Formation, Detection, and Characterization of Extrasolar Habitable Planets
Proceedings IAU Symposium No. 293, 2012
N. Haghighipour, ed.

doi:10.1017/S1743921313012453

Current and Future of Microlensing Exoplanet Search

Takahiro Sumi

Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan,
email: sumi@ess.sci.osaka-u.ac.jp

Abstract. Gravitational microlensing has a unique sensitivity to exoplanets at outside of the snow-line with masses down to the Earth-mass. Because of the rarity and short timescale of the planetary signal, the survey groups, MOA-II in New Zealand and OGLE-IV in Chile carry out the wide field survey observation towards the galactic bulge to issue alerts in real time. Then telescopes of the follow-up groups conduct high cadence follow-up observation to get dense sampling of the short planetary signal. Recent high cadence survey observations by MOA-II and OGLE-IV have started to find exoplanets without follow-up observation systematically. This is a transition to the next generation 24-hour high cadence survey network which can reveal the mass function of exoplanets down to Earth-mass outside of the snow-line. The Wide Field Infrared Survey Telescope (WFIRST) is the highest ranked recommendation for a large space mission in the recent New Worlds, New Horizons (NWNH) in Astronomy and Astrophysics 2010 Decadal Survey. Exoplanet microlensing program is one of the primary science of WFIRST. WFIRST will find about 2,000 bound planets and 1,000 unbound planets by the high precision continuous survey with 15 min. cadence. WFIRST can complete the statistical census of planetary systems in the Galaxy, from the outer habitable zone to gravitationally unbound planets – a discovery space inaccessible to other exoplanet detection techniques.

Keywords. planetary systems: formation, gravitational microlensing

1. Introduction

Since the first discovery of exoplanets orbiting main-sequence stars in 1995 (Mayor & Queloz 1995; Marcy *et al.* 2005), more than 450 exoplanets have been discovered via the radial velocity method (Mayor *et al.* 2004, 2009) and more than 300 have been detected via their transits (Udalski *et al.* 2004; Konacki *et al.* 2005). Several planetary candidates have also been detected via direct imaging (Marois *et al.* 2008; Lagrange *et al.* 2009) and astrometry (Pravdo & Shaklan 2009). Among the currently known extrasolar planets, 16 have been discovered by the gravitational microlensing method. Although the radial velocity and transit discoveries are more numerous, microlensing is uniquely sensitive to the cold planets down to Earth-mass.

In a gravitational microlensing event, a foreground lens object is detected as a result of the characteristic magnification of a background source star as it passes behind the gravitational field of the lens. The lens object is detected by means of its mass and not its luminosity. The magnification of a microlensing event is described by (Paczyński 1986)

$$A(u) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}, \tag{1.1}$$

where u is the projected separation of the source and lens in units of the Einstein radius R_{E} which is given by

$$R_{\rm E}(M,x) = \sqrt{\frac{4GM}{c^2} D_{\rm s} x(1-x)}. \tag{1.2}$$

In this equation, M is the lens mass, $x = D_{\rm l}/D_{\rm s}$ is the normalized lens distance and $D_{\rm l}$ and $D_{\rm s}$ are the observer-lens and the observer-source distances. An angler Einstein radius, $\theta_{\rm E} = R_{\rm E}/D_{\rm l}$, is more commonly used as one of the observable. The time variation of $u = u(t)$ is

$$u(t) = \sqrt{u_0^2 + \left(\frac{t-t_0}{t_{\rm E}}\right)^2}, \tag{1.3}$$

where u_0, t_0, $t_{\rm E} = R_{\rm E}/v_{\rm t}$ and $v_{\rm t}$ are, respectively, the minimum impact parameter in units of $R_{\rm E}$, the time of maximum magnification, the event timescale and the transverse velocity of the lens relative to the line of sight toward the source star. From light curve alone, one can determine the values of u_0, t_0 and $t_{\rm E}$, but not the values of M, x or $v_{\rm t}$.

Following the suggestion of Paczyński (1986), Paczyński (1991) and Griest *et al.* (1991) several teams have carried out microlensing surveys toward the Large and Small Magellanic Cloud (LMC, SMC) and Galactic Bulge (GB). Since the first microlensing event have been found by MACHO collaboration towards the LMC (Alcock *et al.* 1993), to date, well over eight thouthands microlensing events mostly in the GB have been detected by those groups: OGLE (Udalski *et al.* 1994, 2000; Woźniak *et al.* 2001; Udalski 2003), MOA (Bond *et al.* 2001; Sumi *et al.* 2003), MACHO (Alcock *et al.* 1997, 2000) and EROS (Afonso *et al.* 2003). Thousands of detections are expected in the upcoming years from MOA-II† and OGLE-IV‡.

Liebes (1964) and Mao & Paczyński (1991) first proposed exoplanet searches via gravitational microlensing. The planet orbiting around the lensing star cause microlensing one of the images lensed by the primary lens as shown in Figure 1. The planet's gravity induces small caustics, which can generate small deviations in standard single-lens microlensing light curves given by Eq. (1.1). In addition to the three single-lens model parameters, i.e., t_0, $t_{\rm E}$, and u_0, the standard binary lens model has four more parameters, the planet-host mass ratio q, projected separation s, the angle of the source trajectory relative to the binary lens axis α, and source radius relative to the Einstein radius $\rho = \theta_*/\theta_{\rm E}$, or the source radius crossing time $t_* = \rho t_{\rm E}$.

Compared to other techniques, microlensing is sensitive to smaller planets, down to an Earth mass (Bennett & Rhie 1996), and in wider orbits of 1-6 AU outside of snow line (Gaudi *et al.* 2010). Because microlensing observability does not depend on the light from the lens host star, it is sensitive to planets orbiting faint host stars like M-dwarfs and even brown dwarfs. Furthermore, it is sensitive to distant host stars at several kpc from the Sun, which allows the Galactic distribution of planetary systems to be studied.

In 2003, the gravitational microlensing method yielded its first definitive exoplanet discovery (Bond *et al.* 2004). So far 15 planetary systems with 16 planets have been found by this technique (Udalski *et al.* 2005; Beaulieu *et al.* 2006; Gould *et al.* 2006; Gaudi *et al.* 2008; Bennett *et al.* 2008; Dong *et al.* 2009b; Janczak *et al.* 2010; Bachelet *et al.* 2012; Bennett *et al.* 2012), which have very distinct properties from those detected by other techniques. Beaulieu *et al.* (2006) found a ~ 5.5 Earth-mass planet, which was the lowest-mass planet detected at that time. This detection and the discovery of a slightly more massive planet by Gould *et al.* (2006) demonstrated that microlensing is well suited

† `https://it019909.massey.ac.nz/moa/`
‡ `http://www.astrouw.edu.pl/~ogle/ogle4/ews/ews.html`

https://doi.org/10.1017/S1743921313012453 Published online by Cambridge University Press

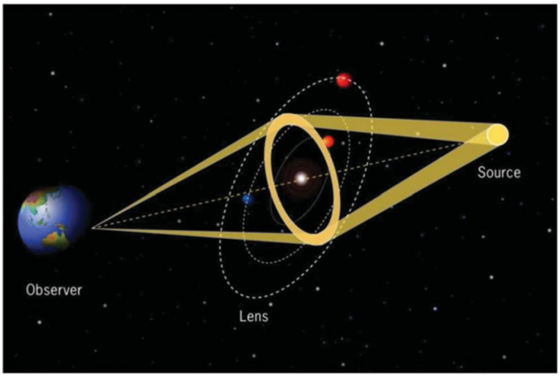

Figure 1. Schematic of a planetary microlensing event.

to detecting low-mass planets at orbital distances that are currently beyond the reach of other methods. At the time of the discovery of these two cold Neptune-mass planets or "Super Earths", two Jovian planets had also been found. These discoveries indicate that cold Neptune in orbits beyond the "snow-line" (Ida & Lin 2004; Laughlin, Bodenheimer & Adams 2004; Kennedy, Kenyon & Bromley 2006) around late-type stars, are significantly more common than gas giants with frequency of $\geqslant$16% at 90% confidence (Gould *et al.* 2006), which is consistent with theoretical simulations (Ida & Lin 2004) based on the core accretion model. On the other hand, microlensing has also revealed the most massive M-dwarf planetary companion (Udalski *et al.* 2005; Dong *et al.* 2009a), which would likely be difficult to form by core accretion (Laughlin, Bodenheimer & Adams 2004). Gaudi *et al.* (2008) discovered a system with a Jupiter and a Saturn orbiting an M dwarf in a configuration very similar to that of our solar system. Remarkably, this event yielded a direct measurement of the masses of the planets and the host star, that was confirmed by direct observation of the host star. This system (OGLE-2006-BLG-109Lb,c) is the only known multi-planet system with measured masses for the star and planets (aside from our own Solar System). The light curve of this event also yielded information about the orbit of the Saturn-mass planet that confirms that this system is similar to ours (Bennett *et al.* 2010). A planet was also found to orbit a very low mass host star or brown dwarf (Bennett *et al.* 2008), and this planet was also the lowest mass exoplanet known at the time of its discovery.

2. Current observation

The event rate of the microlensing is order of 10^{-5} per star per month. Furthermore, the probability of detecting a planet is only a percent of them. High cadence observation is needed to resolve the short-lived planetary signal. To fulfill these hard requirements, the microlensing community has been organizing a global network, which collaborate each other with the following three step strategy.

1. Survey: Survey groups like MOA and OGLE conduct wide field survey observations toward the galactic bulge to find microlensing events. The second phase of MOA, MOA-II, carry out a very high cadence photometric survey of 50 million stars in 22 bulge fields (of 2.2 deg^2 each) with a 1.8 m telescope at Mt. John Observatory in New Zealand. MOA-II detects $\sim$600 microlensing events with 8 months observation every year. Since 2010, the OGLE-IV survey monitors the bulge with the 1.3-m Warsaw telescope at Las Campanas Observatory, Chile, with 1.3 deg.^{2} field-of-view (FOV) and better astronomical seeing than MOA. OGLE-IV detects about 1,500 events every season. The OGLE photometry

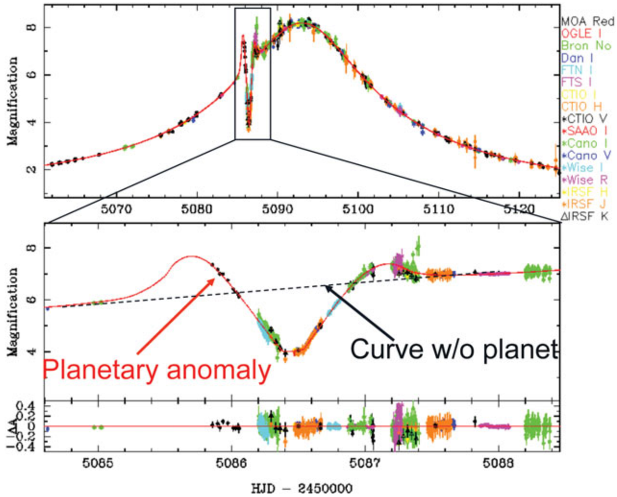

Figure 2. Light curve of the planetary microlensing event MOA-2009-BLG-266. This planet has a mass of $m_p = 10.4 \pm 1.7\ M_\odot$ and orbits a star of mass $M_* = 0.56 \pm 0.09 M_\odot$ at a semimajor axis of $a = 3.2^{+1.9}_{-0.5}$ AU and an orbital period of $P = 7.6^{+7.7}_{-1.5}$ yrs. The top panel: entire light curve. Bottom panel: zoom around the planetary anomaly with residuals from the best fit. After the event was found by MOA, the observer kept monitoring the progress of the event by the MOA realtime anomaly alert system. The planetary anomaly was found on the MOA data at HJD=2455086 and the anomaly alert was issued before dawn of New Zealand. The follow-up telescopes around the world have covered most of the planetary anomaly.

is usually more precise and fills gaps in the MOA light curves due to the difference in longitude.

2. Alert: All detected events are alerted and their light curves are made public on their web in realtime. Both survey groups and follow-up groups monitor the progress of the events and if they found that an event is evolving to high magnification which is more sensitive to planets than usual events, then they issue a “high magnification alert”. If an anomaly due to either planet or stellar binary is found during the event, then an “anomaly alert” is issued to prompt immediate follow-up observations for confirming the anomaly.

3. Follow-up: By responding to the alerts, telescopes all around the world from the follow-up groups, μFUN, PLANET, RoboNet-II and MiNDSTEp, conduct high cadence follow-up observations of these alerted events. Some telescopes conduct follow-up observations of the selected regular events as many as they can and they are also used to find high magnification events and anomaly. If a high magnification and/or an anomaly alerts are issued, more telescopes including amatures with $\sim$30 cm telescopes conduct more extensive follow-up than usual.

There are two channels for detecting planets; (1) High magnification events in which a source crosses a central caustic near the primary star. It is easier for a follow-up as we know an anomaly occurs near the peak of the event and we have enough time to prepare after the “high magnification alert”. Furthermore, a probability of finding planet among the high magnification events is high. (2) On the other hand, in regular low magnification events, the planetary anomaly can mostly be found when the source crosses a planetary caustics which are located far from the primly. So such an anomaly is difficult to follow as we don’t know when it will happen and have to wait for and respond quickly to an “anomaly alert” for the high cadence survey observation. However, the size (cross section) of the planetary caustics are larger than the central caustic. So the event rate is

https://doi.org/10.1017/S1743921313012453 Published online by Cambridge University Press

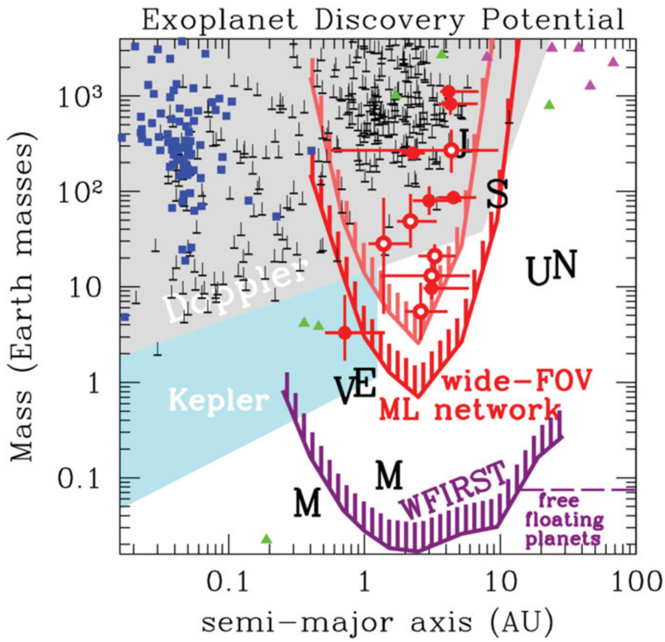

Figure 3. Detected exoplanets and sensitivity of various methods. Black lower limit and gray area: Radial velocity. Blue square: Transit. Magenta triangle: Direct imaging. Green triangle: timing. Red circle and upper red line: Current ground base microlensing, where filled circles indicate the planets with mass measurements, while open circles represent planet with mass estimated by Bayesian. Lower red line: Next generation 24 hour network. Purple line: WFIRST. Cyan area: Kepler. WFIRST can detect analogs of all of the solar system's planets except for Mercury. WFIRST combining with Kepler can cover most of the parameter space of the exoplanets.

higher than the central caustic events and more sensitive to low mass planets and thus potentially more important. Such low magnification events can be detected more often by the next generation survey network and space experiment as mentioned in the later sections.

Since MOA-II has started a high cadence survey observation with 15-50 min. cadence, thanks to its wide FOV in 2006, the probability of finding a short planetary anomaly in realtime has increased significantly. In 2010, the forth phase of OGLE, OGLE-IV also started similar high cadence survey observation.

Figure 2 show an example how a cold super-Earth has been detected by this strategy (Muraki *et al.* 2011). After the event was found by MOA, the observer kept monitoring the progress of the event by the MOA realtime anomaly alert system. A possible planetary anomaly was found on the MOA data at 2009 September 11 (HJD=2455076) and the anomaly alert was issued before dawn of New Zealand. The first data in response to the MOA's anomaly alert came from the μFUN group with observations from the 0.4 m telescope Bronberg Observatory in Pretoria, South Africa and the 1.0 m telescope of Wise Observatory in Israel, which were able to begin observations 4 hr after the anomaly alert. Final data set consists of observations from 13 different telescopes, which covered most of the planetary anomaly.

This strategy has been working pretty successfully so far and have found over 20 exoplanets including unpublished ones. Figure 3 shows the distribution of the detected planets and sensitivity by various methods. The microlensing has demonstrated

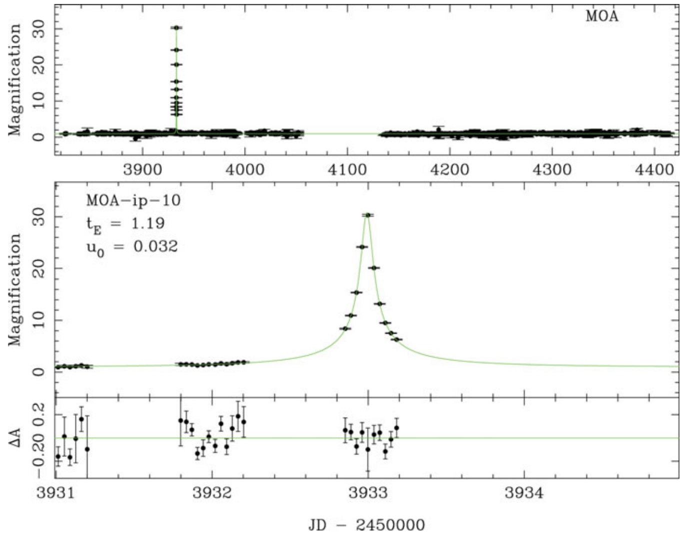

Figure 4. Light curve of free-floating planet candidate MOA-ip-10. Top panel shows light curve in two years. Bottom panel shows the zoom around the event with residual from the best fit shown by green solid line. The event timescale $t_{\rm E}$ is proportional to a square root of the lens mass, and it is $\sim$ 1 day for Jupiter mass. The mass of the lens object of this event is likely a Jupiter mass since its $t_{\rm E}$ is only 1.2 days.

sensitivity extending down to planets of mass $< 10M_{\odot}$ in orbits beyond the snow line (Bennett & Rhie 1996; Beaulieu *et al.* 2006; Bennett *et al.* 2008). Thus, it can provide a complementary probe of the physics of planet formation for planets that have migrated little from their putative birth sites. A statistical analysis of some of the first microlensing discoveries (Gould *et al.* 2010) indicates that cold, Saturn-mass planets beyond the snow line are more common than gas giants found in closer orbits with the Doppler radial velocity method (Cumming *et al.* 2008). Another microlensing study (Sumi *et al.* 2010) of the mass function slope showed that planets of $\sim 10M_{\odot}$ are even more common than these cold Saturns, in general agreement with the core accretion theory prediction for failed gas giant cores (Kennedy & Kenyon 2008; Thommes *et al.* 2008). Cassan *et al.* (2012) combined these two studies with some additional data, and found that there are one or more planets per stars in the galaxy.

Microlensing is also sensitive to the free-floating planets as it doesn't require the light from the objects. The timescale of the event, $t_{\rm E}$, is proportional to a square root of the lens mass and it is typically ~20 days for regular stars and ~1 day for a Jupiter-mass object. So the free-floating planets can be detected as the short timescale single lens events. Thanks to the 10-50 min. cadence survey observation, MOA-II have found 10 short single lens events with the timescale of less than 2 days (Sumi *et al.* 2011). Figure 4 shows one of these events. Their lenses are either unbound or very distant from the host stars, while the low abundance of distant planets by the direct imaging prefers that most of them are unbound. Although we cannot identify each of the lens has planetary mass because the actual mass, distance and velocity of the lens is degenerated in $t_{\rm E}$, we can statistically conclude that the typical lens mass of these short events are a Jupiter mass. With a statistical analysis by using the standard galactic density and velocity model, we estimated that the unbound or distant Jupiter mass objects are $1.8^{+1.7}_{-0.8}$ times as common as main-sequence stars. Such free-floating planetary mass objects are expected from the formation theory through the planet-planet scattering, while such a high abundance was

https://doi.org/10.1017/S1743921313012453 Published online by Cambridge University Press

very surprising. This may suggest that other formation mechanisms like gravitational instability theory (Boss 2006) plays important role in this mass range. Future works can constrain the abundance and mass function of these objects more accurately.

3. Next generation 24-hour survey network

Although the current observation is working well, the three step strategy mentioned above is rather complicated. The simpler observations are preferred to simplify a statistical estimate of the planet abundance to avoid any systematics. Furthermore, the number of detected planets is still limited and needed to be increased.

To solve these problems, the next generation 24-hour survey by the network of three or four wide FOV survey telescopes with several square degrees FOV in different continents at different longitude are proposed (Gaudi 2012; Shvartzvald and Maoz 2012). Such network can monitor tens of millions of stars every 1020 min for 24 hours continuously and, so, detect and simultaneously monitor thousands of microlensing events per year with the cadence required to detect perturbations due to Earth-mass planets without follow-up observation. This strategy is very simple. It does not need any alert nor follow-up observation. The cadence of the survey will be kept unchanged due to the possible existence of the planet in the on-going events.

As mentioned in the previous section, low magnification (planetary caustic) events can be detected more efficiently by the next generation survey network because the continuous 24 hours monitoring can detect short planetary anomaly anywhere in the event, i.e., the peak, tails and baleine. This next-generation network can also increase the detection of short timescale microlensing events due to free-floating or very distant planets.

As mentioned earlier, MOA-II and OGLE-IV have already started high cadence survey in New Zealand and Chile, so we are currently in a transition to the next generation

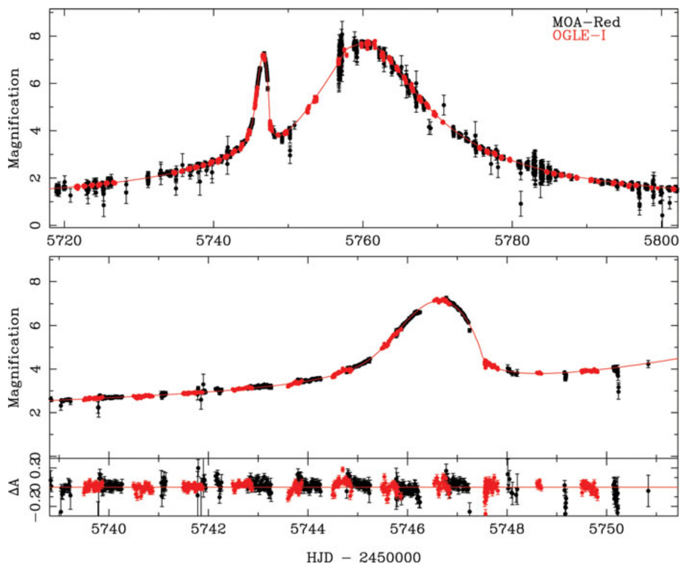

Figure 5. Light curve of the planetary microlensing event OGLE-2011-BLG-0265/MOA-2011-BLG-197. Top panel shows the entire event. Middle and Bottom panel show the zoom of the planetary anomaly and residual from the best fit planetary model shown as red solid line. Black and Red data indicate the MOA-II and OGLE-IV data. The short planetary signal was nicely covered by high cadence survey data by MOA-II and OGLE-IV. The blank region is the time zone of Africa where an another survey telescope is required to compile the network.

network. Figure 5 shows that the short planetary signal was nicely covered by high cadence survey data by MOA-II and OGLE-IV.

Furthermore, the 1-m telescope at Wise Observatory in Israel with the LAIWO camera, with a 1 $\deg^2$ FOV has recently started monitoring 8 $\deg^2$ Bulge fields with a cadence of $\sim$30 min. (Shvartzvald and Maoz 2012), while a realtime analysis has not stated yet. The Korean Microlensing Telescope Network (KMTNet) is currently building the three 1.6m wide FOV (4 deg.^{2}) telescopes at Cerro Tololo Chile, Sutherland South Africa, Siding Springs Australia, for which first lights are scheduled for early 2013, early 2014 and late 2014, respectively.

So, the next generation network will be realized very soon. The expected sensitivity of the next generation survey network is about a order of magnitude better than the current survey as shown in Figure 3.

4. Space exoplanet microlensing survey by WFIRST

The Wide Field Infrared Survey Telescope (WFIRST) is the highest ranked recommendation for a large space mission in the New Worlds, New Horizons (NWNH) in US Astronomy and Astrophysics 2010 Decadal Survey. Its wide field IR survey capability is suitable for microlensing and the Exoplanet microlensing survey is one of the primary mission of the WFIRST. Note that ESA's Euclid mission also have similar capability and microlensing exoplanet program is listed as one of the extended missions.

Three WFIRST designs, a primary of 1.1-m, 1.3m and 2.4m, are currently considered, and it is aimed to launch some time around 2023-2025 By using many near IR detectors (H2RG or H4RG) WFIRST can realize very wide FOV of 0.36-0.6 $\deg^2$. See more details on the final report by the WFIRST Science Definition Team (Green *et al.* 2012).

WFIRST's space-based microlensing surveys has many significant advantages compared from the ground:

1. Continuous accurate photometry without effects of weather, seeing, crowding of stars.

2. The main-sequence Bulge sources are needed to detect sub-Earth mass planets because the finite source effect wash out the signal for giant sources (Bennett & Rhie 2002). The near-IR observations improve the photon collection for moderately reddened solar-type and later source stars

3. The high spatial resolution by space can identify the primary lens stars and, so, able to estimates the mass of primary and planet for 70% of the discovered systems (Bennett, Anderson & Gaudi 2007).

WFIRST will carry out a 15min. cadence microlensing survey of 300 million stars towards the Galactic bulge. Figure 6 shows Simulated WFIRST light curve of microlensing event with Earth mass planet. One can see how robustly WFIRST can detect Earth-mass planets. If the planet populations of typical disk stars are similar to our own Solar System, then this survey is expected to detect more than two thousands cold exoplanets in the mass range of 0.1—10,000 Earth masses, including over two hundreds planets with roughly the mass of Earth or smaller. If there is one free-floating planets for every star in the Galaxy, then WFIRST will detect more than a thousand of them including a hundred of them with Earth mass or smaller. This census will provide unprecedented insights into the formation and evolution of planetary systems and the frequency of habitable worlds.

The WFIRST sensitivity is two order of magnitude better than the next generation ground-base experiment as shown in Figure 3. Especially WFIRST is more sensitive in wider range in semi-major axis, possible to detect low-mass planets at outer edge of the habitable zone. WFIRST can detect analogs of all of the solar system's planets except

https://doi.org/10.1017/S1743921313012453 Published online by Cambridge University Press

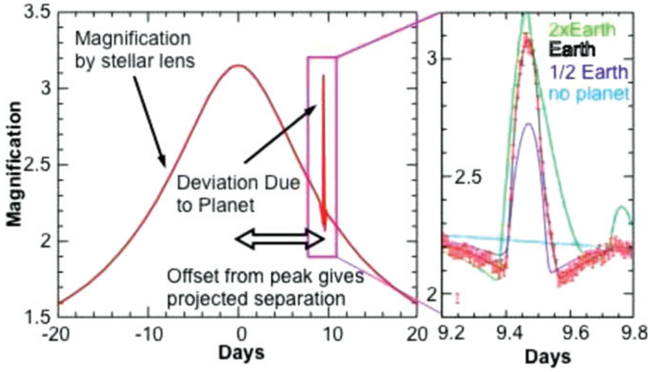

Figure 6. Simulated WFIRST light curve of microlensing event with Earth mass planet with 15 min. cadence. Green, black and purple solid lines indicate the model with 2 Earth-mass, Earth-mass and half Earth-mass planet. Earth-mass planets can robustly be detected. Note that a microlensing signal of low-mass planet is not so small while the probability is small.

for Mercury and very complementary to Kepler. WFIRST combining with Kepler can cover most of the parameter space of the exoplanets.

5. Conclution

Microlensing is very unique and complementary to other techniques in terms of the sensitivity on planet's parameter space. One of drawbacks of microlensing has been a small number of detections. However this is getting to be solved in the next generation microlensing network very soon and be significantly improved by the WFIRST space mission. The physical mass of the host and planet could have been measured only in a fraction of events from the ground. Only the planet-host mass ratio have been measured regularly. On the other hand, the WFIRST space mission is qualitatively different as it can measure the masses of the host and planets in 70% of the discovered systems.

Although the details of planets detected by microlensing can not be examined later by other methods, large sample by the next generation network and WFIRST can complete a statistical census of planetary systems in the Galaxy begun by Kepler, from the outer habitable zone to free floating planets, including analogs to all of the planets in our Solar System with the mass of Mars or greater.

References

Afonso, C., *et al.* 2003, *A&A*, 404, 145
Alcock, C., *et al.* 1993, *Nature*, 365, 621
Alcock, C., *et al.* 1997, *ApJ*, 486, 697
Alcock C., *et al.*, 2000b, *ApJ*, 541, 734
Bachelet, E., *et al.* 2012, , *ApJ*, 754, 73
Beaulieu, J.-P., *et al.* 2006, *Nature*, 439, 437
Bennett, D. P. & Rhie, S. H. 1996, *ApJ*, 472, 660
Bennett, D. P. & Rhie, S. H. 2002, *ApJ*, 574, 985
Bennett, D. P., *et al.* 2008, *ApJ*, 684, 663
Bennett, D. P., *et al.* 2010, *ApJ*, 713, 837
Bennett, D. P., *et al.* 2012, *ApJ*, 757, 119
Bennett, D P., Anderson, J., & Gaudi, B. 2007, *ApJ*, 660, 781
Bond, I. A., *et al.* 2001, *MNRAS*, 327, 868

Bond, I. A., *et al.* 2004, *ApJ*, 606, L155
Boss, A. P. 2006, *ApJ*L, 644, L79
Cassan, A., *et al.*, 2012, *Nature*, 481, 167
Cumming, A., Butler, R. P., Marcy, G. W., Vogt, S. S., Wright, J. T., & Fischer, D. A. 2008, *PASP*, 120, 531
Dong, S., *et al.* 2009a, *ApJ*, 695, 970
Dong, S., *et al.* 2009b, *ApJ*, 698, 1826
Gaudi, B. S. 2012, *Annual Review of Astronomy and Astrophysics*, 50, 411
Gaudi, B. S., *et al.* 2008, *Science*, 319, 927
Gaudi, B. S., 2010, in *Exoplanets*, ed. S. Seager (Tucson, AZ: Univ. Arizona Press), 79
Gould, A., *et al.* 2006, *ApJ*, 644, L37
Gould, A., *et al.* 2010, *ApJ*L, 720.1073
Green, J., *et al.* 2012, eprint arXiv:1208.4012
Griest, K., *et al.* 1991, *ApJ*, 372, L79
Ida, S. & Lin, D. N. C.. 2004, *ApJ*, 616, 567
Janczak, J., *et al.* 2010, 711, 731
Kennedy, G. M. & Kenyon, S. J. 2008, *ApJ*, 673, 502
Kennedy, G. M., Kenyon, S. J., & Bromley, B. C. 2006, *ApJ*, 650, L139
Konacki, M., *et al.* 2005, *ApJ*, 624, 372
Lagrange, A. M., *et al.* 2009, *A&A*, 493, L21
Laughlin, G., Bodenheimer, P., & Adams, F. C. 2004, *ApJ*, 612, L73
Liebes, S. 1964, *Phys. Rev.*, 133, 835
Mao, S. & Paczyński, B. 1991, *ApJ*, 374, L37
Marcy, G. W., *et al.* 2005, *ApJ*, 619, 570
Marois, C., *et al.* 2008, *Science*, 322, 1348
Mayor, M. & Queloz, D. 1995, *Nature*, 378, 355
Mayor, M., *et al.* 2004, *A&A*, 415, 391
Mayor, M., *et al.* 2009, *A&A*, 493, 639
Muraki, Y., *et al.* 2011, *ApJ*, 741, 22
Paczyński, B. 1986, *ApJ*, 304,1
Paczyński, B. 1991, *ApJ*, 371, L63
Pravdo, S. H. & Shaklan, S. B., 2009, *ApJ*, 700, 623
Smith, M. C., Mao, S., & Woźniak, P. R. 2002, *MNRAS*, 332, 962
Sumi, T., *et al.*, 2003, *ApJ*, 591, 204
Sumi, T., *et al.*, 2010, *ApJ*, 710,1641
Sumi, T., *et al.*, 2011, *Nature*, 473, 349
Shvartzvald, Y. & Maoz, D. 2012, *MNRAS*, 419, 3631
Thommes, E. W., Matsumura, S., & Rasio, F. A. 2008, *Science*, 321, 814
Udalski, A., *et al.* 1994, *Acta Astronomica*, 44, 165
Udalski A., Zebruń K., Szymański, M., Kubiak M., Pietrzyński G., Soszyński I., & Woźniak P. R. 2000, *Acta Astronomica*, 50, 1
Udalski, A. 2003, *Acta Astron.*, 53, 291
Udalski, A., *et al.* 2004, *Acta Astron.*, 54, 313
Udalski, A., *et al.* 2005 *ApJ*, 628, L109
Woźniak, P. R., *et al.* 2001, *Acta Astronomica*, 51, 175