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Gravitational Microlensing

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GRAVITATIONAL MICROLENSING ¹

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Gravitational lensing - i.e. light deflection by gravity - has become an important tool for exploring our Universe, in particular to determine its matter content. There are cases in which the deflection angles are tiny, of the order of milliarcseconds or smaller, such that the multiple images are not observable. However, lensing magnifies the affected source, and since the lens and the source are moving relative to each other, this can be detected as a time-variable brightness. This behaviour is referred to as gravitational microlensing, a very powerful method to search for dark matter in the halo of our own Galaxy, if it consists of massive astrophysical compact halo objects (MACHOs), and to study the content of low-mass stars in the galactic disk. Since the discovery of the first microlensing events in September 1993 by monitoring millions of stars in the Large Magellanic Cloud (LMC) and in the direction of the galactic centre, more than 200 events have been found. Preliminary analysis of the events towards the LMC indicate that the halo dark matter fraction in the form of MACHOs is of the order of 50%, assuming a standard spherical halo model. This article provides an overview of gravitational microlensing and of the main results achieved so far. Indeed, gravitational microlensing research has expanded very rapidly in the last few years, and many new applications have been suggested, including the detection of Earth like planets around stars in our Galaxy.

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1 Introduction

An important problem for contemporary astrophysics and cosmology is the determination of the amount and the nature of matter present in the Universe. This knowledge is directly related to the question of the fate of the Universe: will it expand forever or, after a phase of expansion, collapse again. There are several astrophysical observations which indicate that most of the matter present in the Universe is actually dark and, therefore, cannot be detected using telescopes or radiotelescopes. The most recent studies seem to suggest that the total matter density is only about 30% of the “closure density” of the Universe: the amount of mass that would make the Universe balance between expanding forever and collapsing. Measurements based on high-redshift supernovae suggest that there is also a non-vanishing cosmological constant, such that the sum of matter density and cosmological constant implies a flat Universe [1].

Important evidence for the existence of large quantities of dark matter comes from the measured rotation curves of several hundreds of spiral galaxies [2], which imply the presence of a huge dark halo in which these galaxies are embedded. Typically, a galaxy including its halo contains ~ 10 times more dark than luminous matter, the latter being in the form of stars and gas.

There are also clear indications for the presence of important quantities of dark matter on larger scales, in particular in clusters of galaxies. This was first pointed out in 1933 by the Swiss astrophysicist Fritz Zwicky [3]. Since then, much effort has been put into the search for dark matter, the nature of which is still largely unknown. It may be, at least partly, in the form of normal baryons (protons and neutrons) or consist of new types of weakly interacting particles, found with the large particle accelerators on Earth. Dark matter seems also to be needed in order to understand the formation of galaxies and the large scale-structures in the Universe.

This review, however, will restrict itself to a discussion of the dark matter in galactic halos and, more specifically, in the halo of our Galaxy. There is clear evidence that the halo of our Galaxy is similar to the other known spiral galaxies and contains a huge amount of dark matter. An important fraction of dark matter present in our halo is possibly made of ordinary baryons clumped into compact objects like low-mass stars or brown dwarfs with typical masses of the order of $\sim 0.1 M_{\odot}$ (solar masses). Such objects would be too faint to be observed with telescopes. Instead, they can be detected indirectly due to the light deflection they induce on the light coming from more distant stars which lie roughly on the line of sight. This phenomenon is referred to in the literature as gravitational microlensing.

2 Mass of the Milky Way

The best evidence for dark matter in galaxies comes from the observed rotation curves in spiral galaxies. Measurements of the rotation velocity v_{rot} of stars up to the visible edge of the spiral galaxies (of about 10 kpc) and of atomic hydrogen gas in the disk beyond the optical radius (by measuring the Doppler shift in the characteristic 21-cm radio line emitted by neutral hydrogen gas) imply that v_{rot} remains constant out to very large distances, rather than showing a Keplerian fall-off, as expected if there is no more matter beyond the visible edge. These observations started around 1970 [4], thanks to the improved sensitivity in both optical and 21-cm radio bands. Now there are observations for over a thousand spiral galaxies with reliable rotation curves out to large radii. In almost all of them, the rotation curve is flat or slowly rising out to the last measured point, implying, therefore, the presence of huge amounts of dark matter.

There are also measurements of the rotation velocity for our own Galaxy. However, these observations turn out to be rather difficult, and the rotation curve has been measured accurately only up to a distance of about 20 kpc. Without any doubt, our own Galaxy has a typical flat rotation curve and thus it is possible to search directly for dark matter characteristic of spiral galaxies in the Milky Way.

To infer the total mass of the Milky Way, one can also study the proper motion of the Magellanic Clouds and of other satellite dwarf galaxies of our Galaxy. From these proper motion observations, it follows that within 100 kpc, the Galactic halo has a mass $\sim 5.5 \pm 1 \times 10^{11} M_{\odot}$ and a substantial fraction ($\sim 50\%$) of this mass is distributed beyond the present distance of the Magellanic Clouds of about 50 kpc [5]. Beyond 100 kpc, the mass may continue to increase to $\sim 10^{12} M_{\odot}$ within its tidal radius of about 300 kpc. However, the uncertainties are still substantial, and the different values for the total mass content of our Galaxy have to be treated with caution. For comparison, the total mass of the luminous disk of our Galaxy is estimated to be $6 \times 10^{10} M_{\odot}$.

3 Candidates for dark matter

The question which naturally arises is what is the nature of dark matter in galactic halos? It possibly consists of hitherto undetected types of stable particles, which do not interact via strong or electromagnetic forces, for example, axions or supersymmetric particles like neutralinos. The latter are predicted in the framework of supersymmetric extensions of unified theories

for the interactions between the elementary particles. There are important efforts underway to search for such new particles using existing and planned particle accelerators. Nevertheless, as yet, nothing has been found. Such particles are expected to move slowly and are thus referred to in the literature as cold dark matter. Cold dark matter will not be discussed in more detail, but recent studies seem to point to a discrepancy between the calculated (through N-body simulations) rotation curves for dwarf galaxies assuming a halo of cold dark matter and those observed [6, 7, 8]. If confirmed, cold dark matter would be excluded as a major constituent of the halo of dwarf galaxies and possibly also of spiral galaxies.

A more viable possibility is that the dark matter is comprised of baryons. In the framework of the big bang model for cosmology, one can understand the formation of the light elements, such as hydrogen, helium and lithium. From the observed abundances of the primordial light elements, it is in turn possible to estimate the total amount of baryonic matter in the Universe. Current observations of the light elements indicate that the baryons can make up at most about 10% of the “closure density”. It is clear that this amount of baryonic matter is larger than would be inferred by taking into account only the luminous matter (which makes up about 1% of the “closure density”) and, therefore, it follows that primordial nucleosynthesis entails that an important fraction of the baryonic matter in the Universe is non-luminous, and such an amount of dark matter falls surprisingly close to that required by the rotation curves of spiral galaxies.

The next question concerns the form taken by the non-luminous baryons. Some possibilities can either be almost excluded or are severely constrained by present observations. Hot ionized hydrogen gas cannot contribute substantially to the halo dark matter, otherwise there would be a large X-ray flux - detectable by present X-ray satellites - for which there are stringent upper limits which imply that at most about 4-5% of the total dark matter is in such a form [9].

From the measurement of the emission in the 21-cm radioband, it is possible to detect and to determine the abundance of neutral hydrogen gas. Its contribution to the total mass of the halo is extremely small (less than 1%).

A further possibility is that the hydrogen gas is in molecular form, clumped into very cold clouds, as we proposed recently [10, 11]. Indeed, the observation of such clouds is very difficult and, therefore, at present there are no limits on their contribution to the halo dark matter. On the contrary, several indirect observations even suggest that an important fraction of dark matter is in this form. In particular, energetic cosmic ray protons, which are produced in the galactic centre and in the disk, diffuse into the halo and scatter

on the protons in the clouds. This process induces the production of energetic gamma-rays which can be detected with satellites, like the Compton Gamma Ray Observatory (GRO). Recently, a team of the EGRET instrument on board the GRO analysed carefully the observed diffuse gamma-rays and found evidence that some of them are most probably produced in the halo [12]. Remarkably enough, the observed flux is in good agreement with the one predicted [10, 11] by assuming that an important fraction of the halo dark matter is in the form of cold molecular hydrogen clouds. Of course, this detection and its interpretation have to be confirmed, possibly by a new generation of more powerful gamma-ray satellites.

Baryons could otherwise have been processed into compact objects, often referred to in the literature as massive astrophysical compact halo objects (MACHOs), such as stellar remnants (for a detailed discussion see ref. [13]). If their mass is below $\sim 0.08 M_{\odot}$, they are too light to ignite hydrogen-burning reactions. The possible origin of such brown dwarfs or Jupiter-like bodies, by fragmentation or some other mechanism, is at present not well understood [10, 11].

Otherwise, MACHOs might be either low-mass ($\sim 0.1 - 0.3 M_{\odot}$) hydrogen burning stars (also called M-dwarfs) or white dwarfs. As a matter of fact, a deeper analysis makes the M-dwarf option look problematic. The null result of several searches for low-mass stars both in the disk and in the halo of our Galaxy suggests that the halo cannot be mostly in the form of hydrogen-burning main-sequence M-dwarfs. Optical imaging of high-latitude fields taken with the Wide Field Planetary Camera of the Hubble Space Telescope indicates that less than $\sim 6\%$ of the halo can be in this form [14]. However, this result is derived under the assumption of a smooth spatial distribution of M-dwarfs, and the problem becomes considerably less severe in the case of a clumpy distribution [15]. Recent observations of four nearby spiral galaxies carried out with the satellite Infrared Space Observatory (ISO) seem also to exclude M-dwarfs as significantly contributing to halo dark matter [16].

A scenario with white dwarfs as a major constituent of the galactic halo dark matter has been explored [17]. However, it requires a rather ad hoc initial mass function sharply peaked around $2 - 6 M_{\odot}$. Future Hubble deep-field exposures could either find the white dwarfs or put constraints on their fraction in the halo [18]. A substantial component of neutron stars and black holes with masses higher than $\sim 1 M_{\odot}$ is also excluded, for otherwise they would lead to an overproduction of heavy elements relative to the observed abundances. Given these facts, the most promising candidate for MACHOs are brown dwarfs.

4 Gravitational microlensing

The idea that light rays could be deflected by gravity was considered by Newton and Laplace among others (for a historical account, see for instance the book by Schneider et al. [19]). However, the correct description of the phenomenon is possible only in the framework of the general theory of relativity formulated in its final version in 1915 by Einstein. Einstein himself proposed studying the gravitational deflection of light rays from stars due to the Sun in order to verify his theory. Indeed, the first observation of the light deflection was made in 1919, when the apparent angular shift of stars close to the limb of the Sun was measured during a total solar eclipse. The results confirmed clearly the angular value for the light deflection as predicted by general relativity [20], which is twice as much as one would expect using “naive” Newtonian mechanics. The latter leads to a deflection angle at the solar limb of $0.''84$.

In 1936, following calculations done in 1911 [21], Einstein published a paper on the deflection induced by a star on the light rays emitted by a more distant star [22]. He came to the conclusion that the chance for such a phenomenon to occur, due to the requirement for a very accurate alignment between the stars, was totally negligible and thus that his calculations would not have any practical consequences. The recent developments of microlensing show that Einstein’s conclusion, although understandable at that time, was too pessimistic. Indeed, the formulae developed by Einstein in his 1936 paper are still the basis for the description of gravitational lensing.

In 1937, Zwicky [23] pointed out that the chance that distant galaxies act as gravitational lenses is much higher than for stars, and he provided a list of possible applications, which remains valid even today. Gravitational lensing was then first found in 1979 when two very close quasars were clearly identified as being the lensed images of a single object. Since this first discovery, the field of gravitational lensing has grown dramatically and today is one of the most important and promising fields of modern astrophysics.

The effect of double imaging of a distant source by a point mass located close to the line of sight, and acting as a gravitational lens, has been proposed many times. In 1979, Chang and Refsdal [24], and in 1981, Gott [25] noted that even though a point mass in a halo of a distant galaxy would create an unresolvable double image of a background quasar, the time variation of the combined brightness of the two images could be observed. In this way, the effect of non-luminous matter in the form of MACHOs could be observed. The term *microlensing* was proposed by Paczyński [26] to describe gravitational lensing which can be detected by measuring the intensity variation of a macro-image made up of any number of unresolved micro-images.

The idea to use gravitational light deflection to detect MACHOs in the halo of our Galaxy by monitoring the light variability of millions of stars in the Large Magellanic Cloud (LMC) was first proposed by Paczyński in 1986 [27] and then further developed – from a theoretical point of view – in a series of papers by De Rújula, Jetzer and Massó [28, 29], Griest [30] and Nemiroff [31]. Since these first studies, the field has grown very rapidly, especially since the discovery of the first microlensing events at the end of 1993.

Much research activity is also devoted to studying microlensing in the context of quasar lensing. Today, several cases of quasars are known which are lensed by foreground galaxies, producing multiple observable images. The stars contained in the lensing galaxy can act as microlenses on the quasar and as a result induce time-dependent changes in the quasar brightness, but in a rather complicated way, since here the magnification is a coherent effect of many stars at the same time. This is an interesting field of research, which could also lead to important results on the problem of the dark matter in galaxies [32]. This article, however, will not discuss such *extragalactic* microlensing but will be restricted to *galactic* microlensing.

The following will present the main features of microlensing, in particular the probability and the rate with which it occurs (for reviews see also ref. [33, 34, 35]). An important issue is determining from the observations the mass of the MACHOs that acted as gravitational lenses as well as the fraction of halo dark matter that they comprise.

4.1 Microlensing probability

When a MACHO of mass M is sufficiently close to the line of sight between us and a more distant star, the light from the source star suffers a gravitational deflection. As a consequence, we see two images of the source (Fig. 1). For a cosmological situation, where the lens is a galaxy or even a cluster of galaxies and the source is a very distant quasar, one indeed sees two or more images which are typically separated by an angle of some arcseconds. However, in the situation being considered here, namely of a MACHO of typically $\sim 0.1 M_{\odot}$ and a source star located in the LMC at about 50 kpc from us, the separation angle turns out to be of the order of some milliarcseconds. Thus, the images cannot be seen separately. However, the measured brightness of the source star varies with time. It increases until the MACHO gets to the shortest distance from the line of sight between the observer on Earth and the source star. Afterwards, the brightness decreases and eventually returns to its usual unlensed value. The magnification of the original star brightness turns out to be typically of the order of 30% or even more, corresponding to an increase of at least 0.3 magnitudes of the source star (see Figs. 2, 3).

Such an increase is easily observable.

An important quantity is the optical depth τ due to gravitational microlensing, which is the probability that a source is found within a circle of radius $r \leq R_E$ around a MACHO. If the lens and the source can be considered as pointlike, then R_E is given by the following equation

$$R_E = \left(\frac{4GM}{c^2} \frac{D_{ds}D_d}{D_s} \right)^{1/2} \quad (1)$$

where G is Newton's constant, c the speed of light, M the mass of the lens and the distances D_{ds} , D_d and D_s as defined in Fig. 1. R_E is called the Einstein radius. In the extreme case where the source and the lens are perfectly aligned, the images are no longer two points but rather a full circle, whose radius (measured in the plane going through the lens and perpendicular to the line of sight) is equal to the Einstein radius. If the source gets closer to a MACHO than R_E (as measured in the lens plane), then its magnitude increases by a factor $A \geq 1.34$ (equality is obtained for $r = R_E$).

Assuming a spherical halo made entirely of MACHOs, one finds an optical depth towards the LMC of $\tau = 5 \times 10^{-7}$. This means that at any one moment out of 2 million stars, one is being lensed. From this number it can be seen that in order to obtain a reasonable number of microlensing events, an experiment has to monitor several million stars in the LMC or in other targets such as the galactic centre region (referred also as the galactic bulge).

The magnification of the brightness of a star by a MACHO is a time-dependent effect, since the MACHO, which acts as the lens, changes its location relative to the line of sight to the source as it moves along its orbit around the galaxy. Typically, the velocity transverse to the line of sight for a MACHO in the galactic halo is $v_T \approx 200$ km/s, which can be inferred from the measured rotation curve of our Galaxy. Clearly, the duration of the microlensing phenomenon and thus of the brightness increase of the source star depends on the MACHO mass, its distance and transverse velocity (see Table 1).

Since the light deflection does not depend on the frequency of the light, the change in luminosity of the source star will be achromatic. For this reason, the observations are done in different wavelengths in order to check that. Moreover, the light curve will be symmetric with respect to the maximum value, since the transverse velocity of the MACHO is in excellent approximation constant during the period in which the lensing occurs. The probability that a given star is lensed twice is practically zero. Therefore, the achromaticity, symmetry and uniqueness of the signal are distinctive features that allow a microlensing event to be discriminated from background events such

as variable stars (some of which are periodic, others show chromaticity and most often the light curve is not symmetric).

4.2 Microlensing rate towards the LMC

Another important quantity is the microlensing rate, which depends on the mass and velocity distributions of MACHOs. To determine this one has to model the Galaxy and its halo. For simplicity one usually assumes a spherically symmetric shape for the halo with matter density decreasing as $1/r^2$ with distance, to obtain naturally a flat rotation curve. The velocity distribution is assumed to be Maxwellian. The least known quantity is the mass distribution of the MACHOs. For that, one makes the simplifying assumption that all MACHOs have the same mass. The number N_{ev} of microlensing events (such that the increase in magnitude is at least 30%) can then be computed. Table 1 shows some values for N_{ev} assuming monitoring of a million stars for 1 year in the LMC.

Table 1 The expected number of events N_{ev} is obtained for a halo made entirely of MACHOs of a given mass.

MACHO mass ($M_\odot$)	Mean R_E (km)	Mean microlensing duration	N_{ev}
10^{-1}	0.3×10^9	1 month	4.5
10^{-2}	10^8	9 days	15
10^{-4}	10^7	1 day	165
10^{-6}	10^6	2 h	1662

5 Present status of microlensing research

Microlensing allows the detection of MACHOs located in the galactic halo in the mass range $10^{-7} < M/M_\odot < 1$ [29], as well as MACHOs in the disk or bulge of our Galaxy [36, 37]. Since the first proposal in 1986 [27], microlensing searches have turned very quickly into reality and in less than a decade they have become an important tool for astrophysical investigations. Microlensing is also very promising for the search of planets around other stars in our Galaxy and generates large databases for variable stars, a field which has already benefited a lot. Due to the increasing observations and to that new experiments are becoming operative, the number of microlensing events is growing rapidly - almost daily - and, therefore, the following presentation will not be exhaustive. Moreover, most of the following results should be considered as preliminary. Within a few more years, the amount of data

will be such that several open problems will be solved or at least substantial progress will be achieved.

5.1 Microlensing towards the Magellanic Clouds

In September 1993, the French collaboration EROS (Expérience de Recherche d'Objets Sombres) [38] announced the discovery of two microlensing candidates, and the American–Australian collaboration MACHO (for the collaboration they use the same acronym as for the compact objects) of one candidate [39] by monitoring several millions of stars in the LMC (Fig. 4).

The MACHO team went on to report the observation of eight events (one being a binary lensing event; see Fig. 5) by analysing their first 2 years of data monitoring about 8.5 million stars in the LMC [40]. The inferred optical depth is $\tau = 2.1_{-0.7}^{+1.1} \times 10^{-7}$ when considering six events ² (or $\tau = 2.9_{-0.9}^{+1.4} \times 10^{-7}$ when considering all the eight detected events). Correspondingly, this implies that about 45% (or 50%) of the halo dark matter is in the form of MACHOs and they find an average mass of $0.46_{-0.17}^{+0.30} M_{\odot}$ assuming a standard spherical halo model. Notice that when using a method based on mass moments, a somewhat lower average value for the mass is obtained, namely $0.27 M_{\odot}$ (based on six events) [41]. Since the true shape of the halo is not known, one could also consider a flattened halo or one with anisotropy in velocity space [42], in which case the resulting value for the average mass would decrease significantly. Moreover, it might well be that not all the MACHOs are in the halo: some could be stars in the LMC itself or located in an extended disk of our Galaxy, in which case an average mass value including all events would produce an incorrect value. These considerations show that at present, the value for the average mass has to be treated with care.

In the meantime, other events towards the LMC have been detected by the MACHO group, and placed on their list of alert events. The MACHO group has implemented an on-line data reduction system so that microlensing events can be “caught in the act” and “early warnings” or “alerts” can be released. This allows a much better time coverage of the light curve. Two more events were reported in 1996, seven in 1997, and three by the time of writing in 1998. Full analysis of the 1996, 1997 and 1998 seasons has not yet been completed.

As mentioned, one of the events discovered in the first 2 years data was due to a lens made of two objects, namely a binary system. Such events are more rare, but their observation is not surprising; since almost 50% of

²The two disregarded events are the binary lens and one which is rated as marginally consistent with microlensing.

the stars are double systems, it is quite plausible that MACHOs also form binary systems. The light curve is then more complicated than for a single MACHO.

EROS has also searched for very low mass MACHOs by looking for microlensing events with time scales ranging from 30 min to 7 days [43]. The lack of candidates in this range places significant constraints on any model for the halo that relies on objects in the range $5 \times 10^{-8} < M/M_{\odot} < 2 \times 10^{-2}$. Indeed, such objects may make up at most 20% of the halo dark matter (in the range between $5 \times 10^{-7} < M/M_{\odot} < 2 \times 10^{-3}$ at most 10%). Similar conclusions have also been reached by the MACHO group [40].

Recently, the MACHO team reported [44] the first discovery of a microlensing event towards the Small Magellanic Cloud (SMC). Full analysis of the 4-year data on the SMC is still underway, so that more candidates may be found in the near future. A rough estimate of the optical depth leads to about the same value as found towards the LMC. The same event was also observed by EROS [45] and the Polish-American OGLE (Optical Gravitational Lensing Experiment) collaboration [46]. A second event was discovered in 1998 and found to be due to a binary lens [47]. This event has been followed by the different collaborations, so that the combined data lead to a quite accurate light curve, from which it is possible to obtain an upper limit for the value of the proper motion of the lens. The results indicate that the lens system is most probably located in the SMC itself, in which case the lens may be an ordinary binary star. Following this result it has been argued that most, if not all lenses are located in the Magellanic Clouds. This issue can be settled once more data will be available.

Since the middle of 1996, the EROS group has been using a new 1-m telescope, located in La Silla (Chile), which is fully dedicated to microlensing searches using larger CCD cameras. The improved experiment is called EROS II.

5.2 Microlensing towards the galactic centre

The OGLE team [48] announced its first discovered event towards the galactic bulge in September 1993. Since then, OGLE has found altogether 18 microlensing events in its data from the 1992 - 1995 observing seasons, one being a binary lens. Based on their first nine events, the OGLE team estimated the optical depth towards the bulge as $\tau = (3.3 \pm 1.2) \times 10^{-6}$ [49]. This has to be compared with the theoretical calculations which lead to a value $\tau \simeq (1 - 1.5) \times 10^{-6}$ [36, 37]. It does, however, not take into account the contribution of lenses located in the bulge itself. In fact, when also the effect of microlensing by galactic bulge stars is taken into account, the opti-

cal depth gets bigger [50] and might easily be compatible with the measured value. This implies that the galactic centre region has the shape of a bar with its major axis pointing almost towards us. In the meantime, the OGLE group has obtained a new dedicated 1.3-m telescope at the Las Campanas Observatory. The OGLE-2 collaboration started observations in 1996 and is monitoring the bulge, the LMC and the SMC.

The French DUO (Disk Unseen Objects) [51] team found 12 microlensing events (one being a binary event) by monitoring the galactic bulge during the 1994 season with the 1-m Schmidt telescope of ESO (the European Southern Observatory). The photographic plates were taken in two different colours to test achromaticity.

To date, the MACHO [52] collaboration has found more than ~ 150 microlensing events towards the galactic bulge, most of which are listed among the alert events, which are constantly updated ³. During their first season, they found 45 events towards the bulge, which led to an estimated optical depth of $\tau \simeq 2.43^{+0.54}_{-0.45} \times 10^{-6}$, which is roughly in agreement with the OGLE result, and also implies the presence of a bar in the galactic centre. The mean mass based on the mass moment method leads, for the events discovered during the first year of operation by the MACHO team [52], to an average value of $0.16 M_{\odot}$ [53], under the assumption that the lenses are located in the disk. This mass value suggests that the lenses are faint stars. They also found three events by monitoring the spiral arms of our Galaxy in the region of Gamma Scutum. Meanwhile, the EROS II collaboration also found some events towards the spiral arm regions. These results are important for studying the structure of our Galaxy.

The MACHO team also detected in a long-duration event, the parallax effect due to the motion of the Earth around the Sun [54]. This effect manifests itself by making the light curve no longer perfectly symmetric with respect to the maximum value.

Some globular clusters lie in the galactic disk about half-way between us and the galactic bulge. If the globular clusters contain MACHOs, the latter can also act as lenses for more distant stars located in the bulge. Recently, we have analysed the microlensing events towards the galactic bulge which lie close to three globular clusters, and found evidence that some microlensing events are indeed due to MACHOs located in the globular clusters [55]. If this finding is confirmed, once more data are available, it would imply that globular clusters also contain an important amount of dark matter in the form of MACHOs, probably as brown or white dwarfs.

³Current information on the MACHO collaboration's alert events is maintained at the WWW site <http://darkstar.astro.washington.edu>.

5.3 Microlensing towards the Andromeda galaxy

Microlensing searches towards the Andromeda galaxy (M31) have also been proposed [56, 57, 58]. In this case, however, one has to use the so-called “pixel-lensing” method. Since the source stars are in general no longer resolvable, one has to consider the luminosity variation of a whole group of stars, which are, for instance, registered on a single pixel element of a CCD camera. This makes the subsequent analysis more difficult; on the other hand, if successful it allows M31 and other objects to be used as targets, which would otherwise not be possible to use. For information on the shape of the dark halo, which is presently unknown, it is important to observe microlensing in different directions.

Two groups have started to perform searches. The French AGAPE (Andromeda Gravitational Amplification Pixel Experiment) [59] uses the 2-m telescope at Pic du Midi and the American VATT/COLUMBIA [60] uses the 1.8-m VATT-telescope (Vatican Advanced Technology Telescope) located on Mt. Graham and the 4-m KNPO telescope. Both teams showed that the pixel-lensing method works; however, the small number of observations so far does not allow the drawing of firm conclusions. Both the AGAPE and the VATT/COLUMBIA teams found some candidate events (the latter team six events altogether) which are consistent with microlensing; however, additional observations are needed to confirm this.

Pixel-lensing could also lead to the discovery of microlensing events towards the M87 galaxy in the nearby Virgo cluster, in which case the best way would be to use the Hubble Space Telescope [61]. It might also be interesting to look towards dwarf galaxies of the local group or globular clusters [62]. This would provide information along different lines of sight and thus allow reconstruction of the shape of the dark halo.

5.4 Further developments

A new collaboration between New Zealand and Japan, called MOA (Microlensing Observations in Astrophysics), started in June 1996 to perform observations using the 0.6-m telescope of the Mt. John Observatory [63]. The targets are the LMC and the galactic bulge. In particular, they will search for short-timescale events. Another experiment will soon start using the new 1.5-m telescope at Toppo di Castelgrande in southern Italy. The goal is to perform pixel-lensing on the Andromeda galaxy.

There are also networks involving different observatories, for instance, PLANET (Probing Lensing Anomalies NETwork, [64]) and GMAN (Global Microlensing Alert Network) with the aim of performing accurate photometry

on alert microlensing events. The GMAN collaboration obtained accurate photometric data on a 1995 event towards the galactic bulge. The light curve clearly shows a deviation due to the rather large diameter of the source star [65]. A major goal of the PLANET and GMAN collaborations is to find planets via accurate photometry of binary microlensing events [66, 67, 68]. This way, one may detect planets with the mass of the Earth ⁴. The signal would typically last about 2 h, which would require taking frequent data points. Moreover, microlensing searches are also very powerful ways to generate a large database for the study and discovery of many new variable stars.

At present, the only information available from a microlensing event is its duration, which depends on three parameters: distance, transverse velocity and mass of the MACHO. A possible way to obtain more information is to observe an event from different locations, typically with an Astronomical Unit ($\sim 1.5 \times 10^8$ km) in separation. This could be achieved by putting a “parallax” satellite into solar orbit [69, 70].

6 Conclusions

The mystery of dark matter is still unsolved. However, thanks to the ongoing microlensing experiments there is hope that progress on its nature in the galactic halo can be achieved within the next few years. Substantial progress will also be made in the study of the structure of our Galaxy, especially when data from the observations towards the spiral arms become available. Microlensing is also very promising for the discovery of planets, in particular those with a mass comparable to that of the Earth. Although a rather young observational technique, microlensing has already enabled us to make substantial progress and the prospects for further contributions to solve important astrophysical problems look very bright.

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⁴On January 9, 1999 the Microlensing Planet Search collaboration announced the discovery of a possible extra-solar planet with a mass between that of the Earth and Neptune.

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Figure 1: Setup of a gravitational lens situation: The lens L located between source S and observer O produces two images S_1 and S_2 of the background source. D_d is the distance between the observer and the lens, D_s between the observer and the source and D_{ds} between the lens and the source.

Figure 2: Einstein ring (dashed) and some possible relative orbits of a background star with projected minimal distances $p = r/R_E = 0.1, 0.3, \dots, 1.1$ from a MACHO M (from [34]).

Figure 3: Light curves for the different cases of Fig. 2. The maximal magnification is $\Delta m = 0.32$ mag, if the star just touches the Einstein radius ($p = 1.0$). For smaller values of p the maximum magnification gets larger. t is the time in units of t_0 (from [34]).

Figure 4: Microlensing event observed by the MACHO collaboration in their first year data towards the LMC. The event lasted about 33 days. The data are shown for blue light, red light and the ratio red light to blue light, which for perfect achromaticity should be equal to 1 (from [39]).

Figure 5: Binary microlensing event towards the LMC by the MACHO collaboration (taken from the web page <http://darkstar.astro.washington.edu>). The two light curves correspond to observations in different colors taken in order to test achromaticity.