by two independent methods (optical and radio methods), the CS deficit angle should lie in the range between $0.1''$ and $5-6''$. When a CS is detectable by optical methods, the characteristic 'spot' size on the anisotropy map should be no less than 100°.

The fields of the HST (4.5 square degrees in all) were studied in the search for gravitationally lensed pairs formed by straight long CSs. Four candidates for CS-induced gravitational lenses were discovered; however, the accuracy accessible to researchers is not high enough to unambiguously elucidate the nature of these candidates.

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Search for exoplanets using gravitational microlensing

A F Zakharov

1. Gravitational lensing: introduction

There are different regimes of gravitational lensing depending on the mass of the gravitational lens. Assuming that both the lens and the source are located at cosmological distances, different regimes correspond to different angular distances between images. The case of a stellar-mass gravitational lens is referred to as gravitational microlensing. The angular distance between images in this case is proportional to the square root of the lens mass, so the lensing of a planet with a mass a few times smaller than Earth's ($10^{-6} M_\odot$, where $M_\odot$ is the solar mass) is called nanolensing.

Thus, searches for sufficiently light exoplanets using gravitational lensing can be dubbed gravitational nanolensing. Different methods of searches for exoplanets are known, including the Doppler shift of spectral lines, transits, and pulsar timing. In this paper, we show that gravitational microlensing is one of the most promising methods of searching for Earth-like exoplanets (with masses of order $M_\oplus$) located at distances of several astronomical units (AU) from a star, and there is hope that exoplanets with a solid surface temperature in the range $1-100\,^\circ$C (i.e., with the temperature of liquid water) can be discovered.

A detailed discussion of gravitational lensing can be found in monograph [1] (see also review [2]). Nevertheless, we shall remind the reader of the basic facts and report on new results in this field.

Gravitational lensing is based on the gravitational light bending effect. It can be visualized as if a gravitating body attracts photons. Gravitational light bending was first discussed by Sir Isaac Newton [3]. Such a bending appears to be the natural conclusion from the corpuscular theory of light advocated by Newton. A derivation of the light deflection angle in Newtonian gravity was first published by the German astronomer Johann Georg von Soldner [4].

In General Relativity (GR), the light deflection angle in the gravitational field was obtained by Albert Einstein [8]:

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

where M is the mass of the gravitating body, p is the impact parameter, c is the speed of light in vacuum, and G is the Newtonian constant of gravitation. If $M = M_\odot$ and $p = R_\odot$ (where $R_\odot$ is the solar radius), the respective light deflection angle is $1.75''$. In 1919, this prediction was confirmed by

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measuring the displacements in coordinates of stars near the solar limb during the total solar eclipse of May 29. The observations were carried out in Príncipe island (near South Africa) and in the village of Sobral in northeast Brazil [6]. During several subsequent decades, nevertheless, observers checked the predictions of GR and sometimes came to the conclusion that these predictions were in disagreement with experiment (for example, the measurements of the star displacements carried out by E Freundlich in Sumatra Island during the total solar eclipse in 1929). Nevertheless, by the middle of the 1950s it was concluded that observations of light bending in the gravitational field generally corresponded to theoretical predictions [7].

Using formula (1), one can derive the gravitational lens equation:

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

where D_s, D_d, and D_{ds} are the respective distances between the source and the observer, the lens and the observer, and the source and the lens. Vectors $\boldsymbol{\eta}$ and $\boldsymbol{\xi}$ determine the coordinates in the source and the lens planes, respectively:

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

If the source, lens, and observer are located along one straight line, the right side of Eqn (2) must vanish ($\boldsymbol{\eta} = 0$), and then, by substituting $\boldsymbol{\Theta}$ from Eqn (3) into Eqn (2), we obtain the so-called Einstein–Chwolson radius [1] [11]

$$\xi_0 = \sqrt{\frac{4GMD_d D_{ds}}{c^2 D_s}} \tag{4}$$

and, correspondingly, the Einstein–Chwolson angle determined by the relation $\theta_0 = \xi_0/D_d$. If $D_s \gg D_d$, then

$$\theta_0 \approx 2'' \times 10^{-3} \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{D_0}{D_d}\right)^{-1/2}, \tag{5}$$

where $D_0 = 1$ kpc.

1.1 Gravitational lensing regimes

There are many reviews and monographs devoted to gravitational lensing and microlensing [1, 11–15]. Recently, gravitational lensing in the strong gravity limit has been considered [16–22].

In the simplest case of a point-like gravitational lens (the Schwarzschild lens), the angular distances between images are on the order of the Einstein–Chwolson diameter $2\theta_0$, which is proportional to the square root of the lens mass (for fixed values of other parameters). At cosmological distances between objects and the typical mass $10^{12} M_\odot$ of the lensing galaxy, the angular distance between images is on the order of a few arcseconds; this is the standard gravitational macrolensing regime. For stellar-mass ($\sim M_\odot$) gravitational lenses at cosmological distances between the source, lens, and the image, the characteristic distance between the images is on the order of 10^{-6} arcseconds; this is the gravitational microlensing regime. If the mass of the gravitational lens is around the mass of Earth ($10^{-6} M_\odot$), the characteristic angular separation between the images is about 10^{-9} arcseconds (the gravitational nanolensing regime) (Table 1) (see Refs [12, 23, 24]). In fact, 10^{-9} arcseconds is a very small angle: for example, it corresponds to a coin 2.5 cm in diameter seen from a distance of 4.5×10^9 km (or about 30 AU, which is approximately the distance from the Sun to Neptune).

Table 1. Gravitational lensing regimes [12].

Regime	Deflection angle, arc s	Mass, $m/M_\odot$	Lens
Kilolensing	10^3	10^{18}	Supercluster
Macrolensing	10^0	10^{12}	Galaxy
Millilensing	10^{-3}	10^6	Black hole
Microlensing	10^{-6}	10^0	Star
Nanolensing	10^{-9}	10^{-6}	Planet (Earth-like)
Picolensing	10^{-12}	10^{-12}	?
Femtolensing	10^{-15}	10^{-18}	Comet

At present, micro- and nanoarcsecond angular resolutions are unreachable; however, the photometrical signatures of gravitational micro- and nanolensing can be obtained from the monitoring of background sources, as was proposed in Ref. [25]. Nevertheless, there are projects aimed at reaching an angular resolution of a few microarcseconds (in different spectral ranges), such as the NASA's Space Interferometry Mission (SIM) project, the ESA's Global Astrometric Interferometer for Astrophysics (GAIA) mission [26], the NASA's MicroArcsecond X-ray Imaging Mission (MAXIM) [27, 28] [2], and the Russian Radioastron mission. The nanosecond angular resolution in the millimeter wave band is planned to be achieved in the Millimetron space mission [3].

If the gravitational lens is a solar-mass ($M = M_\odot$) star in our Galaxy at a distance of 1 kpc, then $\theta_0 \approx 2'' \times 10^{-3}$. If the lens is an Earth-like ($M = 10^{-6} M_\odot$) planet located at the same distance from the observer, $\theta_0 \approx (2 \times 10^{-6})''$.

According to the terminology introduced above, if the lens mass is $M \sim M_\oplus$ ($M \sim 10^{-6} M_\odot$), the regime is called microlensing (nanolensing), irrespective of the characteristic distances. For example, one can talk of nanolensing when searching for planets by their contribution to the gravitational lensing.

The phenomenon of gravitational lensing can lead to the appearance of multiple images [1, 11]. For a point-like lens (the Schwarzschild lens), two images or a ring appear. The total solid angle of two images is larger than the solid angle of the source. The ratio of the sum of solid angles of both images to that of the source, which is called the amplification coefficient A of a gravitational lens, is just the result of gravitational focusing.

2. Gravitational microlensing

Gravitational microlensing has been intensively discussed in the literature [2, 15, 29–37]. If the source S lies on the Einstein–Chwolson cone, the amplification coefficient is $A = 1.34$. The corresponding characteristic time T_0 of microlensing is usually determined as the half-time it takes

[1] Chwolson [8] described the arising of ring-like images, and Einstein presented the basic equations for the gravitational focusing in the case of a point-like gravitational lens [9], now referred to in the literature as the Schwarzschild lens. It was realized later that Einstein had considered the phenomenon of gravitational focusing in unpublished notes [10] in 1912.

[2] Projects SIM and MAXIM will not likely be realized.

[3] See http://www.asc.rssi.ru.

for the lens to cross the Einstein–Chwolson cone:

$$T_0 = 3.5 \text{ months} \sqrt{\frac{M}{M_\odot} \frac{D_\mathrm{d}}{10 \text{ kpc}}} \frac{300 \text{ km s}^{-1}}{V_\perp},$$

where $V_\perp$ is the transverse velocity component of the lens. For $V_\perp \sim 300$ km s^{-1} (which is the characteristic velocity of stars in the Galaxy), the characteristic crossing time of the Einstein–Chwolson cone is about 3.5 months. Thus, the light curve of a background star changes on this time scale.

Some characteristic values of the parameters describing gravitational microlensing are as follows. For a distance between the lens and the Sun of about 10 kpc, the characteristic Einstein–Chwolson cone angle is about $0.001''$, which corresponds to linear distances of about 10 AU. Clearly, it is difficult to resolve such a small angular distance between the images by ground-based telescopes, at least in the optical range.

Einstein noted in due time that the phenomenon of gravitational lensing is difficult to discover in nature if the gravitational lens is a star, since the angle between the images is very small [4] [9]. Nonetheless, in the last few years the possibility of measuring the Einstein–Chwolson diameter $2\theta_0$ by resolving multiple images produced in microlensing has been discussed. In order to resolve multiple images, it was proposed to use an optical interferometer, for example, the VLTI (Very Large Telescope Interferometer) [38]. Moreover, in the astrometric space mission GAIA [5] to be launched in the near future, an angular resolution on the order of 10 microarcseconds can be achieved. In principle, this would allow one to resolve multiple images of sources arising due to microlensing. Astrometric microlensing in future astrometric missions was considered in papers [41, 42].

The phenomenon of microlensing in distant gravitationally lensed quasars was analyzed in paper [43], which was published shortly after the discovery of the first gravitational lensing system [44]. Due to a high optical depth (probability), this phenomenon was first disclosed in paper [45]. Later on, signatures of microlensing in different spectral ranges were found in various gravitational lens systems [46, 47], in particular, in SBS 1520 + 530 in the optical spectrum, from observations carried out with the RTT-150 telescope [48]. The optical depth for microlensing of distant quasars was discussed in papers [49–52]. The influence of microlensing on light curves in different spectral ranges was analyzed in papers [53, 54]. The modeling of light curves (including X-ray light curves) was carried out after the discovery of X-ray microlensing for some gravitational lens systems [55–58] with the NASA's Chandra X-ray Observatory. Its telescope has an angular resolution of approximately 0.5 arcseconds, which enables, in principle, individual macro images in gravitational lens systems to be resolved.

The gravitational microlensing of a star by another star produces a symmetric and achromatic light curve, which is the main signature of the phenomenon. This statement holds true if the lens is spherically symmetric and the source is point-like. However, if the source is not point-like and the color is distributed across the stellar disk and (or) the gravitational field of the lens is not exactly spherically symmetric, then the light curve can be asymmetric and (or) chromatic [1].

The searches for microlensing events are closely related to the question of dark matter (DM). It has been known for a long time that only a small part of gravitating matter is visible [59, 60]. Presently, the matter density (in units of the critical density) is known to be $\Omega_\mathrm{m} \approx 0.3$ (including the baryonic matter density $\Omega_\mathrm{b} \approx 0.05 - 0.04$; however, the luminous matter density is $\Omega_\mathrm{lum} \leqslant 0.005$), and the density corresponding to the Λ-term is on the order of $\Omega_\Lambda = 0.7$ [61–64]. Thus, only a small part of the total matter density in the Universe is in the form of the baryonic matter density (to say nothing of the luminous matter). It is assumed often that galactic halos are quite 'natural' regions in which both baryonic and non-baryonic dark matter can reside. If DM formed objects with masses in the range of $(10^{-5} - 10)\,M_\odot$, microlensing could help detect them. Clearly, using microlensing, it is possible to discover dim low-mass stars and massive planets. Therefore, prior to the beginning of intensive microlensing observations in our and nearby galaxies, there was hope to shed light on the nature of dark matter in the halo of our Galaxy.

As noted above, the possibility of discovering microlensing phenomenon was discussed in paper [25]. Systematic searches for microlensing events using the characteristic features of the light curves of individual stars started after B Paczynski's discussion of the possibility of detecting compact dark objects of planetary or stellar masses in the Galactic halo by monitoring several million stars in the Large Magellanic Cloud (LMC) [65]. At the beginning of the 1990s, new calculation facilities and a huge amount of observational data appeared, which helped in relatively rapidly realizing Paczynski's ideas (the situation was significantly different when Byalko's paper [25] was published). It was proposed that such objects be referred to as 'machos' (after Massive Astrophysical Compact Halo Objects) [66]. What is more, MACHO is the name of the American–Australian–British collaboration which monitored stars in the LMC and the galactic bulge using the 1.3-meter telescope at the Mount Stromlo Observatory on Mount Stromlo in Australia. [6] To search for microlensing events, several million stars were monitored in the direction of two sky targets: (a) stars in the LMC and the Small Magellanic Cloud (SMC), since the LMC and SMC are nearby galaxies in the direction outside of the galactic plane, passing through the galactic halo, and (b) stars in the Galactic bulge, which allows one to estimate the distribution of microlenses in the direction close to the Galactic plane. The first microlensing events were reported in the direction toward the LMC by the MACHO collaboration [67] and by the EROS (Expérience pour la Recherche d'Objets Sombres) [7] French collaboration [69].

The first discovery of microlensing events towards the Galactic bulge was reported by the American–Polish OGLE (Optical Gravitational Lensing Experiment) collaboration, which employs the 1.3-meter telescope of the Las Campanas Observatory, Chile. In 2001, the third phase of the OGLE-III experiment started; in this experiment, 200 mln stars have been observed every 1–3 nights. During several recent years, the OGLE-III collaboration has discovered several hundred microlensing events each year [70, 71]. The OGLE-III phase was completed [8] in May 2009. The Early Warning System (EWS) helped to discover many microlensing events (Table 2).

[4] Nevertheless, microlensing can be discovered from observations of the variable light curves of background stars, as was proposed by Byalko [25].
[5] http://astro.setec.esa.nl/gaia, see also [26, 39, 40].
[6] The MACHO project was completed at the end of 1999.
[7] The EROS project was completed in 2003 [68].
[8] http://www.astrouw.edu.pl/ogle/ogle3/ews/ews.html.

Table 2. Microlensing events discovered in the OGLE-III experiment.

Year of observations	Number of events
2002	around 350
2003	around 450
2004	around 600
2005	around 550
2006	around 600
2007	around 600
2008	around 650

To search for microlensing events, astronomers in Japan and New Zealand formed the MOA (Microlensing Observations in Astrophysics) collaboration [9] [72].

To study the distribution of machos in a direction other than toward the LMC or SMC, the Andromeda Nebula (M31 galaxy) located at a distance of 778 kpc from the Sun can be used. This is a nearby galaxy in Earth's northern hemisphere [73–76]. In the 1990s, two collaborations, AGAPE (Andromeda Gravitational Amplification Pixel Experiment, Pic du Midi Observatory, France) [10] and VATT (Vatican Advanced Technology Telescope), started the monitoring of pixels, and not of individual stars [68, 80], since during observations of the Andromeda galaxy, many stars fall inside one pixel. At the present time, several dozen pixel lensing events have been reported [81, 82]. Monte Carlo simulations are necessary to theoretically interpret these observations [83–86].

As early as 15 years ago, it was clear that the microlensing phenomenon had really been discovered [30]. Nevertheless, it is difficult to precisely determine how many truly microlensing events were identified, since new types of stellar variability can have a similar observational appearance. [11] The most important results of the microlensing observations and their theoretical interpretation can be summarized as follows.

The observed light curves, which are related to microlensing candidate events, can be interpreted well by sufficiently simple theoretical models; however, this interpretation is sometimes questionable. For example, even for the MACHO No. 1 event different fits by a single microlens were reported, but significant deviations between the theoretical curve and experimental data near the light curve maximum were seen. Still, a binary microlens model yields a much better fit which fully agrees with observations [87, 88]. The fit by a noncompact microlens model was also proposed [89–97].

For the EROS BLG-2000-5 event, the PLANET (Probing Lensing Anomalies NETwork) collaboration determined the component masses of a binary microlens, $0.35\,M_{\odot}$ and $0.262\,M_{\odot}$, and the distance to the lens, 2.6 kpc from the Sun [98].

Some extended microlensing events were connected with stellar-mass black holes [99]. For example, the initial mass estimates for the MACHO-96-BLG-5 and MACHO-96-BLG-6 events were reported to be $M/M_{\odot} = 6^{+10}_{-3}$ and $M/M_{\odot} = 6^{+7}_{-3}$, respectively, i.e., the mass exceeded the Oppenheimer–Volkoff limit, suggesting microlensing by black holes. Later estimates showed that the MACHO-99-BLG-22, MACHO-96-BLG-5, and MACHO-96-BLG-6 events can be associated with black holes with a probability falling down from 78% to 37%, and to 2%, respectively [100].

The optical depth in the direction of the Galactic bulge (on the order of 3×10^{-6}) turned out to be somewhat larger than the initial estimates [101], which additionally supports the existence of a bar-like structure.

The MACHO collaboration analyzed the data obtained during 5.7 years of photometry of 11.9 mln stars in the LMC and discovered 13–17 microlensing event candidates [102] (the number of candidates depends on the selection rule applied). The optical depth toward the LMC obtained from the observations, $\tau(2 < \hat{t} < 400\,\text{days}) = 1.2^{+0.4}_{-0.3} \times 10^{-7}$ (here $\hat{t}$ is the microlensing event duration), turned out to be smaller than a theoretical estimate based on the assumption that the halo dark mass falls within macho-like objects. Based on the MACHO collaboration observations, the most likely fraction of machos in the halo mass is $f = 0.2$. The following probability estimates were also reported: $P(0.08 < f < 0.5) = 0.95$, and $P(f = 1) < 0.05$. The most likely estimate of the mass of a macho is $M = (0.15 - 0.9)\,M_{\odot}$, and the halo mass within the sphere of radius 50 kpc must be about $9^{+4}_{-3} \times 10^{10}\,M_{\odot}$.

The EROS collaboration reported the probability estimate $P(M \in [10^{-7}, 1]\,M_{\odot},\ f > 0.4) < 0.05$ [103, 104] and the estimate of the optical depth toward the LMC, $\tau < 0.36 \times 10^{-7}$ (at a 95% C.L.), which means that the macho mass fraction in the total halo mass is no higher than 7% [105].

On the other hand, the OGLE collaboration estimated the macho mass fraction in the halo mass as $(8 \pm 6)\%$ [106]. Essentially, this means the lack of macho detection if their abundance in the galactic halo is at the level of 19% for $M = 0.4\,M_{\odot}$, and 10% for the mass range $(0.01 - 0.2)\,M_{\odot}$ [106]. However, these conclusions are based on an assumption about the form of the mass and space distributions of microlenses, which are poorly known. In principle, the gravitational microlensing studies can be used to improve the parameters of these distributions, provided that several thousand microlensing events are available.

Thus, the following general conclusion can be made. A very important physical phenomenon, gravitational microlensing, was discovered, but some of its quantitative characteristics must be improved. Therefore, the question of the nature of about 80% (or even 93%, according to the EROS collaboration) of the galactic halo dark matter persists (before the microlensing observations, there was a hope to significantly advance in solving the dark matter question). So, the situation is quite adequately reflected by the title of Kerins's report [107], "Machos and clouds of uncertainty." This means that there is a wide field for future research, including pixel lensing and microlensing of gravitationally lensed systems, with the most interesting and important being searches for exoplanets using microlensing.

3. Methods of searching for exoplanets

Nearly 20 years ago, Mao and Paczynski [108] estimated the probability of finding exoplanets using the microlensing phenomenon, and noted that this probability is highest in the direction toward the Galactic bulge. In spite of the fact that the first exoplanet was discovered around the millisecond pulsar PSR 1257 + 12 [109], this prediction by Mao and

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

[10] The POINT-AGAPE (POINT — after Pixel-lensing Observation with the Isaac Newton Telescope (INT)) collaboration started observations in 1999 using INT with a 2.5-m mirror [77, 78]; the robotic telescope MIT Angstrom Project was also proposed [79].

[11] Some events, first reported to be microlensing candidates by the EROS-1, EROS-2, MACHO-2, and MACHO-3 collaborations, were later interpreted in terms of stellar variability [30].

Paczynski proved to be essentially correct, and presently microlensing is recognized as an effective method of searching for exoplanets.

The most effective method of discovering exoplanets is based on radial velocity measurements using the HARPS (High Accuracy Radial velocity Planet Searcher) spectrograph. This spectrograph is mounted on the 3.6-m telescope of the European Southern Observatory at La Silla (Chile). The typical measurement error is ~ 1 m s^{-1}, more precisely, varying within the range of 0.7–2 m s^{-1}, depending on the observational conditions [110]. Radial velocity estimates are listed in Table 1 of review [111]. Using this method, more than 300 exoplanets have been found to date.

About 100 exoplanets have been discovered taking advantage of the transit method. Some transits (observed both by ground-based and space telescopes [12]) are described in paper [112] (see also Table 2 in review [111]). The launch of the Kepler space telescope increases significantly the efficiency of the transit method for discovering exoplanets. Let us recall that the Kepler telescope has a mirror diameter which is more than three times larger than that of the COROT (COnvection ROtation and planetary Transits) space telescope, and the field of view more than 100 times larger than that of COROT. The COROT group discovered interesting planetary systems, such as the COROT-7b planet with a radius of about two Earth radii [113]. The follow-up observations of this system with the HARPS spectrograph detected two exoplanets with near-Earth masses: $(4.8\pm 0.8)\,M_{\oplus}$ (COROT-7b), and $(8.4\pm 0.9)\,M_{\oplus}$ (COROT-7c) [114].

According to the database collected by Jean Schneider (CNRS–LUTH, Paris Observatory),[13] by now more than 500 exoplanets and about 400 exoplanet candidates have been discovered; nevertheless, there are no reliable criteria to distinguish between them. Several planetary systems have been discovered by pulsar timing.

One exoplanet was found by astrometric measurements (see, for example, the Jet Propulsion Laboratory press release of May 28, 2009,[14] and there is hope that new planetary systems will be discovered by this method in the forthcoming space missions, such as the James Webb Space Telescope (JWST) and GAIA.

It is important that there is a possibility of using different exoplanet search methods to be certain that the assertion about the existence of planets made with the aid of a single search method is valid. The radial velocity method and transits and (or) astrometric measurements can be complementary to each other (for example, the radial velocities of Gliese 876b were measured and the exoplanet was observed by the HST). For more details see Refs [111, 115–118].

4. Searches for exoplanets using gravitational microlensing

As the presence of a planet near the star-lens breaks the symmetry of the lens system, fold caustics [11, 119, 120] arise, resulting in the appearance of the characteristic deviations in the light curve of the star-lens from the case without a planet. These features are used to discover exoplanets by gravitational microlensing. Thus, it is necessary first to find a microlensing event, and then to measure the characteristic deviation in the observed light curve. It should be noted that monitoring of a large number of stars is needed to detect microlensing events, while observations of the light curves of the background stars with microlensing signatures are required for discovering exoplanets. The latter can be done using relatively small telescopes with a small field of vision. In this case, it is very important to have an early alert monitoring system for microlensing event candidates, similar to that organized by the OGLE collaboration.

Table 3. Exoplanets discovered by the microlensing [123–126].

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

As noted in Section 3, Mao and Paczynski [108] stressed that the probability of discovering exoplanets using microlensing is sufficiently high (see also papers [121, 122]). These conclusions are supported by available observations.

Exoplanets discovered by microlensing observations in the direction of the Galactic bulge are listed in Table 3 [123–127]. For the planetary system in the last row of this table, two possible distance intervals between the planet and star-lens are given [123, 128]. Discoveries of exoplanets were discussed in papers [71, 123, 124, 126, 129–132]. It should be noted that the first exoplanet was discovered by the MOA-I collaboration, which used a small 0.6-m telescope [123, 129]. This microlensing event was discovered by the OGLE collaboration, but the MOA-I group had a CCD (charge-coupling device) with a larger field of view and made five exposures per field of view. This fact clearly shows that important results can be obtained by even modest observational facilities used in the right way.

Eight exoplanets were discovered by microlensing, including three Earth-group exoplanets with masses $10M_{\oplus}$ (which are also called super-Earth exoplanets). Table 3 illustrates that this technique is very effective in detecting Earth-group exoplanets located at a distance of 1 AU from the star-lens.

The detection of an exoplanet with the mass of about $5.5\,M_{\oplus}$ [133] is one of the most important discoveries. It was the lightest exoplanet in 2006. [15] Essentially, this means that Earth-group planets with a solid surface have a sufficiently wide spread in the Universe [130, 134, 135].

Pixel microlensing in the direction of the Andromeda galaxy (M31) can be an effective means of discovering exoplanets in other galaxies [136–141]. In this case, the emission from several thousand stars falls within one pixel,

[12] Recently, the Kepler space mission reported the discovery of about 1000 exoplanets.

[13] http://www.exoplanet.eu.

[14] http://www.jpl.nasa.gov/news/news.cfm?release = 2009-090.

[15] Later on, the discovery of a light exoplanet with $m_{\rm p}\sin i = 1.94\,M_{\oplus}$ at a distance of order 0.03 AU in the Gliese 581 b system (GJ 581 b), which has several exoplanets, was reported [110].

and then only the lensing of giant stars can result in detectable radiation flux variations in one pixel. Giant stars can have radii on the order of 1 AU (the distance from Earth to the Sun); therefore, the probability estimates of the potentially detectable deviation of the light curve of a star-lens with an exoplanet from the case without exoplanets should be made using Monte Carlo simulations of the pixel lensing [138, 139].

Since the discovery of an exoplanet using pixel lensing is naturally divided into two stages (namely, searches for pixel lensing events and detection of the exoplanet signatures in these events), an early alert online system seems to be required for research groups involved in the Andromeda galaxy monitoring, as was done by the OGLE collaboration for microlensing searches in the Galactic bulge. This system would allow even small telescopes with a narrow field of view to be used in monitoring the pixel lensing candidates and, possibly, to discover deviations from the light curve, signaling the presence of an exoplanet in the lens system.

The PA-N2-99 event observed by the POINT-AGAPE collaboration [142] showed an anomaly which is most likely due to the presence of a panet system in the lens [138–140]. This suggests that the first extragalactic exoplanet has been found. For example, in Wikipedia's article about the Andromeda galaxy, one can read that an exoplanet was discovered around a star in this galaxy, with a reference to paper [138]. As mentioned above, stellar sources for pixel lensing are red giants (we recall that the lensing of only giants leads to detectable effects, since there are many thousands of stars in one pixel). Therefore, their size is comparable to the Einstein–Chwolson radius and the size of caustics, and the finite size of the sources should be taken into account, as in searches for quasar microlensing events [53, 143]. It is well known [144–152] that the amplification of a point-like source is different from the analogous parameter of a finite-size source. If the source diameter is small, the probability of discovering the signatures of a binary lens (or a planet near the star) is proportional to the size of the region near the caustic. Nevertheless, giant stars considered as background sources have larger angular sizes, so the probability that some part of the source is close to the caustic increases (see papers [138–140] for more detail).

5. Conclusions

Several dozen super-Earth exoplanets [16] with masses in the range (1–10) $M_{\oplus}$ have been discovered by different means [110, 124, 130, 157–164]. It is easy to see that the fraction of Earth-mass exoplanets detected by gravitational microlensing is rather high in comparison with exoplanets found by other methods. Searches for low-mass exoplanets are related to searches for life in the Universe. The locations of exoplanets near the habitation zone [165–167] are being studied in detail using different methods, including the dynamical analysis of multiplanet systems [168–177]. Clearly, Earth-mass planetary systems with distances of about 1 AU between the stars and such planets are the most intriguing from this point of view. Gravitational microlensing is a very effective method of searching for such exoplanets. In this context, the MPF (Microlensing Planet Finder) American project can be much more effective than other dedicated space missions for exoplanet searches (see Fig. 2 in paper [125], and Fig. 1.9 in paper [123]).

For distant planetary systems discovered by microlensing (or pixel lensing), using other additional methods is rather difficult (at least at present), since these methods are not sensitive enough for such systems. Nevertheless, direct observations of a planet, for example, by a space telescope [178], can be useful in reducing uncertainty in the estimates of the parameters of the planetary system. An interesting possibility for directly observing Earth-like exoplanets can be realized using a space telescope and a stellar screen that significantly decreases the emission flux from the star possessing an exoplanet. Such a possibility is being discussed in the New Worlds Observer project [179–181]. It is assumed that the screen and telescope will be located in the vicinity of the Lagrangian L_2 point. The telescope has a diameter of about 4 m, the size of the screen is of order 50 m, and the distance between the screen and the telescope is on the order of 80,000 km. Such an approach was earlier discussed in the literature; however, the technical feasibility of detecting low-mass exoplanets by a screen several dozen meters in diameter was noticed quite recently [182]. Thus, at the present time the principal technology for direct detection of low-mass exoplanets is available.

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