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EXOPLANET SEARCHES WITH GRAVITATIONAL MICROLENSING

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Abstract. There are different methods for finding exoplanets such as radial spectral shifts, astrometrical measurements, transits, timing etc. Gravitational microlensing (including pixel-lensing) is among the most promising techniques with the potentiality of detecting Earth-like planets at distances about a few astronomical units from their host star. We emphasize the importance of polarization measurements which can help to resolve degeneracies in theoretical models. In particular, the polarization angle could give additional information about the relative position of the lens with respect to the source.

1. INTRODUCTION

Already before the discovery of exoplanets Mao & Paczynski (1991) showed how efficient is gravitational microlensing as a tool to search for extrasolar planets, including the low mass ones, even at relatively large distances from their host stars. Later on, observations and simulations gave the opportunity to confirm the robustness of Mao & Paczynski (1991) conclusions. Exoplanets near the snow line may be also detected

Table 1: Exoplanets discovered with microlensing.

Star Mass ($M_\odot$)	Planet Mass	Star–planet Separation (AU)
$0.63^{+0.07}_{-0.09}$	$830^{+250}_{-190} M_\oplus$	$4.3^{+2.5}_{-0.8}$
0.46 ± 0.04	$(1100 \pm 100) M_\oplus$	(4.4 ± 1.8)
$0.22^{+0.21}_{-0.11}$	$5.5^{+5.5}_{-2.7} M_\oplus$	$2.6^{+1.5}_{-0.6}$
$0.49^{+0.14}_{-0.18}$	$13^{+4.0}_{-5.0} M_\oplus$	$3.2^{+1.5}_{-1.0}$
0.50 ± 0.04	$(226 \pm 25) M_\oplus$	(2.3 ± 0.2)
0.50 ± 0.04	$(86 \pm 10) M_\oplus$	(4.6 ± 0.5)
$0.64^{+0.21}_{-0.26}$	$20^{+7}_{-8} M_\oplus$	$3.3^{+1.4}_{-0.8}$
$0.084^{+0.015}_{-0.012}$	$3.2^{+5.2}_{-1.8} M_\oplus$	$0.66^{+0.19}_{-0.14}$
$0.30^{+0.19}_{-0.12}$	$260.54^{+165.22}_{-104.85} M_\oplus$	$0.72^{+0.38}_{-0.16}/6.5^{+3.2}_{-1.2}$
0.67 ± 0.14	$28^{+58}_{-23} M_\oplus$	$1.4^{+0.7}_{-0.3}$
$0.38^{+0.34}_{-0.18}$	$50^{+44}_{-24} M_\oplus$	$2.4^{+1.2}_{-0.6}$
$0.19^{+0.30}_{-0.12}$	$2.6^{+4.2}_{-1.6} M_J$	$1.8^{+0.9}_{-0.7}$
0.56 ± 0.09	$10.4 \pm 1.7 M_\oplus$	$3.2^{+1.9}_{-0.5}$
$0.44^{+0.27}_{-0.17}$	$2.4^{+1.2}_{-0.6} M_J$	$1.0 \pm 0.1/3.5 \pm 0.5$
$0.67^{+0.33}_{-0.13}$	$1.5^{+0.8}_{-0.3} M_J$	2^{+3}_{-1}
$0.75^{+0.33}_{-0.41}$	$3.7 \pm 2.1 M_J$	$8.3^{+4.5}_{-2.7}$
0.26 ± 0.11	$0.53 \pm 0.21 M_J$	$2.72 \pm 0.75/1.50 \pm 0.50$

with this technique as it was shown, for instance, in Fig. 8 in Mao (2012). Moreover, in contrast with conventional methods, such as transits and Doppler shift measurements, gravitational microlensing gives a chance to find exoplanets not only in the Milky Way (Beaulieu et al. 2006, Dominik 2010, Wright & Gaudi 2012, Gaudi 2012, Mao 2012), but also in nearby galaxies, such as the Andromeda galaxy (Ingrosso et al. 2009, 2011), so pixel-lensing towards M31 provides an efficient tool to search for exoplanets and indeed an exoplanet might have been already discovered in the PA-N2-99 event (An et al. 2004, Ingrosso et al. 2009). Since source stars for pixel-lensing towards M31 are basically red giants (and therefore, their typical diameters are comparable to Einstein diameters and the caustic sizes) one has to take into account the source finiteness effect (Pejcha & Heyrovský, 2009). In the case of relatively small size sources, the probability to have features due to binary lens (or planet around star) in the light curves is also small since it is proportional to the caustic area. Giant star sources have large angular sizes and relatively higher probability to touch caustics (Ingrosso et al. 2009).

2. EXOPLANET SEARCHES WITH GRAVITATIONAL MICROLENSING

Since the existence of planets around lens stars leads to the violation of circular symmetry of lens system and, as a result, to the formation of fold and cusp type caustics (Schneider, Ehlers, Falco 1992, Zakharov 1995, Petters, Levine, Wambsganss, 2001), one can detect extra peaks in the microlensing light curve due to caustic crossing by the star source as a result of its proper motion.

A list of exoplanets detected with microlensing searches toward the Galactic bulge is given in Table 1 (see, Bennett et al. 2006; Bennett et al. 2008; Bennett 2008;

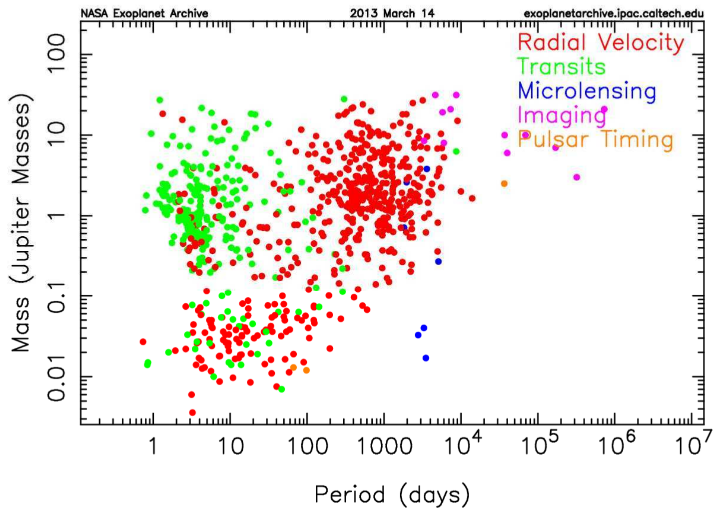

Figure 1: All exoplanets found with different techniques until March 14, 2013, see http://exoplanetarchive.ipac.caltech.edu/exoplanetplots/.

Dong et al. 2009; Mao 2012; Kains et al. 2013). For some planetary systems two probable regions for the planet-to-star distance are given due to the planet and star-lens parameter degeneracy (Dominik 1999; Bennett 2009), see rows 9, 14, 17 in Table 1. Reports about these discoveries were published by Bond et al. (2004); Udalski et al. (2005); Beaulieu et al. (2006); Gould et al. (2006); Gaudi et al. (2008); Bennett et al. (2008); Dong et al. (2009a,b); Janczak et al. (2010); Miyake et al. (2011); Batista et al. (2011); Muraki et al. (2011); Yee et al. (2012); Bachelet et al. (2012); Bennett et al. (2012). It is remarkable that the first exoplanet has been discovered by the MOA-I collaboration with only a 0.6 m telescope (Bond et al. 2004; Bennett 2009). This microlensing event was also detected by the OGLE collaboration, but the MOA observations with a larger field of view CCD, made about 5 exposures per night for each of their fields. This was an important advantage and shows that even observations with modest facilities (around 1 meter telescope size and even smaller) can give a crucial contribution in such discoveries. Until now four super-Earth exoplanets (with masses about $10M_\oplus$) have been discovered by microlensing (see Table 1 and Fig. 1), showing that this technique is very efficient in detecting Earth mass exoplanets at a few AU from their host stars, since a significant fraction of all exoplanets discovered with different techniques and located in the region near the so-called snow line (or the habitable zone) found with gravitational microlensing. Some of these exoplanets are among the lighest exoplanets see lines 3 and 8 in Table 1. For comparison, Doppler shift measurements help to detect an Earth-mass planet orbiting our neighbor star a Centauri B. The planet has an orbital period of 3.236 days and is about 0.04 AU from the star (Dumusque et al. 2012). Recently, a sub-Mercury size exoplanet Kepler-37b has been discovered with a transit technique (Barclay et al., 2013). It means that the existence of cool rocky planets is a common phenomenon in the Universe (Beaulieu et al. 2006; Dominik 2006; Dominik, Horne, Bode, 2006). Moreover, recently, Cassan et al. (2006) claimed that around 17% of stars host Jupiter-mass planets ($0.3 - 10\ M$J), cool Neptunes ($10 - 30M_\oplus$) and super-Earths ($10 - 30M_\oplus$) have relative abundances per star in the Milky Way such as 52% and 62%, respectively. Analysis of Kepler space telescope data also shows that a significant fraction of all stars has to have exoplanets (Fressin et al. 2013). Pixel-lensing towards M31 may provide an efficient tool to search for exoplanets in that galaxy (Chung et al. 2006; Kim et al. 2007; Ingrosso et al. 2009), and indeed an exoplanet might be already discovered in the PA-N2-99 event (Ingrosso et al. 2009). Since source stars for pixel-lensing towards M31 are basically red giants (and therefore, their typical diameters are comparable to Einstein diameters and the caustic sizes) one has to take into account the source finiteness effect, similarly to microlensing in quasars (Agol & Krolik 1999; Popović et al. 2006; Jovanović et al. 2008; Zakharov, 2009). As it is well known the amplifications for a finite source and for a point-like source are different because there is a gradient of amplification in respect of a source area. If the source size is rather small, the probability to produce features of binary lens (or planet around star) is proportional to the caustic area. However, giant stars have large angular sizes and relatively higher probability to touch planetary caustics (see Ingrosso et al. 2009, for more details).

3. POLARIZATION CURVES FOR MICROLENS SYSTEMS WITH EXOPLANETS

For extended sources, the importance of polarization measurements was pointed out by Bogdanov, Cherepashchuk & Sazhin (1996) for point-like lens and by Agol (1996) for binary lens (see also, Ignace, Bjorkman & Bryce (2006)). For point-like lens polarization could reach 0.1% while for binary lens it could reach a few percent since the magnification gradient is much greater near caustics. It has been shown that polarization measurements could resolve degeneracies in theoretical models of microlensing events (Agol, 1996). Calculations of polarization curves for microlensing events with features in the light curves induced by the presence of an exoplanet and observed towards the Galactic bulge have been done (Ingrosso et al., 2012). Here we emphasize that measurements of the polarization angle could give additional information about the gravitational microlensing model. For instance, for a point-like lens the direction for the maximal polarization (which is perpendicular to the line connecting star and lens) may allow to infer the direction of lens proper motion, thus allowing to eventually pinpoint the lens in following observations. Even in the case of binary lens, the orientation of polarization vector corresponds to the orientation of the fold caustic (or more correctly to the tangent vector to the fold caustic at the intersection point with the path of source), provided the source size is small enough.

In Fig. 2, the polarization curve and the polarization angle are shown for the OGLE-2005-BLG-169 event, where a binary system formed by a main sequence star with mass $M_\odot \sim 0.5\ M_\odot$ and a Neptune-like exoplanet with mass about 13 $M_\oplus$ is expected from the light curve analysis (Gould et al., 2006). The event parameters are $t_E = 42.27$ days, $u_0 = 1.24 \times 10^{-3}$, $b = 1.0198$, $q = 8.6 \times 10^{-5}$, $\alpha = 117.0$ deg, $\rho_* = 4.4 \times 10^{-4}$, where $t_E, u_0, b, q, \alpha, \rho_*$ are the Einstein time, the impact parameter, the projected distance of the exoplanet to the host star, the binary component mass ratio, the angle formed by the source trajectory and the separation vector between the lenses, and the source star size, respectively (all distances are given in R_E units).

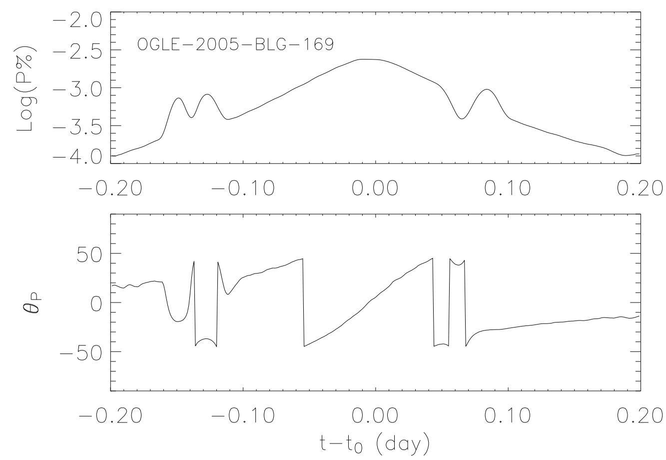

Figure 2: Polarization curve (top panel) and polarization angle (bottom panel) for the OGLE-2005-BLG-169 event.

The effect of the source transiting the caustic (see Gould et al. (2006) is clearly visible both in the polarization curve (see top panel in Fig. 2) and in the flip of the polarization angle (see bottom panel). We would like to stress that the high peak magnification ($A \simeq 800$) of the OGLE-2005-BLG-169 event leading to I-magnitude of the source about 13 mag at the maximum gives the opportunity to measure the polarization signal for such kind of events by using present available facilities. In this case, polarization measurements might give additional information about the caustic structure, thus potentially allowing to distinguish among different models of exoplanetary systems. Recently, Gould et al. (2012) found that a variable giant star source mimics exoplanetary signatures in the MOA-2010-BLG-523S event. In this respect, we emphasize that polarization measurements may be helpful in distinguishing exoplanetary features from other effects in the light curves.

4. CONCLUSIONS

Now there are campaigns of wide field observations by Optical Gravitational Lensing Experiment (OGLE) (Udalski, 2003) and Microlensing Observations in Astrophysics (MOA) (Bond et al., 2001) and follow-up observations MicroFUN[1] and PLANET[2]. It is important to note that small size (even less than one meter diameter) telescopes acting in follow-up campaigns contributed in discoveries of light Earth-like exoplanets and it is a nice illustration that a great science can be done with modest facilities. As it was shown by Ingrosso et al. (2012) polarization measurements are very perspective to remove uncertainties in exoplanet system determination and they give an extra proof for a conventional gravitational microlens model with suspected exoplanets.

[1]http://www.astronomy.ohio-state.edu/ microfun/microfun.html.
[2]http://planet.iap.fr/.

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References

Agol, E.: 1996, *Mon. Not. R. Astron. Soc.*, **279**, 571.
Agol, E. & Krolik J.: 1999, *Astrophys. J.*, **524**, 49.
An J. H. et al.: 2004, *Astrophys. J.*, **601**, 845.
Bachelet, E. et al.: 2012, *Astrophys. J.*, **755**, 91.
Barclay, Th. et al.: 2013, *Nature*, **494**, 452.
Batista, V. et al.: 2011, *Astron. & Astrophys.*, **529**, A102.
Beaulieu, J.-P. et al.: 2006, *Nature*, **439**, 437.
Bennett, D.P.: 2009, *arXiv:*0902.1761v1[astro-ph.EP].
Bennett, D.P. et al.: 2006, *Astrophys. J. Lett.*, **647**, L171.
Bennett, D.P. et al.: 2008, *Astrophys. J.*, **684**, 663.
Bennett, D.P. et al.: 2012, *Astrophys. J.*, **757**, 119.
Bogdanov, M. B. & Cherepashchuk, A. M., Sazhin, M. V.: 1996, *Astrophys. & Space Science*, **235**, 219.
Bond, I.A., et al.: 2001, *Mon. Not. R. Astron. Soc.*, **327**, 868.
Bond, I.A., et al.: 2004, *Astrophys. J. Lett.*, **606**, L155.
Cassan, J.-P. et al.: 2012, *Nature*, **481**, 167.
Chung S.-J. et al.: 2006, *Astrophys. J.*, **650**, 432.
Dominik, M.: 1999, *Astron. & Astrophys.*, **349**, 108.
Dominik, M.: 2006, *Mon. Not. R. Astron. Soc.*, **367**, L31.
Dominik, M., Horne K., Bode M. F.: 2006, *Astron. & Geophys.*, **367**, 3.25.
Dominik, M.: 2010, *Gen. Rel. Grav.*, **42**, 2075.
Dong, S. et al.: 2009a, *Astrophys. J.*, **695**, 970.
Dong, S. et al.: 2009b, *Astrophys. J.*, **698**, 1826.
Dumusque, X. et al.: 2012, *Nature*, **491**, 212.
Fressin, F. et al.: 2013, *arXiv:*1301.0842v1[astro-ph.EP].
Gaudi, B. S.: 2012, *Annual Rev. Astron. & Astrophys.*, **50**, 411.
Gaudi, B. S., et al.: 2008, *Science*, **319**, 927.
Gould, A. et al.: 2006, *Astrophys. J.*, **644**, L37.
Gould, A. et al.: 2012, *arXiv*:1210.6045v2[astro-ph.SR].
Ignace, R., Bjorkman, E. & Bryce, H. M.: 2006, *Mon. Not. R. Astron. Soc.*, **366**, 92.
Ingrosso, G. et al.: 2009, *Mon. Not. R. Astron. Soc.*, **399**, 219.
Ingrosso, G. et al.: 2011, *Gen. Rel. Grav.*, **43**, 1047.
Ingrosso, G. et al.: 2012, *Mon. Not. R. Astron. Soc.*, **426**, 1496.
Janczak, J. et al.: 2010, *Astrophys. J.*, **711**, 731.
Jovanović P. et al.: 2008, *Mon. Not. R. Astron. Soc.*, **386**, 397.
Kains N. et al., 2013, *arXiv*:1303.1184 [astro-ph.EP].
Kim, D., et al.: 2007, *Astrophys. J.*, **666**, 236.
Mao, S.: 2012, *Res. Astron. Astrophys.* **12**, 947.
Mao, S., Paczynski, B.: 1991, *Astrophys. J.*, **374**, L37.
Miyake, N. et al.: 2011, *Astrophys. J. Lett.*, **728**, L37.
Muraki, Y. et al. 2011, *Astrophys. J.*, **741**, 22.
Pejcha, O. & Heyrovský D.: 2009, *Astrophys. J.*, **690**, 1772.
Petters, A.O., Levine, H. & Wambsganss, J.: 2001, *Singularity Theory and Gravitational Lensing*, Boston, Birkhäuser.
Popović, L.Č. et al.: 2006, *Astrophys. J.*, **637**, 620.
Schneider, P., Ehlers, J. & Falco, E.E.: 1992, *Gravitational Lenses*, Berlin, Springer.
Sumi, T. et al.: 2010, *Astrophys. J.*, **710**, 1641.
Udalski, A. : 2003, *Acta Astron.*, **53**, 291.

Udalski, A. et al.: 2005, *Astrophys. J. Lett.*, **628**, L109.
Wright, J.T., Gaudi, B. S., 2012, *arXiv*:1210.2471v2[astro-ph.EP].
Yee J.C. et al., 2012, *Astrophys. J.*, **755**, 102.
Zakharov, A.F.: 1995, *Astron. & Astrophys.*, **293**, 1.
Zakharov, A.F.: 2009, *New Astron. Rev.*, **53**, 202.
Zakharov, A.F.: 2011, *Physics – Uspekhi*, **54**, 1077.
Zakharov, A.F. et al.: 2010, *Mem. della Soc. Astron. Ital. Suppl.*, **15**, 114.