe (Dyson *et al.* 1920) marked a breakthrough for Einstein’s theory of curved space–time, which had previously been met with a lot of scepticism.

For impact parameters \(\xi\) of the light ray much larger than Schwarzschild’s gravitational radius for a body of mass \(M\)

\[
R_S = \frac{2GM}{c^2},
\]

where \(G\) denotes the universal gravitational constant and \(c\) the vacuum speed of light, the full equations of General Relativity (Einstein 1915) yield a deflection angle

\[
\alpha = \frac{2R_S}{\xi},
\]

independent of wavelength.\(^2\) With \(R_S \sim 3\) km for the Sun, \(\xi \gg R_S\) appears to be an almost perfect approximation even for light rays grazing near the surface of a star, whereas relativistic effects of higher order only need to be considered for stellar remnants in the form of neutron stars and black holes (but not for white dwarfs).\(^3\)

\((b)\) The gravitational ‘lens’

With the deflection angle increasing with the proximity of the light ray to the deflecting massive body, one encounters just the opposite behaviour as for deflection by a lens, where the deflection vanishes for a light ray passing through the centre and increases outwards. Coincidently, the gravitational bending of light is similar to light passing through the foot of a wine glass (e.g. Liebes 1969; Refsdal & Surdej 1994). Despite Lodge (1919) having already pointed out that ‘it is not permissible to say that the solar gravitational field acts like a lens, for it has no focal length’, the (inappropriate) term ‘gravitational lens’ has survived.

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\(^1\)Later John Napier, Professor of Astronomy at the University of St Andrews (1951–1959).

\(^2\)Consequently, ‘light’ means any form of electromagnetic radiation in this context.

\(^3\)Aspects of the gravitational bending of light beyond the weak-field approximation have been discussed by, for example, Virbhadra & Ellis (2000) and Saca & Peralta (2002).
For an observed star at distance $D_S$ and a deflector of mass $M$ at distance $D_L$, the ‘angular Einstein radius’

$$\theta_E = \sqrt{2 R_S \frac{\pi_{LS}}{1 \text{AU}}} = \sqrt{\frac{4GM}{c^2}(D_L^{-1} - D_S^{-1})}, \quad (1.3)$$

where $\pi_{LS} = 1 \text{AU}(D_L^{-1} - D_S^{-1})$ is the relative parallax between the lens and the source star, provides the unique characteristic scale of gravitational lensing by point-like objects. Just from elementary geometry, and the deflection angles approximated as being small, one finds the source star being mapped to a circle with angular radius $\theta_E$ on the sky, if it happens to lie exactly behind the gravitational lens as seen from the observer. Otherwise, for a finite separation $\eta$ of the source star from the lens–observer axis, one observes two distorted images (see figure 1).

If one measures angular separations from the observer–lens axis in units of $\theta_E$ by means of dimensionless coordinates $u = \eta/(D_S\theta_E)$ and $x = \xi/(D_L\theta_E)$ for the source and image positions, respectively, one finds the simple relation

$$u = x - \frac{1}{x} \iff x_\pm = \frac{1}{2}(u \pm \sqrt{u^2 + 4}) \quad (1.4)$$

with the image positions $x_\pm$ as the two solutions of a quadratic equation.\(^4\) For stellar lenses and galactic distances, the images themselves cannot be resolved with today’s telescopes ($\theta_E \sim 1 \text{mas}$),\(^5\) leaving us with a brightening as observable signature, resulting from the combined magnification of both images

$$A(u) = \sum_\pm \left| \frac{x_\pm}{u} \frac{dx_\pm}{du} \right| = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}, \quad (1.5)$$

as found by Einstein (1936), which for $u \ll 1$ can be approximated as $A(u) \simeq u^{-1}$, whereas $A(u) \simeq 1 + 2u^{-4}$ for $u \gg 1$. For an observer separated by $\chi$ from the lens–source axis, one finds $u = [(D_L^{-1} - D_S^{-1})\chi]/\theta_E$, while $\theta_E \propto D_L^{-1/2}$ for $D_S \gg D_L$, so that $u \propto \chi D_L^{1/2}$ and $A \propto \chi^{-1}\sqrt{D_L}$. Einstein referred to the ‘lens-like action of a star by the deviation of light in the gravitational field’ as a ‘most curious effect’, given that, for a fixed separation of the observer from the lens–source axis, the magnification not only does not decrease with distance, but even increases. In fact, he had already derived these results in 1912—as his notebook shows (Renn et al. 1997)—but was not convinced by the feasibility of respective observations, concluding that ‘there is no great chance of observing this phenomenon’. Zwicky (1937), however, pointed out that whole galaxies rather than stars would be better suited to provide a detection. About 30 years later,Refsdal (1964) concluded that ‘due to progress in experimental technique we find, contrary to Einstein, that the effect may be of practical interest’, and his subsequent work together with the independent work by Liebes (1964) mentions almost all the various configurations of lens and source objects and the related astrophysical applications that have

\(^4\)For $u = 1$, this is the quadratic equation that yields the golden ratio (and its conjugate) $x_\pm = (1 \pm \sqrt{5})/2$. Unfortunately, this is not mentioned in the delightful book by Livio (2002).

\(^5\)But will be with tomorrow’s interferometers.

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Figure 1. The gravitational bending of light received from an observed star (S) at distance $D_S$ from the observer (O) by an angle $\alpha$ due to an intervening foreground star (L) at distance $D_L$, where the light path has been approximated by two straight lines. The arising two distorted images, corresponding to light rays passing the foreground ‘lens’ star at $\xi_+$ or $\xi_-$, respectively, are denoted by $I_+$ or $I_-$. While $L_-$ is located inside the Einstein circle of radius $\theta_E$ around the lens star, $I_+$ is outside. If the separation $\eta$ between the source star and the observer–lens axis vanishes, the source star is mapped onto the Einstein circle.

been studied up to now. It finally was the bending of radio emission of a quasar (0957+561) by means of the gravity of a galaxy that showed the first observed gravitational lens system (Walsh et al. 1979).

(c) Gravitational microlensing events

Einstein’s original idea of a brightening of distant stars due to bending of light caused by the gravity of intervening foreground stars was picked up with the suggestion of using this phenomenon, now commonly referred to as ‘gravitational microlensing’,6 for studying a possible population of dark compact objects in the Milky Way halo (Petrou 1981; Paczyński 1986). Experimental efforts started in 1990, and led to the first reported observation of a ‘microlensing event’ by the MACHO (MAssive Compact Halo Object) team (Alcock et al. 1993) more than 80 years after the first (known) discussion of this effect.

If we consider the observed source star to move on the sky with a proper motion $\mu$ relative to the foreground ‘lens’ star, one can define a characteristic event time scale $t_E = \theta_E/\mu$, and the dimensionless angular separation normalized to the angular Einstein radius $\theta_E$ reads

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

(1.6)

6Chang & Refsdal (1979) realized that stars near the light path further split macro-images of an observed quasar that arises from the gravitational bending of light by a foreground galaxy into micro-images, which due to their separation of a few $\mu$as are not resolved, but leave only a flux variation as observable effect. Each of the four characteristics, namely (i) gravitational bending of light by stars, (ii) further splitting of macro-images into micro-images, (iii) image separations of a few $\mu$as, and (iv) observed flux variation as a result of unresolved images, has been used as the defining criterion of ‘gravitational microlensing’.

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Figure 2. Schematic view of the sensitivity of the successfully applied techniques for detecting planets orbiting stars other than the Sun as a function of planet mass and temperature. The formation of habitable planets like Earth can be understood only if models of planet formation and orbital migration can be made to match the distribution of planets in a wider range, indicated by the red circle, around the habitable zone. Obtaining such requires complementary evidence from several techniques.

where the closest angular approach $u_0$ is realized at epoch $t_0$. For a source star with flux $F_S$ blended with a background flux $F_B$ on the detector, one finds a total observed flux

$$F(t; t_E, u_0, t_0; F_S, F_B) = F_S A[u(t; t_E, u_0, t_0)] + F_B,$$

(1.7)

where $A(u)$ is given by equation (1.5). The magnification becomes a characteristic curve $A[u(t; t_E, u_0, t_0)]$ (Refsdal 1964; Paczyński 1986), described by three parameters, out of which only the event time scale $t_E$ is related to properties of the lens or source star, while it convolutes the lens mass, and the source–lens relative parallax and proper motion. Observed light curves $F(t; t_E, u_0, t_0; F_S, F_B)$ are symmetric with respect to a peak at $t_0$, and smaller $u_0$ correspond to larger peak magnifications.\(^7\)

2. Planets

Despite the fact that mankind probably ever since the beginning of its existence has wondered about possible ‘other worlds’, it is only since the 1990s that the planets in the Solar system have been known to have extra-solar relatives (Wolszczan & Frail 1992; Mayor & Queloz 1995).

Since stars outshine their planets, a direct detection of emitted or reflected light from planets is currently only feasible for large orbital separations and the biggest planets (e.g. Chauvin et al. 2004; Marois et al. 2008). The orbital

\(^7\)More about gravitational microlensing can be found, for example, in the review by Paczyński (1996).
motion of planets around their parent star, however, allows their presence to be revealed by several indirect signatures. The first detection of an extra-solar planet (Wolszczan & Frail 1992) resulted from a perturbation to the regularity of the timing of the regularly received packets of electromagnetic radiation originating from pulsars, a special class of stellar remnants (Hewish et al. 1968). It was a real surprise to find that planets can reside in such an environment, and this is still puzzling.

A mere 3 years later, the observable periodic shift of the wavelength of lines in the spectrum of stars due to the Doppler effect, caused by the stellar velocity due to the gravitational pull of the orbiting planet, provided the first discovery of a planet orbiting a star other than the Sun (Mayor & Queloz 1995). But, again, one did not find the expected: this planet, 51 Pegasi b, is roughly half as massive as Jupiter, while it orbits closer to its host star than Mercury comes to the Sun. The properties of more than 400 extra-solar planets known so far¹ reveal a huge variety, far in excess of what we see in the Solar system, and show that there are planetary systems quite different from ours.

The only currently exploited indirect signal characteristic for the presence of a planet that depends on the planet radius rather than the planet mass arises when the planet passes in front of its parent star, and by blocking out part of the starlight creates a periodic dimming. This phenomenon is well known in the Solar system,⁹ but not before 1999 was it observed for another star (Charbonneau et al. 2000). Such planetary transits come with an even larger preference for planets in close orbits than detections by means of stellar Doppler wobbles.

As illustrated in figure 2, gravitational microlensing fills a gap in probing planet parameter space by being sensitive to orbits too large to allow detection by other indirect techniques, but not large enough to detect emitted or reflected light from the planet. In particular, microlensing can reveal signals of planets whose periods would otherwise exceed the life-time of monitoring campaigns or their investigators.

Similar to the Sun being an ordinary star, there is no distinct class of ‘exoplanets’ around other stars, but instead there is a generic population of ‘planets’, of which those in the Solar system are representatives. The paradigm that the development and presence of life requires liquid water on the planet’s surface defines a ‘habitable zone’ around its host star (e.g. Hart 1979; Kasting et al. 1993), demanding that the planet can be neither too hot nor too cold. Finding another planet just like Earth that is home to life would already lead to a fundamental change in how we assess our role within the Universe. The formation and evolution of planets is, however, full of interdependencies and interactions between the many bodies within a planetary system, and a clue about our origins requires us to probe models on a census that covers the full variety of planets: those like our own, and those quite unlike our own.

¹With the current planet detection rate, this number is likely to be already out of date when this article is published. For an up-to-date list, the reader is referred to ‘The Extrasolar Planets Encyclopaedia’. See http://www.exoplanet.eu.

⁹Notably, Venus transited across the Sun on 8 June 2004, and will do so again on 6 June 2012; after which, one will have to wait for a bit more than another 100 years to see such an event.
3. Studying planet populations by gravitational microlensing

(a) A three-step observing strategy

In order to have a reasonable chance of detecting gravitational microlensing events, one would aim for observing regions of the sky with a large number of resolved stars, while also ensuring that many foreground stars intervene close to the line of sight. The Galactic bulge appears to be a good compromise between a dense stellar field and the crowding level, while both bulge and disc stars provide a known population of foreground stars giving rise to microlensing events.

With only one in a million observed Galactic bulge stars being magnified by more than 30 per cent at any given time (Paczyński 1991; Kiraga & Paczyński 1994), current microlensing surveys as carried out by OGLE (Optical Gravitational Lensing Experiment; http://ogle.astrouw.edu.pl) or MOA (Microlensing Observations in Astrophysics; http://www.phys.canterbury.ac.nz/moa), which monitor $\gtrsim 2 \times 10^8$ stars, detect about 700 events per annual season\(^{10}\) in real time, i.e. while they are ongoing. Given the larger number of stars near the lower end of the main sequence, it is mainly M- and K-dwarf stars that constitute the gravitational lenses, with a typical mass $M \sim 0.3 M_\odot$. A source distance $D_S \sim 8.5$ kpc and lens distance $D_L \sim 6.5$ kpc, roughly corresponding to the far and the near end of the Galactic bulge, respectively, and a proper motion $\mu \sim 15 \mu\text{as d}^{-1}$ yield a ‘typical’ event time scale $t_E \sim 20$ days, i.e. about a month.

Planetary rather than stellar masses lead to a smaller angular Einstein radius $\theta_E$, so that respective microlensing events would not only be of shorter duration, but also occur with a smaller probability. Consequently, Liebes (1964) concluded that ‘the primary effect of planetary deflectors bound to stars other than the sun will be to slightly perturb the lens action of these stars’, rather than planets being revealed from short time-scale events where these act as primary deflectors. In fact, Mao & Paczyński (1991) found that the detection of planets in microlensing events is aided by the gravitational action of their host stars, leading to a ‘resonance’ if the angle on the sky between star and planet coincides with the angular Einstein radius $\theta_E \sim 300 \mu$as, which corresponds to a projected current planet–star separation $r_E = D_L \theta_E \sim 2$ AU.

Consequently, these considerations led to the implementation of a three-step observing strategy of survey, follow-up and anomaly monitoring (Gould & Loeb 1992; Elachi et al. 1996; Dominik et al. 2002, 2007). While survey telescopes monitor hundreds of millions of stars in the Galactic bulge for stellar microlensing events at least once a night, the most promising microlensing events are being monitored densely (approx. hourly) by networks of follow-up telescopes in order to detect microlensing ‘anomalies’, i.e. deviations from an ‘ordinary’ light curve, compatible with lensing by an isolated source star. Once such an anomaly is flagged up or suspected, high-cadence or quasi-continuous observations on the respective target are carried out with the survey and follow-up telescopes, as well as with other instruments that join in on a target-of-opportunity basis.

\(^{10}\)Roughly from March to October, according to the visibility of the Galactic bulge from Chile or New Zealand, respectively.
Figure 3. Model light curve of microlensing event OGLE-2005-BLG-390 (the 390th event detected by the OGLE survey in 2005 towards the Galactic bulge), together with data acquired with six different telescopes (colour-coded), which shows a 15–20% deviation lasting about a day, caused by a 5 Earth-mass planet (Beaulieu et al. 2006). Had an Earth-mass planet been in the same spot, it would have led to a 3% deviation over 12 h, indicated by the other curve shown (orange, La Silla Danish; blue, Perth; black, OGLE; brown, MOA; cyan, Faulkes North; magenta, Tasmania).

(b) Planetary signals and detecting them

If a planet were an isolated object of mass $M_p$, the time scale of the planetary deviation (see figure 3) would be

$$t_p = \left(\frac{M_p}{M}\right)^{1/2} t_E,$$

which evaluates to about a day for a Jupiter-mass planet and about 1.5 h to one of Earth mass. However, owing to the tidal field of the planet’s host star at the position of the planet (cf. Chang & Refsdal 1979), the planetary signal is lengthened by a fair factor and the planet’s detectability is increased. As long as the source star can be considered point-like, the signal amplitude can exceed any threshold regardless of the mass of the planet; it is just the signal duration and the probability for it to occur that decrease towards smaller masses (namely with $\sqrt{M_p}$, which is a remarkably weak dependence). For a star of radius $R_\star$, however, the signal duration cannot fall below

$$2t_\star = \frac{2R_\star}{D_S\mu} \sim 2 \text{ h} \left(\frac{R_\star}{R_\odot}\right).$$

The finite source size reduces the amplitude of the planetary deviation, but it also spreads it over a longer duration. The longer duration actually increases the detectability as long as the signal amplitude exceeds the detection threshold, but planets become undetectable if the size of the source star imposes a too strict maximal signal amplitude. While the detection of Earth-mass planets is
Figure 4. Planet detection efficiency as a function of planet mass and orbital radius (a circular orbit assumed) for a simulated three-step microlensing planet search composed of survey (with sampling interval $\Delta t = 1 \, \text{d}$), follow-up ($\Delta t = (90 \, \text{min}) A^{-1/2}$), and anomaly monitoring ($\Delta t = 5 \, \text{min}$). The contours shown refer to a ‘typical’ microlensing event with $u_0 = 0.3$ (i.e. peak magnification $A_0 \sim 3.5$), angular Einstein radius $\theta_E = 274 \, \mu\text{as}$ and proper motion $\mu = 13.7 \, \mu\text{as} \, \text{d}^{-1}$, so that the event time scale is $t_E \equiv \theta_E/\mu = 20 \, \text{days}$. The adopted $t_s \equiv \theta_s/\mu = 0.04 \, \text{d} \sim 1 \, \text{h}$ corresponds to a main-sequence star with radius $R_* = D_S \theta_s \sim 1 \, R_\odot$ in the Galactic bulge at a distance $D_S \sim 8.5 \, \text{kpc}$. While follow-up observations were considered to start at magnification $A = 1.5$ and stop at $A = 1.06$, anomaly monitoring mode was activated on the suspicion of an ongoing anomaly, defined by a datum point deviating from an ordinary model light curve by more than twice its photometric uncertainty. Also by definition, a planet ‘detection’ required at least five data points within a contiguous sequence on the same side of the model prediction to show such a discrepancy. The photometric uncertainty was chosen as 3% for the unmagnified target and decreasing according to photon statistics, with a systematic uncertainty of 0.5% added in quadrature. The horizontal blue lines indicate the masses of the planets in the Solar system.

substantially affected by the finite size of even main-sequence stars ($R \sim 1 \, R_\odot$), a hard limit is only reached for companions to the lens star with a mass comparable to that of the Moon (e.g. Paczyński 1996), and such detections do not even require space-based observations.

If a planet is located at given angular separation $\theta_p$ from its host star, it may or may not provide a detectable deviation to the observed light curve, depending on whether the planet happens to be in the vicinity of one of the two images resulting from the deflection of light by its host star, which depends on the orientation angle $\psi$ of the trajectory of the source star with respect to the line connecting the lens star with its planet. The planet detection efficiency $\varepsilon$ becomes

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a natural function of the separation parameter \( d \equiv \theta_p/\theta_E \) and the planet-to-star mass ratio \( q \equiv M_p/M \), which together with \( \psi \) make three additional parameters for describing a microlensing light curve resulting from a binary lens system compared with a single isolated lens, while \( t_s \) constitutes a further parameter if the source size cannot be neglected. The planet mass \( M_p \) can only be inferred directly when one not only knows the angular source size \( \theta_* \) (e.g. from stellar typing) along with \( t_s \), but also determines the lens–source parallax \( \pi_{\mathrm{LS}} \) with further observations. Otherwise, one needs to recur to a probabilistic approach by means of an adopted model of the stellar populations of the Milky Way (Dominik 2006).

Not only does the lens star affect gravitational lensing by the planet, but the planet also breaks the symmetry in the lens action by its host star (e.g. Dominik 1999). Consequently, a distortion of the observed light curve near its peak arises, caused by the combined effect of all planets orbiting the lens star (Gaudi et al. 1998). This creates an additional potential for detecting planets if the source–lens separation \( u_0 \) becomes quite small, i.e. the related peak magnification \( A_0 \) becomes quite large (Griest & Safizadeh 1998; Rattenbury et al. 2002). Moreover, one can rather accurately predict when a potential planetary deviation is to occur. However, the number of events above a given threshold in \( A_0 \) is roughly inversely proportional to \( A_0 \), and the prospects for detecting planetary signals as well as their duration scale with \( M_p \) rather than \( \sqrt{M_p} \). The rarity of suitable events and the suppression of the signal amplitude due to the finite size of the source star make planet detection around peaks of high magnification increasingly unattractive the smaller the planet mass.

(c) Microlensing and planet population statistics

By studying gravitational microlensing events on observed stars in the Galactic bulge, one can infer the statistics of planets orbiting two distinct stellar populations, comprising the bulge and disc of the Milky Way. Constructing a catalogue of microlensing planets, however, is not an appropriate concept. Given that a planetary signature only shows once, ‘detections’ do not fulfil the scientific requirement of repeatability and the opportunity of independent confirmation or falsification (except for independent evidence if planetary deviations are monitored by several telescopes over their course). However, for determining properties of the planet populations, it is only statistical information that matters. Thereby, a ‘fuzzy logic’ approach involving an assessment of the probability associated with ranges of planet model parameters for each of the observed microlensing events appears more suitable than a ‘binary logic’ approach that can only distinguish between events pointing to a planet of given properties and events without a sign of a planet. In any case, the observed sample distribution is a statistical representation of the convolution of the underlying distribution function of the properties of the planets as realized in nature with the detection efficiency of the observing campaign. The detection efficiency can be meaningfully evaluated only if the monitoring strategy strictly follows well-defined criteria (allowing for simulation), and it therefore must not be based on ad hoc human judgement, which is essentially unpredictable and irreproducible.

If one optimizes microlensing planet searches for the number of revealed planets, one mainly probes cool planets around low-mass stars. In fact, as shown in figure 4, the planet detection efficiency peaks in a region between

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0.7 and 10 AU. Given that the luminosity of a main-sequence star of 0.3 $M_\odot$ is only about 1 per cent of that of the Sun, a planet similar to Jupiter (orbiting the Sun at 5.2 AU) with the same equilibrium temperature would reside at about 0.5 AU and take roughly eight months to complete its orbit. In the Solar system, massive gas giants like Jupiter and Saturn are found outside the so-called ‘ice boundary’ or ‘snow line’, where planet formation is boosted by the presence of icy clumps in addition to grains of dust, sand and pebbles (e.g. Ida & Lin 2004), so that microlensing is particularly well suited to study planets in this region. In fact, around a star half as massive as the Sun, a pair of planets with comparable masses and temperatures to Jupiter and Saturn, respectively, has already been found (Gaudi et al. 2008), making this system, to our knowledge, a half-scale ‘look-alike’ of the Solar system with regard to similarities in the probed properties of the detected gas-giant planets, whereas one in particular does not know anything about potential inner rocky planets. A small, but not negligible, 3 per cent of the Earth-mass planets that would be detected have been estimated to reside in the habitable zone around their host star (Park et al. 2006). One can, however, shift the detection efficiency of monitoring campaigns towards planets with specific properties at the cost of lowering it on average.

By not facing a restriction to the Solar neighbourhood, the technique of gravitational microlensing draws the stars that can be probed for the presence of planets from an unparalleled huge reservoir.

4. Innovation and outlook

Since the first microlensing survey by the EROS (Experience de la Recherche d’Objets Sombres) team in 1990 (Auborg et al. 1993), the two recent decades have seen substantial technological improvement, substantially building upon the continuing development of CCD detectors, new communication technologies by means of the World Wide Web, and ever-increasing computer performance. Similarly to Einstein in 1936, we are unable to predict which new core technologies will emerge.

The success of a microlensing planet search campaign, requiring prompt monitoring of short-lasting transient phenomena, critically depends on rapid communication and open real-time data access. Only with the establishment of the OGLE Early Warning System (Udalski et al. 1994), alerting the scientific community and providing daily data updates, and subsequently similar technology put into place by other survey teams, has a meaningful selection and prioritization of targets for follow-up become possible.

While a round-the-clock microlensing follow-up network relying on human observers and target selection, first realized by PLANET (Probing Lensing Anomalies Network; http://www.planet-legacy.org) in 2005 (Albrow et al. 1998), was well suited to break into the new domain of planets below 10 Earth masses (Beaulieu et al. 2006), automated systems are required for deriving planet population statistics.

The RoboNet team (http://robonet.lcogt.net; Burgdorf et al. 2007; Tsapras et al. 2009) pioneered the use of automated event prioritization algorithms (Horne et al. 2009) with robotic-telescope observations, and a pilot study

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within the MiNDSTEp (Microlensing Network for the Detection of Small Terrestrial Exoplanets; http://www.mindstep-science.org) campaign (Dominik et al. submitted) has recently demonstrated the readiness to detect signatures of Earth-mass planets with a fully deterministic monitoring strategy involving automated anomaly detection (Dominik et al. 2007), realized by means of the ARTEMiS (Automated Robotic Terrestrial Exoplanet Microlensing Search; http://www.artemis-uk.org) system (Dominik et al. 2008). With data being assessed and displayed on figures just minutes after the observations have been carried out, a phenomenon with no great chance to be observed has been turned into a public live event at the forefront of science. (http://www.artemis-uk.org/catch-a-planet.html)

New dedicated wide-field microlensing surveys will reduce the sampling interval to about 10–15 min, which enables the detection of low-mass planets already from survey data. Moreover, follow-up with lucky-imaging cameras, which overcome the image degradation due to the Earth’s atmosphere by taking a high-speed series of images and selecting the fortunate moments when the turbulent fluctuations are the smallest (Fried 1978; Tubbs et al. 2002), could provide images of unprecedented quality and push the detection limits substantially below Earth mass. Several pan-Galactic or all-sky surveys are upcoming or planned, which will monitor microlensing events regardless of whether this is desired or not. The increased survey capabilities might also make it possible to identify planetary mass objects directly by means of short microlensing events.

ESA’s Gaia mission (http://www.esa.int/science/gaia) will for the first time offer a large-scale opportunity for detecting microlensing events not by their photometric, but by their astrometric signature (e.g. Dominik & Sahu 2000; Belokurov & Evans 2002).

Advanced techniques for measuring brightness variations of unresolved stars offer the opportunity to detect planets in other galaxies, such as the Andromeda galaxy (Covone et al. 2000; Chung et al. 2006), and such a planetary signal might have already been seen (Ingrosso et al. 2009).

Image credit: respective parts of figure 2 (conception/arrangement by K. Horne and M. Dominik): ESO, NASA, ESA, A. Schaller (STScI), G. Bacon (STScI), Korean Astronomy and Space Science Institute (KASI), Chungbuk National University (CBNU), Astrophysical Research Center for the Structure and Evolution of the Cosmos (ARCSEC), C. Marois/National Research Council Canada. The author would like to thank Antje Kohnle for her helpful comments on the manuscript.

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Martin Dominik was born in 1969 in Hagen/Westphalia, Germany. In 1988, he began to study physics at Universität Dortmund, Germany, where he graduated with a Diploma in physics in 1993, and was promoted to Doctor of natural sciences (Dr. rer. nat.) in 1996. In January 1998, supported by the German Research Foundation (DFG), he moved to the Space Telescope Science Institute (STScI) in Baltimore, MD (USA), and continued his path as a Marie Curie Fellow at the Kapteyn Instituut of the Rijksuniversiteit Groningen, The Netherlands, in June of the same year. In January 2000, he suddenly fell ill, and re-emerged at the University of St Andrews in 2003, three years later. Since October 2006, he holds a Royal Society University Research Fellowship.

Martin was dragged from theoretical physics into astronomy with new developments in the emerging field of gravitational lensing, where his doctoral thesis ‘Galactic microlensing beyond the standard model’ served as an introduction for students and newcomers for more than a decade. Fascinated about the wide range of applications of this phenomenon, most recent efforts concentrated on the detection of extra-solar planets.

Martin is a strong advocate of communication being an essential part of science, and science being an integral part of society. He is politically engaged in creating and maintaining a proper environment to foster curiosity and innovation in scientific research. Since October 2009, he is both a German and British citizen.