GRAVITATIONAL MICROLENSING AND DARK MATTER IN OUR GALAXY: 10 YEARS LATER

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Astro Space Centre of Lebedev Physics Institute, Moscow, Russia Abstract. Foundations of standard theory of microlensing are described, namely we consider microlensing stars in Galactic bulge, the Magellanic Clouds or other nearby galaxies. We suppose that gravitational microlenses lie between an Earth observer and these stars. Criteria of an identification of microlensing events are discussed. We also consider such microlensing events which do not satisfy these criteria (non-symmetrical light curves, chromatic effects, polarization effects). We describe results of MACHO collaboration observations towards the Large Magellanic Cloud (LMC) and the Galactic bulge. Results of EROS observations towards the LMC and OGLE observations towards the Galactic bulge are also presented. Future microlensing searches are discussed.

A standard microlens model is based on a simple approximation of a point mass for a gravitational microlens. Gravitational lensing (gravitational focusing) results from the effect of light bending by a gravitating body (the phenomenon was discussed by I. Newton, but in the framework of Newtonian gravity a formal derivation of the light bending angle was published by J. Soldner [1]).

In the framework of general relativity (GR) using a weak gravitational field approximation the correct bending angle is described by the following expression derived by Einstein in 1915 just after his formulation of GR

$$\delta\varphi = -\frac{4GM_*}{c^2p}.\tag{1}$$

The derivation of the famous Einstein's formulae for the bending angle of light rays in gravitational field of a point mass M_* is practically in all monographs and textbooks on general relativity and gravity theory (see, for example books [2,3]).

The law was firstly confirmed by Sir A. Eddington for observations of light ray bend by the Solar gravitational field near its surface. The angle is equal to 1.75", therefore Einstein prediction was confirmed by observations very soon after its discovery.

The gravitational lens effect is a formation of several images instead of one (see details in [4,5]). We have two images for a point lens model (Schwarzschild lens model). The total square of the two images is larger than a source square. The ratio of these two squares is called gravitational lens amplification A. That is a reason to call gravitational lensing as gravitational focusing. The angular distance between two images is about angular size of so-called Einstein's cone.

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The angular size of Einstein's cone is proportional to the lens mass divided by the distance between a lens and an observer. Therefore, if we consider a gravitational lens with typical galactic mass and a typical galactic distance between a gravitational lens and an observer then the angular distance between images will be about few angular seconds; if we suppose that a gravitational lens has a solar mass and a distance between the lens and an observer is about several kiloparsecs then an angular distance between images will be about angular millisecond.

If a separation angle is ~ 1", then one may observe two images in optical band although this problem is a complex one, but one cannot observe directly two images by Earth's observer in the optical band if a separation angle is ~ 0.001". Therefore, the microlensing effect is observed on changing of a luminosity of a source S^{b} .

If the source S lies on the boundary of the Einstein cone, then we have A = 1.34. Note, that the total time of crossing the Einstein cone is T_0 . Sometimes the microlensing time is defined as a half of T_0 we suppose that $D_d < D_{ds}$ (here we assume that D_{ds} is the distance from the source S to the lens D; D_d is the distance from the lens D to the observer O; D_s is the distance from the source S to the observer O)

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

where v is the perpendicular component of a velocity of a dark body. If we suppose that the perpendicular component of a velocity of a dark body is equal to $\sim 300 \text{ km/s}$ (that is a typical stellar velocity in Galaxy), then a typical time of crossing Einstein cone is about 3.5 months. Thus, a luminosity of a source S is changed with the time.

We will give numerical estimations for parameters of the microlensing effect. If the distance between a dark body and the Sun is equal to ~ 10 kpc, then the angular size of Einstein cone of the dark body with a solar mass is equal to ~ 0.001" or the linear size of Einstein cone is equal to about 10 astronomical units. It is clear that since typical distances between two images are about Einstein diameters therefore is very difficult to resolve the images by ground based telescopes at least in an optical band. It was a reason that both Einstein and Chwolson thought if gravitational lenses and sources are stars then separation angle is very small to be detectable. However, recently, a direct method to measure Einstein angle ϕ_E was proposed to resolve double images generated by microlensing with an optical interferometer (say VLTI) [6](see also [7] for a

 $^{^{}b}$ Since the angle is very small Einstein and Chwolson thought that gravitational lens effect could not be detectable if sources and lenses are stars. Now there are chances to measure such angles in IR band therefore there is a giant development of observational facilities.

discussion). Moreover, it is plan to launch astrometrical space probe, American SIM^c and European GAIA^d, these instruments will have precisions about 10 micro arc seconds and could determine Einstein radii for any microlensing events.

Astrometric microlensing or motions of visible images due to influence of a gravitational field of microlenses was analyzed in number of papers [8–19], although light bending in gravitational field was discussed by I. Newton (actually that is the same effect but authors presented detailed analysis and pushed new ideas to use the phenomenon to detect even invisible astronomical objects by shifts of images for background sources). An optical depth of microlensing for distant quasars was discussed for different locations of microlenses (see, for example, [20] and references therein.

For observations of extragalactic gravitational lens a typical time for changes of light curve is very long ($\sim 10^5$ years) for its direct observations. Therefore, extragalactic gravitational lenses are discovered and observed by resolving different optical components (images) since typical angular distances between images are about some angular seconds because of a great mass of a gravitational lens. If a gravitational lens is a galaxy cluster then the angular distances between images may be about several minutes. For an identification of gravitational lenses, observers compare typical features and spectra of different images. It is clear that one cannot to resolve different components during microlensing but it is possible to get and analyze a light curve in different spectral bands.

One of the basic criterion for microlensing event identification is the symmetry of a light curve. If we consider a spherically symmetric gravitational field of a lens, a point source and a short duration of microlensing event then the statement about the symmetry of a light curve will be a strong mathematical conclusion, but if we consider a more complicated distribution of a gravitational field lens or an extensive light source then some deviations of symmetric light curves may be observed and (or) the microlensing effect may be chromatic [4,5].

More than 70 years ago it was found that densities of visible matter is about 10% of total density in galactic halos (the invisible is called as dark matter (DM) [21,22])^e Thus baryonic density is a small fraction of total density of the Universe. Probably galactic halos is "natural" places to store not only baryonic DM, but non-baryonic DM also. 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.

For the first time a possibility to discover microlensing using observations of

^chttp://sim.jpl.nasa.gov/whatis/

 $^{^{}d}$ http://astro.estec.esa.nl/GAIA

^eNow it is 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 $\Omega_{\text{lum}} \approx 0.001$), Λ -term density $\Omega_{\Lambda} = 0.7$.

star light curves was discussed in the paper by Byalko in 1969 [23]. 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) [24]. We remark that in the beginning of the nineties new computer and technical possibilities providing the storage and processing of huge volume of observational data were appeared and it promoted at the rapid realization of Paczynski's proposal. Griest suggested to call the microlenses as Machos (Massive Astrophysical Compact Halo Objects) [25]. Besides, MACHO is the name of the project of observations of the US-English-Australian collaboration which observed the LMC and Galactic bulge using 1.3 m telescope of Mount Stromlo observatory in Australia.^f

The first papers about the microlensing discovery were published by the MACHO collaboration [26] and the French collaboration EROS (Expérience de Recherche d'Objets Sombres) [27]^g

First papers about the microlensing discovery toward Galactic bulge were published by US-Polish collaboration (Optical Gravitational Lens Experiment), 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 as a result the collaboration observes more than 200 millions stars observed regularly once every 1-3 nights. Last two years OGLE III detected more than four hundreds microlensing event candidates each year [29].^h

MOA (Microlensing Observations in Astrophysics) is collaboration involving astronomers from Japan and New Zealand [30, 31]^{*i*}

To investigate Macho distribution in another direction one could use searches toward M31 (Andromeda) Galaxy lying at 725 kpc (it is the closest galaxy for an observer in the Northern hemisphere). In nineties two collaborations AGAPE (Andromeda Gravitational Amplification Pixel Experiment, Pic du Midi, France)^{*j*} and VATT started to monitor pixels instead of individual stars [28,33]. These teams reported about discoveries of several microlensing event candidates.

The event corresponding to microlensing may be characterized by the following main features, which allow to distinguish the microlensing event and a stellar variability [4,34,35].

• Since the microlensing events have a very small probability, the events

^fMACHO stopped since end 1999.

^gEROS experiment stopped in 2002 [28].

 $^{^{}h}$ http://www.astrouw.edu.pl/ ogle/ogle3/ews/ews/html

 $^{^{}i} \rm http://www/roe.ac.uk/\%7Eiab/alert/alert/html$

 $^{^{}j}\mathrm{New}$ collaboration, POINT-AGAPE started in 1999 and uses INT (2.5 v Isaac Newton Telescope) [54].

should never repeat for the same star. The stellar variability is connected usually with periodic (or quasi-periodic) events of the fixed star.

- In the framework of a simple model of microlensing when a point source is considered, the microlensing effect must be achromatic (deviations from achromaticity for non-point source were considered, for example in the paper by Bogdanov & Cherepashchuk [36]), but the proper change of luminosity star is connected usually with the temperature changes and thus the light curve depends on a colour.
- The light curves of microlensing events are symmetric, but the light curves of variable stars are usually asymmetric (often they demonstrate the rapid growth before the peak and the slow decrease after the peak of a luminosity).
- Observations of microlensing events are interpreted quite well by the simple theoretical model, but some microlensing events are interpreted by more complicated model in which one can take into account that a source (or a microlens) is a binary system, a source has non-vanishing size, the parallax effect may take place.

The typical features of the light curve of the first microlensing event observed by the MACHO collaboration in the LMC are shown in Fig. 1, where the light curves are shown for two spectral bands (a more recent MACHO fit to the observed amplification of this event gives $A_{\text{max}} = 7.2$). The light curve (in two bands) is fitted by the simple model well enough, but the ratio of luminosities for the bands is shown in the lower panel of figure (the ratio shape is adjusted with the event achromaticity). However, one can note that near the maximal observable luminosity the theoretical curve fits the data of observations not very well.

Now one can carry out accurate testing the achromaticity and moreover the stability of the source spectrum during a microlensing event with the Early Warning systems implemented both by the MACHO and OGLE collaborations. This allows one to study the source properties using large telescopes and to organize intense follow-up studies of light curves using telescope network around the globe.

In addition to the typical properties of individual microlensing events, Roulet and Mollerach note that the population of observed events should have the following statistical properties [4,34].

• Unlike a star variability microlensing events should happen with the same probability for any kind of star therefore the distribution of microlensing



Figure 1: The first microlensing event which was detected by the MACHO collaboration during microlensing searches towards LMC [26].

- The distribution of the maximal amplification factor A_{max} should correspond to a uniform distribution of the variable $u_{\text{min}} = 1/b$ (b is the dimensionless impact parameter).
- The distributions of the amplification A_{\max} and the microlensing event time T should be uncorrelated.

Since for the microlens searches one can monitor several million stars for several years, 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

^kHowever, Roulet and Mollerach noted that for observations in the bulge since observed stars have non-negligible spread along the line of sight, the optical depth is significantly larger for the star lying behind the bulge, thus the lensing probabilities should increase for the fainter stars [34].

the halo; b) stars in the Galactic bulge which allow to test the distribution of lenses near to the Galactic plane.^l

Let us cite well established results of microlensing searches and discuss the questions for which we have now different answers which do not contradict to the observational data. Now it is generally recognized that the microlensing searches towards the Galactic bulge or nearby galaxies are very important for solutions of a lot of problems in astronomy and cosmology. As Paczynski noted, the most important is the consensus that the microlensing phenomenon has been discovered [37]. Now it is impossible to tell which part of the microlensing event candidates is actually connected with the effect since probably there are some variable stars among the event candidates, it could be stellar variability of an unknown kind.^m

- Observed light curves are achromatic and their shapes are interpreted by simple theoretical expressions very well, however, there is not complete consent about "very well interpretation" since even for the event candidate MACHO # 1 the authors of the discovery proposed two fits. Dominik and Hirshfeld suggested that the event could be fitted perfectly in the framework of the binary lens model [38, 39], but Gurevich et al. assumed that the microlensing event candidate could be caused by a noncompact microlens [40].ⁿ
- 2. As expected, binary lenses have been detected and the observed rate of the events correspond to expected value.
- 3. As expected, the parallax effect has been detected.
- 4. Since the observed optical depth is essentially greater than the estimated value, the independent confirmation of the Galactic bar existence was done.
- 5. Using photometric observations of the caustic-crossing binary lens microlensing event EROS BLG-2000-5, PLANET collaboration reported about 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 of the Sun [47].
- 6. Bennett et al. discovered gravitational microlensing events due to stellar mass black holes [48]. 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.

 $^{^{}l}$ In this paper we do not discuss microlensing for distant quasars.

^{*m*}The microlensing event candidates proposed early by the EROS collaboration (#1 and #2) and by the MACHO collaboration (#2 and #3) are considered now as the evidence of a stellar variability [37].

ⁿMicrolensing by non-compact objects considered also in papers [41–46].

Now the following results are generally accepted:

- 1. The optical depth towards the Galactic bulge is equal to $\sim 3 \times 10^{-6}$, so it is larger than the estimated value [49].
- 2. Analysis of 5.7 years of photometry on 11.9 million stars in LMC by MA-CHO collaboration reveals 13 – 17 microlensing events [50] (recent results of the MACHO collaboration on could find in [51]). 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 estimated value. The maximum likelihood analysis gives a MACHO halo fraction f=0.2. Alcock et al. (2000b) gives also estimates of the following probabilities P(0.08 < f < 0.5) = 0.95 and P(f = 1) < 0.05. The most likely MACHO mass $M \in [0.15, 0.9] M_{\odot}$, 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 $P(M \in [10^{-7}, 1] M_{\odot} \& f > 0.4) < 0.05 [52, 53]$. However, these conclusions are based on assumptions about mass and spacial distributions of microlenses but generally speaking these distributions are still unknown.

However there are different suggestions (which are not contradicted to the observational data) about the following issues [37]:

What is the location of objects which dominate microlensing observed towards the Galactic bulge?

Where are the most microlenses for searches towards LMC? The microlenses may be in the Galactic disk, Galactic halo, the LMC halo or in the LMC itself. Are the microlenses stellar mass objects or are they substellar brown dwarfs?

What fraction of microlensing events is caused by binary lenses?

What fraction of microlensing events is connected with binary sources?

Paczynski suggested that we shall have definite answers for some presented issues after some years and since the optical depth towards the Galactic bulge is essentially greater than the optical depth towards the LMC, we shall have more information about the lens distribution towards the Galactic bulge, however, probably, some problems in theoretical interpretation will appear after detections of new microlensing event candidates [37].

The main result of the microlensing searches is that the effect predicted theoretically has been confirmed. This is one of the most important astronomical discoveries.

When new observational data would be collected and the processing methods would be perfected, probably some microlensing event candidates lost their status, but perhaps new microlensing event candidates would be extracted among analyzed observational data. So, the general conclusion may be done. The very important astronomical phenomenon was discovered, but some quantitative parameters of microlensing will be specified in future. However, the problem about 80% of DM in the halo of our Galaxy is still open (10 years ago people believe that microlensing could give an answer for this problem). Thus, describing the present status Kerins wrote adequately that now we have "Machos and clouds of uncertainty" [54].

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