Exoplanet searches with gravitational microlensing

Alexander F. Zakharov[*]
Institute of Theoretical and Experimental Physics,
B. Cheremushkinskaya, 25, 117259, Moscow, Russia,
and
Bogoliubov Laboratory for Theoretical Physics, JINR,
141980 Dubna, RUSSIA

Sebastiano Calchi Novati
Dipartimento di Fisica, Universita di Salerno,
I-84081 Baronissi, ITALY

Francesco De Paolis, Gabriele Ingrosso,
Achille A. Nucita
Dipartimento di Fisica, Universita del Salento
and INFN Sezione di Lecce, CP 193, I-73100 Lecce, ITALY

Philippe Jetzer
Institute for Theoretical Physics, University of Zurich,
Winterthurerstrasse 190, CH-8057 Zurich, SWITZERLAND

Abstract

Different regimes of gravitational lensing depend on lens masses and roughly correspond to angular distance between images. If a gravitational lens has a typical stellar mass, this regime is named microlensing because the typical angular distance between images is about microarcseconds in the case for sources and lenses at cosmological distances. The angular distance depends on as a squared root of lens mass and therefore, for Earth-like planet mass lens ($10^{-6}M_{\odot}$), such a regime is called nanolensing. So, one can name searches for exoplanets with gravitational lens method as gravitational nanolensing. 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.

[*] e-mail address: zakharov@itep.ru

1. Gravitational lensing: introduction

Gravitational lensing is based on the simple physical phenomenon that light trajectories are bent in a gravitational field. In some sense a gravitating body attracts photons. For the first time this fact was discussed by I. Newton [1], but the first derivation of the light bending angle in the framework of Newtonian gravity was published by J. Soldner [2]. Using the weak gravitational field approximation in General Relativity (GR) the correct bending angle is described by the following expression [3]

$$\delta\varphi = \frac{4GM}{c^2 p}, \tag{1}$$

where M, p, c and G are the gravitating body mass, the impact parameter, the speed of light and the Newton constant, respectively. If $M = M_\odot$ and $p = R_\odot$ are the Solar mass and radius, the bending angle is equal to $1.75''$. In 1919 this value was firstly confirmed by the observations of light rays bending by the Solar gravitational field near its surface [4].

Using Eq. (1) one can introduce the gravitational lens equation

$$\vec{\eta} = D_s\vec{\xi}/D_d - D_{ds}\vec{\Theta}(\vec{\xi}), \tag{2}$$

where D_s, D_d and D_{ds} are the source – observer, lens – observer and source – lens distances. Here $\vec{\eta}$ and $\vec{\xi}$ define coordinates in source and lens planes, respectively, and

$$\vec{\Theta}(\vec{\xi}) = 4GM\vec{\xi}/c^2\xi^2. \tag{3}$$

Taking the right hand side of Eq. (2) to be zero ($\vec{\eta} = 0$) and substituting $\vec{\Theta}$ from Eq. (3), one obtains the so-called Einstein – Chwolson radius[1] [8] $\xi_0 = \sqrt{4GMD_dD_{ds}/(c^2D_s)}$ and, correspondingly, the Einstein– Chwolson angle $\theta_0 = \xi_0/D_d$. If $D_s \gg D_d$, we have

$$\theta_0 \approx 2'' \times 10^{-3} \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{\text{kpc}}{D_d}\right)^{-1/2}. \tag{4}$$

1.1. Regimes of Gravitational Lensing

There is a number of reviews and books on gravitational lensing [8, 9, 10, 11, 12, 13]. Gravitational lensing in the strong gravitational field approximation was also analyzed [14, 15, 16, 17, 18].

As it is shown below, in the framework of the simplest point-like lens model (the Schwarzschild lens) angular distances between images are about $2\theta_0$ and it is proportional to the square root of the lens mass, for fixed other

[1] Chwolson [5] described circular images and Einstein [6] obtained basic expressions for gravitational lensing. However, it was found [7] that Einstein analyzed gravitational lensing phenomenon in his unpublished notes in 1912.

Table 1: Different regimes of gravitational lensing [9].

Prefix/name	Deflection angle (arcsecond)	Mass $m/M_\odot$	Lens
kilo-lensing	10^3	10^{18}	Supercluster
macro-lensing	10^0	10^{12}	galaxy
milli-lensing	10^{-3}	10^6	MBH
micro-lensing	10^{-6}	10^0	star
nano-lensing	10^{-9}	10^{-6}	planet
pico-lensing	10^{-12}	10^{-12}	???
femto-lensing	10^{-15}	10^{-18}	comet

parameters. So, if the gravitational lens has a typical galactic mass of about $10^{12}M_\odot$, the distance between images is about a few angular seconds (the standard gravitational macro-lensing regime); if the gravitational lens mass is about a solar mass $M_\odot$, the typical distance between images is about 10^{-6} arcseconds (the gravitational microlensing regime); if the gravitational lens has a typical Earth-like planet mass of about $10^{-6}M_\odot$, the distance between images is about 10^{-9} arcseconds (the gravitational nanolensing regime), see also [9, 19, 20]. Actually, 10^{-9} arcseconds is a very small angle and to imagine it one can try to take a look at one inch coin from the distance of about 4.5×10^9 km (or about 30 AU, which is roughly equal to the distance between Sun and Neptune).

Naturally, at the moment there is no way to resolve micro and nano images but there is a way to discover photometrical features of the phenomena by monitoring light curves of background sources [21]. Moreover, there are projects planning to reach angular resolutions at the microarcsecond level (in different spectral bands) such as NASA Space Interferometry Mission (SIM), ESA Global Astrometric Interferometer for Astrophysics (Gaia) [22], NASA MicroArcsecond X-Ray Imaging Mission (MAXIM) [23, 24], Russian RadioAstron. It is planned to reach even a nanoarcsecond level in mm band with space–ground interferometry technique with Millimetron mission.[2]

If the gravitational lens is one of the closest galaxies at distance D_d = 100 kpc with mass $M = 10^{12}M_\odot$, we have $\theta_0 \approx 200''$. If the gravitational lens is a star in our Galaxy at distance 1 kpc, we have $M = M_\odot$, and $\theta_0 \approx 2'' \times 10^{-3}$. Similar, if the lens is a planet at the same distance with mass about $M = 10^{-6}M_\odot$, then $\theta_0 \approx (2\times10^{-6})''$. According to a standard terminology proposed many years ago, if the lens mass is about $M \simeq M_\odot$ ($M \simeq 10^{-6}M_\odot$) we call this lensing regime as microlensing (nanolensing) independently on locations of sources and lenses. More generally speaking,

[2]See, http://www.asc.rssi.ru.

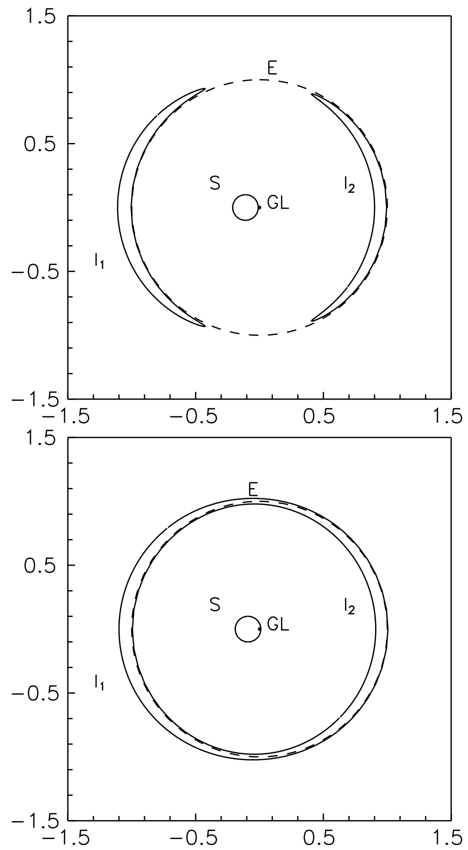

Figure 1: Image formation for a circular source S with a radius $r = 0.1$ and for two different distances d between a source center and gravitational lens on the celestial sphere for $d = 0.11$ (top panel) and $d = 0.09$ (bottom panel), where I_1 and I_2 are images, E is the Einstein – Chwolson ring, GL is a position of gravitational lens on the celestial sphere.

searches for planets through their impacts on gravitational lensing may be named as gravitational nanolensing.

We can introduce dimensionless variables

$$\vec{x} = \vec{\xi}/\xi_0, \quad \vec{y} = D_s\vec{\eta}/(\xi_0 D_d),$$
$$\vec{\alpha} = \vec{\Theta} D_{ds} D_d/(D_s \xi_0), \tag{5}$$

and we write the gravitational lens equation in dimensionless form:

$$\vec{y} = \vec{x} - \vec{\alpha}(\vec{x}) \quad \text{or} \quad \vec{y} = \vec{x} - \vec{x}/x^2. \tag{6}$$

The gravitational lens effect may lead to the formation of several images instead of one (see, for instance, [8, 11]). We have two images (or one ring) for the Schwarzschild point lens model, as one can see in Fig. 1. The total area of the two images is larger than the source area. The ratio between the sum of these two image areas and the source area is called gravitational lens amplification A and it is a result of gravitational focusing. For example, if a circular source with radius r (and area πr^2) is located near the position of a gravitational lens on the celestial sphere, then the ring image area is equal to $2\pi r$ (the width of the ring is r and its circumference is 2π for the unit circle since we express all distances in Einstein – Chwolson radius units) and therefore, the magnification is $2/r$. Thus one could calculate the asymptote for the magnification in the limit $r \to 0$. That is the reason to name gravitational lensing as gravitational focusing.

As one can see, the angular distance between two images is about the angular size of the so-called Einstein – Chwolson cone with the angle $2\theta_0$ (it corresponds to the Einstein – Chwolson diameter).

2. Gravitational Microlensing

There is a number of reviews on gravitational lensing [13, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34]. If a source S lies on the boundary of the Einstein – Chwolson cone, then the amplification $A = 1.34$. The microlensing time T_0 is defined usually as a half of the total time of crossing the cone:

$$T_0 = 3.5 \text{ months} \cdot \sqrt{\frac{M}{M_\odot}\frac{D_d}{10\,\text{kpc}}} \cdot \frac{300\,\text{km/s}}{V_\perp},$$

where $V_\perp$ is the transverse velocity component of the lens. If we suppose $V_\perp \simeq 300$ km/s (that is the typical stellar velocity in the Galaxy), then the typical crossing time of the Einstein cone is about 3.5 months. Thus, the luminosity of a source S is changing within this time. We will give numerical estimates for parameters of the microlensing phenomenon. If the distance between the lens and the Sun is about 10 kpc, then the angular size of Einstein cone is equal to $\sim 0.001''$ and it corresponds to a linear size of about 10 AU. It is clear that since the angular distance between the images is very small, it is very difficult to resolve them by using ground based telescopes, at least in an optical band. Einstein noted that if gravitational lenses and sources are stars, the gravitational lens phenomenon hardly could ever be detectable, since the separation angle between images is very small [6].[3] However, recently, a direct method to measure the Einstein angle $2\theta_0$ was proposed by resolving the double images generated by microlensing. To solve this problem [35] proposed to use an optical interferometer (say, Very Large Telescope Interferometer (VLTI)). Moreover, it was planned to launch astrometrical space probes, such as US SIM[4] and

[3]However, due to the gravitational focusing the light, the microlensing effect may be observed by analyzing the luminosity variations of a background source as it was originally proposed in [21].

[4]http://sim.jpl.nasa.gov/whatis/.

European Gaia[5], since these instruments will have accuracies of about 10 microarcseconds and they could resolve the image splitting in the case of microlensing events. Applications of future space missions for astrometrical microlensing searches are discussed [38, 39].

Microlensing of distant quasars as gravitational lensed sources was considered [40], soon after the first gravitational lens discovery [41]. The phenomenon has been discovered [42] since the optical depth for such systems is very high. Later on, features of microlensing in different bands are found in gravitationally lensed systems [43, 44], in particular event signatures were found with the 1.5 m RTT-150 telescope in the system SBS 1520+530 [45]. The optical depth of microlensing for distant quasars was discussed for different locations of microlenses [46, 47]. The influence of microlensing on spectra in different bands was analyzed [48]. These investigations were inspired by discoveries of microlensing features in X-ray band for gravitationally lensed systems [49]. These results were obtained due to an excellent angular resolution in X-ray band of the Chandra satellite enabling us to resolve different images of gravitationally lensed systems and study their luminosities separately.

Basic criteria for microlensing event identification are that a light curve should be symmetrical and achromatic. If we consider a spherically symmetric lens, a point source and a short duration of microlensing event then the statement about the symmetrical and achromatic light curves will be a correct claim, but if we consider a more complicated distribution of a gravitational lens field or an extended source then some deviations of symmetric light curves may be observed and (or) the microlensing effect may be chromatic [11].

Many years ago it was found that density of visible matter is about a few % of total matter density in galactic halos [50] and the invisible component is called dark matter (DM). It is now known that the matter density (in critical density units) is $\Omega_m = 0.3$ (including baryonic matter $\Omega_b \approx 0.05 - 0.04$, but luminous matter $\Omega_{\rm lum} \leq 0.005$), Λ-term density $\Omega_\Lambda = 0.7$ [51, 52, 53]. Thus, baryonic density is a small fraction of total density of the Universe. Probably galactic halos are "natural" places to store not only baryonic DM, but non-baryonic DM as well. If DM forms objects with masses in the range $10^{-5} - 10\ M_\odot$, microlensing could help to detect such objects. Thus, before intensive microlensing searches it was a dream that microlensing investigations could help us to solve DM problem for Galactic halo at least.

As it was mentioned before, a possibility to discover microlensing by monitoring background stars for the first time was proposed in [21] (however, to increase a probability in the original paper it was proposed to detect very faint flashes for the background star light curves and in this form the idea is hardly ever realizable). Systematic searches of dark matter using typical variations of light curves of individual stars from millions observable stars started after Paczynski's discussion of the halo dark matter discovery using monitoring stars from Large Magellanic Cloud (LMC) [54]. At the begin-

[5] http://astro.estec.esa.nl/gaia, see also [22, 36, 37].

Table 2: Microlensing event candidates discovered in the observational campaign of OGLE-III.

Year of observations	Number of event candidates
2002	about 350
2003	about 450
2004	about 600
2005	about 550
2006	about 600
2007	about 600
2008	about 650

ning of the nineties new computer and technical facilities providing the storage and processing capabilities for the huge volume of observational data appeared and enabled the rapid realization of Paczynski's proposal (the situation was different in time of Byalko's paper). It was suggested to call the microlenses as Machos (Massive Astrophysical Compact Halo Objects) [55]. Besides, MACHO is the name of the US–English–Australian collaboration project which observed the LMC and Galactic bulge using 1.3 m telescope of Mount Stromlo observatory in Australia.[6] Since one can monitor several million stars for several years by the microlens searches, the ongoing searches have focused on two targets: a) stars in the Large and Small Magellanic Clouds (LMC and SMC) which are the nearest galaxies having lines of sight which go out of the Galactic plane and well across the halo; b) stars in the Galactic bulge which allow us to test the distribution of lenses near the Galactic plane. The first papers about the microlensing discovery were published by the MACHO collaboration [56] and the French collaboration EROS (Expérience de Recherche d'Objets Sombres) [57].[7]

First papers about the microlensing discovery toward Galactic bulge were published by the US - Polish Optical Gravitational Lens Experiment (OGLE) collaboration, which used 1.3 m telescope at Las Campanas Observatory. Since June 2001, after second major hardware upgrade OGLE entered into its third phase, OGLE III and as a result the collaboration observed more than 200 million stars regularly once every 1 – 3 nights. During last years OGLE III detected several hundred microlensing event candidates each year [59, 60]. The OGLE-III phase has ended on May 3rd, 2009.[8] During the previous observing seasons the Early Warning System (EWS) of OGLE-III discovered a number of microlensing event candidates (see Table 2).

MOA (Microlensing Observations in Astrophysics) is collaboration involv-

[6]MACHO stopped since the end of 1999.

[7]EROS experiment stopped in 2002 [58].

[8]http://www.astrouw.edu.pl/ogle/ogle3/ews/ews/html. OGLE collaboration plans to start the phase OGLE IV.

ing astronomers from Japan and New Zealand [61].[9]

To investigate Macho distribution in another direction one could use searches toward M31 (Andromeda) Galaxy lying at 725 kpc, which is the closest galaxy for an observer in the Northern hemisphere [62, 63, 64, 65]. On the other hand, there are several suitable telescopes concentrated in this Earth hemisphere. In nineties two collaborations AGAPE (Andromeda Gravitational Amplification Pixel Experiment, Pic du Midi, France)[10] and Vatican Advanced Technology Telescope (VATT) started to monitor pixels instead of individual stars [58, 66]. These teams reported discoveries of several microlensing event candidates [67, 68]. Results of Monte Carlo simulations for these observations and differences between pixel and standard microlensing are discussed [69].

Concerning microlens detections one can say that even many years ago there was no doubt about this issue [26]. However, it is impossible to say exactly which part of the microlensing event candidates is actually connected with the effect, since there are probably some variable stars among the event candidates, it could be stellar variability of an unknown kind.[11] Below we will list the most important results. Observed light curves are achromatic and their shapes are interpreted very well by simple theoretical expressions, however, there is not a complete consensus about "very well interpretation", since even for the event candidate MACHO # 1 the authors of the discovery proposed two fits. It was suggested that this event could be better fitted in the framework of the binary lens model [73, 74], but one can assume that this microlensing event candidate could be caused by a non-compact microlens [75].

Using photometric observations of the caustic-crossing binary lens microlensing event EROS BLG-2000-5, Probing Lensing Anomalies NETwork (PLAN ET) collaboration reported the first microlens mass determination, namely the masses of these components are 0.35 $M_\odot$ and 0.262 $M_\odot$ and the lens lies within 2.6 kpc from the Sun [76].

Gravitational microlensing events due to stellar mass black holes have been discovered [77]. The lenses for events MACHO-96-BLG-5 and MACHO-96-BLG-6 are the most massive, with mass estimates $M/M_\odot = 6^{+10}_{-3}$ and $M/M_\odot = 6^{+7}_{-3}$, respectively. However, it was established later that event MACHO-99-BLG-22 is a strong BH candidate (78%), MACHO-96-BLG-5 is marginal BH candidate (37 %), and MACHO-96-BLG-6 is a weak BH candidate (2%) [78].

The optical depth towards the Galactic bulge is equal to $\sim 3 \times 10^{-6}$, so it is larger than the initially estimated value [79], so that there is an additional feature for a bar like structure for the Galactic bulge.

[9] http://www/roe.ac.uk/%7Eiab/alert/alert/alert/html.

[10] The POINT-AGAPE collaboration started in 1999 with the 2.5 m Isaac Newton Telescope (INT) [70, 71], the new robotic project Angstrom was proposed as well [72].

[11] The microlensing event candidates, which proposed early by the EROS collaboration (#1 and #2) and by the MACHO collaboration (#2 and #3) are now considered as the evidence of a stellar variability [26].

5.7 years analysis of photometry of 11.9 million stars in LMC by MACHO collaboration revealed 13 – 17 microlensing events [80]. The optical depth towards the LMC is equal to $\tau(2 < \hat{t} < 400 \text{ days}) = 1.2^{+0.4}_{-0.3} \times 10^{-7}$, so, it is smaller than the initially estimated value based on the assumption that the halo dark matter is concentrated in Machos. The maximum likelihood analysis gives a Macho halo fraction $f = 0.2$. Estimates of the following probabilities $P(0.08 < f < 0.5) = 0.95$ and $P(f = 1) < 0.05$ are given. The most likely Macho mass $M = 0.15 - 0.9\ M_{\odot}$, depending on the halo model and total mass in Machos out 50 kpc is found to be $9^{+4}_{-3} \times 10^{10} M_{\odot}$. EROS collaboration gives a consistent conclusion. Namely, this group estimates the following probability $P(M \in [10^{-7}, 1]M_{\odot}\ \&\ f > 0.4) <\ 0.05$ [81]. Recently this collaboration concluded that the optical depth toward LMC is $\tau < 0.36 \times 10^{-7}$ (with 95% confidence level) which means that Macho contribution to halo mass is less than 7 % [82]. On the other hand, OGLE collaboration claims that the fraction of mass of compact dark matter objects in the Galactic halo could be 8 ± 6 % [83]. Their results indicate a non-detection of Machos lensing towards the LMC with an upper limit for their abundance in the Galactic halo of 19 % for M = $0.4 M_{\odot}$ and 10 % for masses between 0.01 and 0.2 $M_{\odot}$ [83]. However, these conclusions are based on assumptions about mass and spacial distributions of microlenses but such distributions are not known very well. In principle, microlensing searches are realistic ways to improve our knowledge, but for that aim we would need thousands of events.

When new observational data would be collected and the processing methods would be perfected, probably some microlensing event candidates would loose their status, but perhaps new microlensing event candidates would be extracted among analyzed observational data. Thus, the following general conclusion may be made: the very important astronomical phenomenon was discovered, but some quantitative parameters of microlensing will be specified in future. However, the problem about a content of 80% (or even 93% according to EROS point of view) of DM in the halo of our Galaxy is still open (before microlensing search the people hoped that it could give an answer for this problem). Thus, describing the present status Kerins wrote adequately that now we have "Machos and clouds of uncertainty" [84]. It means that there is a wide field for studies, in particular, pixel microlensing, microlensing of gravitationally lensed systems and extrasolar planet searches seem to be the most promising issues.

3. Methods for Exoplanet searches

About twenty years ago Mao & Paczynski evaluated the probability to find a planet among microlensing events and they noted that with massive searches toward the Galactic bulge the first exoplanet should have been discovered. In spite of the fact that the first planetary system was found around the millisecond pulsar PSR1257+12 [86], the prediction by Mao and Paczynski [85] was almost correct and nowadays we know that microlensing is rather efficient method for exoplanet searches.

At the moment one of the most fruitful technique to find exoplanets is based on measurements of radial velocities with the spectrograph High Accuracy Radial velocity Planet Searcher (HARPS). These facilities are installed at the ESO 3.6 m telescope at La Silla Observatory. A typical uncertainty is about 1 m/s with a full range in the 0.7 – 2 m/s interval depending on weather conditions [87]. A summary for radial velocities searches is given in Table 1 in [88]. At the moment more than 300 planets were discovered by this method.

About 60 planets were discovered by transit method, [89] see also Table 2 in [88]), where ground and space facilities are listed.[12] The recent launch of Kepler mission significantly increases expectations to find new interesting objects with the transit technique. We remind that the diameter of Kepler mirror is more than 3 times larger than the diameter of the Convection Rotation and planetary Transits (CoRoT) telescope mirror and the field of view of Kepler is more than 100 times larger. CoRoT discovered very interesting planetary systems such as CoRoT-7b which radius is about 2 Earth radius [90]. Further observations with HARPS showed that there are two Earth like planets in the system with masses $4.8 \pm 0.8 M_\oplus$ (CoRoT-7b) and $8.4 \pm 0.9 M_\oplus$ (CoRoT-7c) [91].

According to J. Schneider database[13] four planetary systems (with 7 planets and 2 multiple planet systems) are found by timing technique.

At the moment, only one exoplanet has been found by astrometrical measurements (see Jet Propulsion Laboratory press release on May, 28, 2009), but there is a hope that future missions such James Webb Space Telescope (JWST), SIM, Gaia will provide excellent facilities to discover a large number of planetary systems with astrometrical measurements.

An important aspect of exoplanet searches is the opportunity to use different methods to verify conclusions about planetary system existence made with only one technique. For example, radial velocity measurements and transits or (and) astrometrical measurements may be complementary (see for instance, observations of extrasolar planet Gliese 876b with the Hubble Space Telescope and high precision radial velocity measurements).

Much more information about different methods to find exoplanets is given in [88, 92, 93, 94, 95].

4. 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 [8, 96, 97], one can detect extra peaks in the

[12] Recently, it has been claimed that more than one thousand exoplanets have been found with the Kepler space telescope.

[13] See web-site http://exoplanet.eu (developing by J. Schneider). At the moment more than 500 exoplanets have been discovered in total and about 400 exoplanets are called as suspected cases, however, there are no clear criteria to separate these two classes of exoplanets.

Table 3: Exoplanets discovered with microlensing [100, 101, 103].

Star Mass	Planet Mass	Semi-major Axis
$0.63^{+0.07}_{-0.09} M_{\odot}$	$830^{+250}_{-190} M_{\oplus}$	$4.3^{+2.5}_{-0.8}$ AU
$(0.46 \pm 0.04) M_{\odot}$	$(1100 \pm 100) M_{\oplus}$	(4.4 ± 1.8) AU
$0.22^{+0.21}_{-0.11} M_{\odot}$	$5.5^{+5.5}_{-2.7} M_{\oplus}$	$2.6^{+1.5}_{-0.6}$ AU
$0.49^{+0.14}_{-0.18} M_{\odot}$	$13^{+4.0}_{-5.0} M_{\oplus}$	$3.2^{+1.5}_{-1.0}$ AU
$(0.50 \pm 0.04) M_{\odot}$	$(226 \pm 25) M_{\oplus}$	(2.3 ± 0.2) AU
$(0.50 \pm 0.04) M_{\odot}$	$(86 \pm 10) M_{\oplus}$	(4.6 ± 0.5) AU
$0.060^{+0.028}_{-0.021} M_{\odot}$	$3.3^{+4.9}_{-1.6} M_{\oplus}$	$0.62^{+0.22}_{-0.16}$ AU
$0.30^{+0.19}_{-0.12} M_{\odot}$	$260.54^{+165.22}_{-104.85} M_{\oplus}$	$0.72^{+0.38}_{-0.16}$ AU
		or $6.5^{+3.2}_{-1.2}$ AU

microlensing light curve due to caustic crossing by the star source as a result of its proper motion.

As it was noted above, it was pointed out [85] that the probability to discover planetary systems by microlensing is rather high (see also [98, 99]). These conclusions were confirmed by further observations.

A list of exoplanets detected with microlensing searches toward the Galactic bulge is given in Table 3 [100, 101, 102, 103]. For the last planetary system two probable regions for the planet-to-star distance are given due to the planet and star-lens parameter degeneracy [100, 104]. Reports about these discoveries were described in [60, 100, 101, 103, 105, 106, 107, 108]. It is remarkable that the first exoplanet was discovered by the MOA-I collaboration with only a 0.6 m telescope [100, 105]. 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 may give a crucial contribution.

Until now five giant exoplanets and three super-Earth exoplanets (with masses about $10 M_{\oplus}$) have been discovered by microlensing (see Table 3), showing that this technique is very efficient in detecting Earth mass exoplanets at a few AU from their host star.

Among the most important exoplanet discoveries by microlensing [109] we mention 5.5 Earth mass planet (it was the lightest one for some time)[14] It means that the existence of cool rocky planets is a common phenomenon in the Universe [106, 110, 111].

Pixel-lensing towards M31 may provide an efficient tool to search for exoplanets in that galaxy [112, 113, 114]. An anomaly has been found in the POINT-AGAPE event PA-N2-99 [115] and indeed an exoplanet might be already discovered in the PA-N2-99 event [114].

A detailed discussion of the issue is far beyond the present article. However, 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 [48, 116]. As it is well known [117], the amplifications for a finite source and for a point-like source are different. 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 [114], for details).

5. Conclusions

Around a few dozen Earth exoplanets with masses in the range $1 - 10M_{\oplus}$[15] have been discovered using different techniques [87, 101, 106, 119]. One can see that a fraction of super-Earth exoplanets detected with microlensing technique is rather high in comparison with a fraction of all exoplanets. Searches for low mass exoplanets are connected with searches for life in the Universe. Positions of exoplanets in habitable zones [120] were studied with different techniques including dynamical analysis of multi-planetary systems [121]. Clearly, from this point of view the most interesting and exciting planetary systems have masses around the Earth mass and distances between planets and main sequence star have to be about AU. Gravitational microlensing is a very efficient method for discovering such planetary systems. In this context Microlensing Planet Finder (MPF) mission may be very fruitful and comparable with other space missions for exoplanet searches (see Fig. 2 in [102] and Fig. 1.9 in [100]).

For distant planetary systems discovered with microlensing, an usage of complementary methods may be rather difficult (at least at the moment) because they could not be sensitive for such planetary systems. However, a potential direct observations of star (for instance with a space telescope) in a planetary system [122] may be very useful to reduce uncertainties in determination of planetary system parameters.

[14] Recently the discovery of a very light planet with a mass about $m_p \sin i = 1.94M_{\oplus}$ [87] at the distance about 0.03 AU from the host star in the GJ 581 multiple planetary system was reported.

[15] Sometimes people call them super-Earths. Physical properties of these celestial objects is a subject of intensive studies [118].

Acknowledgements

AFZ is grateful to prof. B. Dragović for his kind attention to this contribution and the hospitality in Belgrade.

References

[1] I. Newton, Optics: or a Treatise of the Reflexions, Refractions, Inflexions and Colours of Light (Royal Society, London, 1704)

[2] J.G. Soldner, *Berliner Astron. Jahrbuch*, (1804) 161.

[3] A. Einstein, *Ann. der Phys.* **49** (1916) 769.

[4] F.W. Dyson, A. Eddington, C. Davidson, *Phil Trans. Roy. Soc. A,* **220** (1920) 291.

[5] O. Chwolson, *Astron. Nachrich.* **221** (1924) 329.

[6] A. Einstein, *Science* **84** (1936) 506.

[7] J. Renn, T. Sauer, J. Stachel, *Science* **275** (1997) 184.

[8] P. Schneider, J. Ehlers, E.E. Falco, *Gravitational Lenses* (Berlin, Springer, 1992).

[9] J. Wambsganss, *Gravitational Lenses in the Universe, Proc. of the 31st Liege International Astrophysical Colloquium (LIAC 93)*, Eds: J. Surdej, D. Fraipont-Caro, E. Gosset, S. Refsdal, and M. Remy, (Liege: Universite de Liege, Institut d'Astrophysique, 1993), p. 369.

[10] S. Refsdal, J. Surdej, *Rep. Prog. Phys. 56* (1994) 117.

[11] A.F. Zakharov, Gravitational Lenses and Microlenses (Moscow, Janus-K, 1997).

[12] J.-F. Claeskens, J. Surdej, *Astron. Astrophys. Rev.* **10** (2002) 263.

[13] E. Roulet & S. Mollerach, *Gravitational Lensing and Microlensing*, (World Scientific, Singapore, 2002).

[14] S. Frittelli, T.P. Kling, E. T. Newman, *PRD* **61** (2001) 064021.

[15] V. Bozza et al., *GRG* **33** (2001) 1535.

[16] K.S. Virbhadra, G.F.R. Ellis, *PRD* **65** (2002) 103004.

[17] K.S. Virbhadra, C. R. Keeton, *PRD* **77** (2008) 124014.

[18] K.S. Virbhadra, *PRD* **79** (2009) 083004.

[19] A.F. Zakharov, *New Astron. Rev.*, **53** (2009) 202.

[20] E. Zackrisson & T. Riehm, arXiv:0905.4075v2[astro-ph.CO].

[21] A.V. Byalko, *Sov. Astron.* **13** (1970) 784.

[22] L. Lindegren & M.A.C. Perryman, *A&A Suppl. Ser.* **116** (1996) 579.

[23] W. Cash, A. Shipley, S. Osterman, M. Joy, *Nature* **407** (2000) 160.

[24] N. White, *Nature* **407** (2000) 146.

[25] X.-P. Wu, *ApJ* **435** (1994) 66.

[26] B. Paczynski, *Ann. Rev. Astron. & Astrophys.* **34** (1996) 419.

[27] E. Roulet & S. Mollerach, *Phys. Rep.* **279** (1997) 2.

[28] A.F. Zakharov, M.V. Sazhin, *Physics – Uspekhi* **41** (1998) 945.

[29] S. Mao, arXiv:astro-ph:9909302v1.

[30] Ph. Jetzer, *Naturwissenschaften* **86** (1999) 201.

[31] A.F. Zakharov, *Publ. Astron. Obs. Belgrade* **75** (2003) 27.

[32] A.F. Zakharov, *Proc. 11th Lomonosov Conf. on Elementary Particle Physics "Particle Physics in Laboratory, Space and Universe"*, Ed. A.I. Studenikin, (World Scientific, Singapore, 2005), p. 106.

[33] S. Mao, arXiv:0811.0441v1[astro-ph]

[34] A.F. Zakharov, *Phys. Part. Nucl.* **39** (2008) 1176.

[35] F. Delplancke, K. Gorski, A. Richichi, *A&A* **375** (2001) 701.

[36] M.A.C. Perryman et al., *A&A* **369** (2001) 339.

[37] M. Perryman, J. de Bruijne, U. Lammers, *Exp. Astron.* **22** (2008) 143.

[38] A.F. Zakharov, *Astron. Reports* **50** (2006) 79.

[39] A.F. Zakharov, *Intern. J. Mod. Phys. D* **17** (2008) 1055.

[40] J.R. Gott, *ApJ* **243** (1981) 140.

[41] D. Walsh, R.F. Carswell, R.J. Weymann, *Nature* **279** (1979) 381.

[42] M.J. Irwin, R. L. Webster, P.C. Hewett et al., *AJ* **98** (1989) 1989.

[43] D. Sluse et al., *A&A* **468** (2007) 885

[44] D. Sluse et al., arXiv:0809.2983v1[astro-ph].

[45] I.M. Khamitov et al., *Astron. Lett.* **32** (2006) 514.

[46] C. Canizares, *ApJ* **268** (1982) 508.

[47] A. F. Zakharov, L.Č. Popović, P. Jovanović, *A&A*, **420** (2004) 881; A. F. Zakharov, L.Č. Popović, P. Jovanović, *Proc. of IAU Symposium, "Gravitational Lensing Impact on Cosmology"*, Eds.: Y. Mellier & G. Meylan, (Cambridge University Press, 2005), **225**, p. 363; A. F. Zakharov, L.Č. Popović, P. Jovanović, *Proc. of XXXIXth Rencontres de Moriond "Exploring The Universe"*, Ed.: Y. Giraud-Heraud and J. Tran Thanh Van and J. Dumarchez, (The GIOI Publishers, 2005), p. 41.

[48] L.Č. Popović et al., **ApJ 637** (2006) 620; P. Jovanović,A. F. Zakharov, L.Č. Popović, T. Petrović, *MNRAS* **386** (2008) 397.

[49] G. Chartas et al., *ApJ* **568** (2002) 509; G. Chartas et al., *ApJ* **606** (2004) 78; X. Dai et al., *ApJ* **589** (2003) 100; X. Dai et al., *ApJ* **605** (2004) 45.

[50] J. Oort, *Bull. Astron. Instit. Neth.* **6** (1932) 249; F. Zwicky, *Helvetica Physica Acta* **11** (1933) 110.

[51] P. Astier et al., *A&A* **447** (2006) 31.

[52] E. Komatsu et al., *ApJS* **180** (2009) 330.

[53] A.F. Zakharov et al., *Space Sc. Rev.* **148** (2009) 301.

[54] B. Paczynski, *ApJ* **304** (1986) 1.

[55] K. Griest, *ApJ* **366** (1991) 412.

[56] C. Alcock et al., *Nature* **365** (1993) 621.

[57] E. Aubourg et al., *Nature* **365** (1993) 623.

[58] M. Moniez, *Proc. of the XXXVth Rencontres de Moriond "Cosmological Physics with Gravitational Lensing"*, Ed.: J. Trân Thanh Vân, Y. Mellier & M. Moniez, (EDP Sciences, 2001), p. 3.

[59] A. Udalski et al., *Acta Astron.* **53** (2003) 291.

[60] A. Udalski et al., *ApJ* **628** (2005) L109.

[61] I.A. Bond et al., *MNRAS* **327** (2001) 868.

[62] A. P. S. Crotts, ApJ **399** (1992) L43.

[63] P. Baillon, A. Bouquet, Y. Giraud-Heraud, J. Kaplan, *A&A* **277** (1993) 1.

[64] R. Ansari et al., arXiv:astro-ph/9602015v1

[65] R. Ansari et al., *A&A* **324** (1997) 843.

[66] Y. Le Du, Proc. of the XXXVth Rencontres de Moriond "Cosmological Physics with Gravitational Lensing", Eds.: J. Trân Thanh Vân, Y. Mellier & M. Moniez, (EDP Sciences, 2001), p. 65.

[67] S. Calchi Novati et al., *A&A* **443** (2005) 911.

[68] S. Calchi Novati et al., *ApJ* **695** (2009) 442.

[69] F. De Paolis et al., *A&A* **432** (2005) 501. G. Ingrosso et al., *A&A* **445** (2006) 375. G. Ingrosso et al., *A&A* **462** (2007) 895. A. Riffeser, S. Seitz, R. Bender, *ApJ* **684** (2008) 1093.

[70] E. Kerins et al., *MNRAS* **323** (20010) 13.

[71] V. Belokurov et al., *MNRAS* **357** (2005) 17.

[72] E. Kerins et al., *MNRAS* **365** (2006) 1099.

[73] M. Dominik, A.C. Hirshfeld, *A & A* **289** (1993) L31.

[74] M. Dominik, A.C. Hirshfeld, *A & A* **313** (1995) 841.

[75] A.V. Gurevich, K. P. Zybin, V. A. Sirota, *Phys. Lett. A* **214** (1996) 232; A.V. Gurevich, K. P. Zybin, V. A. Sirota, *Physics – Uspekhi*, **40** (1996) 913; A. F. Zakharov, M. V. Sazhin M.V., *JETP Letters* **63** (1996) 937. A.F. Zakharov, M. V. Sazhin, *JETP* **83** (1996) 1057. A. F. Zakharov, *Phys. Lett. A* **250** (1998) 67. A. F. Zakharov, *Astron. Rep.* **43** (1999) 325. A.F. Zakharov, Proc. of the Intern. Conf. DARK-2000 "Dark Matter in Astro- and Particle Physics", Ed.: H.V. Klapdor-Kleingrothaus, (Springer, 2001), p. 364. A.F. Zakharov, *Proc. of the XXXVth Rencontres de Moriond "Cosmological Physics with Gravitational Lensing"*, Ed.: J. Trân Thanh Vân, Y. Mellier & M. Moniez, (EDP Sciences, 2001), p. 57.

[76] J. H. An et al., *ApJ* **572** (2002) 521.

[77] D. P. Bennett et al., *ApJ* bf 579 (2002) 639.

[78] S. Poindexter et al., *ApJ* **633** (2005) 914.

[79] C. Alcock et al., *ApJ* **541** (2000) 734.

[80] C. Alcock et al., *ApJ* **542** (2000) 281.

[81] T. Lasserre et al., *A&A* **355** (2000) L39. T. Lasserre, *Proc. of the Intern. Conf. DARK-2000, "Dark Matter in Astro- and Particle Physics"*, Ed.: H.V. Klapdor-Kleingrothaus, (Springer, 2000), p. 341.

[82] P. Tisserand et al., *A&A* **469** (2007) 387.

[83] L. Wyrzykowski et al. arXiv:0905.2044v1[astro-ph.EP].

[84] E. Kerins, *Proc. of the XXXVth Rencontres de Moriond "Cosmological Physics with Gravitational Lensing"*, Ed.: J. Trân Thanh Vân, Y. Mellier & M. Moniez, (EDP Sciences, 2001), p. 43

[85] S. Mao, B. Paczynski, *ApJ* **374** (1991) L37.

[86] A. Wolszczan, D. Frail, *Nature* **355** (1992) 145.

[87] M. Mayor et al. arXiv:0906.2780v1[astro-ph.EP].

[88] M. Perryman et al., *Report by the ESA–ESO Working group on Extra-Solar Planets*, at the web-site http://www.stecf.org/coordination/eso-esa/extrasolar/report.pdf; arXiv:astro-ph/0506163

[89] M. Konacki et al., *Nature* **421** (2003) 508.

[90] A. Leger et al., *A & A* **506** (2009) 287.

[91] D. Queloz et al. *A & A* **506** (2009) 303.

[92] M. Perryman, *Rep. Prog. Phys.* **63** (2000) 1209.

[93] S. Udry & N.C. Santos, *Annu. Rev. Astron. Astrophys.* **45** (2007) 397.

[94] N.C. Santos, *New Astron. Rev.* **52** (2008) 154.

[95] J.A. Johnson, *PASP* **121** (2009) 309.

[96] A.F. Zakharov, *A&A* **293** (1995) 1.

[97] A.F. Zakharov, *Ap& SS* **252** (1997) 369.

[98] A. Gould, A. Loeb, *ApJ* **396** (1992) 104.

[99] A.D. Bolatto, E. E. Falco, *ApJ* **436** (1994) 112.

[100] D.P. Bennett, arXiv:0902.1761v1[astro-ph.EP].

[101] D.P. Bennett et al., *ApJ* **684** (2008) 663.

[102] D.P. Bennett et al., *A Census of Exoplanets in Orbits Beyond 0.5 AU via Space-based Microlensing*, White Paper for the Astro2010 Science Frontier Panel, 2008.

[103] S. Dong et al., *ApJ* **698** (2009) 1826.

[104] M. Dominik, *A & A* **349** (1999) 108.

[105] I.A. Bond et al. *ApJL* **606** (2004) L155.

[106] J.-P. Beaulieu et al., *Nature* **644** (2006) L37.

[107] A. Gould et al., *ApJ* **644** (2006) L37.

[108] B.S. Gaudi et al., *Science* **319** (2008) 927.

[109] F. Abe et al., *Science* **305** (2004) 1264

[110] M. Dominik, *MNRAS* **367** (2006) L31.

[111] M. Dominik, K. Horne, M.F. Bode, *Astron. & Geophys.* **367** (2006) 3.25.

[112] S.-J. Chung et al., *ApJ* **650** (2006) 432.

[113] D. Kim et al., *ApJ* **666** (2007) 236.

[114] G. Ingrosso et al., *MNRAS* **399** (2009) 219; G. Ingrosso et al. *General Relativity and Gravitation,* 10.1007/s10714-010-0942-3; arXiv:1001.4342v1 [astro-ph.SR]; G. Ingrosso et al. in the proceedings of the "Twelfth Marcel Grosmann Meeting", held in Paris (France), 12-18, July, 2009; arXiv:1001.2105v1 [astro-ph.CO].

[115] J. H. An J.H. et al., *ApJ* **601** (2004) 845.

[116] E. Agol & J. Krolik, *ApJ* **524** (1999) 49.

[117] H.J. Witt & S. Mao, *ApJ* **430** (1994) 505; M.B. Bogdanov & A.M. Cherepashchuk, *Astron. Lett.* **21** (1995) 505; M.B. Bogdanov & A.M. Cherepashchuk, *Astron. Rep.* **39** (1995) 779; M.B. Bogdanov & A.M. Cherepashchuk, *Astron. Rep.* **44** (2000) 745; M.B. Bogdanov & A.M. Cherepashchuk, *Astron. Rep.* **46** (2002) 996; B.S. Gaudi & A. Gould, *ApJ* **513** (1999) 619; M. Dominik, *MNRAS* **361** (2005) 300; D. Heyrovsky, *ApJ* **656** (2007) 483; O. Pejcha & D. Heyrovsky, *ApJ* **690** (2009) 1772.

[118] D. Valencia, D.D Sasselov, R. J. O'Connell, *ApJ* **665** (2007) 1413; F. Selsis et al., *A & A* **476** (2007) 1373; D.D. Sasselov, *Nature* **451** (2008) 29; D.D. Sasselov, D. Valencia, & R.J. O'Connell, *Physica Scripta* **T130** (2008) 014035.

[119] E. Rivera et al., *ApJ* **634** (2005) 625; C. Lovis et al., *Nature* **441** (2006) 305; S. Udry et al., *A & A* **469** (2007) L43; G.M. Marcy et al., *Physica Scripta* **T130** (2008) 014001; M. Mayor & S. Udry, *Physica Scripta* **T130** (2008) 014010; M. Mayor et al., *A&A* **493** (2009) 639; F. Bouchy et al., *A & A* **496** (2009) 527; A. Howard et al., *ApJ* **696** (2009) 75.

[120] J.F. Kasting et al., *Icarus* **101** (1993) 108; B.W. Jones et al., *ApJ* **622** (2005) 1091; H. Lammer et al., Astron. Astrophys. Rev. **17** (2009) 181.

[121] J.-H. Ji et al., *ApJ* **585** (2003) L139; J.-H. Ji et al., *ApJ* **631** (2005) 1191; J.-H. Ji et al., *ApJ* **657** (2007) 1092; J.-H. Ji et al., *Res. Astron. Astrophys.* **9** (2009) 703; D. Fisher et al., *ApJ* **675** (2008) 790; E. Pilat-Lohinger, *Intern. Journal of Astrobiology* **8** (2009) 175; E. Pilat-Lohinger et al., *ApJ*, **681** (2008) 1639; D.S. McNeil & R.P. Nelson, arXiv:0910.5299v1[astro-ph.EP]; J.T. Wright arXiv:0909.0957v1[astro-ph.EP]; J.T. Wright et al., *ApJ* **693** (2009) 1084.

[122] D.P. Bennett et al., *ApJL* **647** (2006) L171.