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FROM THE 1919 SOLAR ECLIPSE TO GRAVITATIONAL LENSING: ASTROPHYSICAL MANIFESTATIONS OF CURVED SPACETIME

PHILIPPE JETZER
Institute for Theoretical Physics, University of Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland

Abstract. I will briefly present the history of gravitational lensing, which started with the measurement of the light deflection during the solar eclipse of May 1919 and thus confirmed the theory of general relativity. This result was then further confirmed in following solar eclipse observations. Gravitational lensing, after the first discovery of an extragalactic lens system in 1979, has rapidly developed into a very powerful astrophysical tool with several applications, among which the detection of dark matter and the discovery of extra solar planets. I will give a brief overview of the main results achieved so far.

Key words: general relativity, gravitational lensing

1. INTRODUCTION

Gravitational lensing - i.e. light deflection by gravity - has become in the last few years one of the most important fields in present day astronomy. The enormous activity in this area has mainly been driven by the considerable improvements of the observational capabilities. Due to the new wide-field cameras and telescopes which are already in place or will become operational in the near future the rate and the quality of the lensing data will increase dramatically. Gravitational lensing is independent of the nature and the physical state of the deflecting mass, therefore, it is perfectly suited to study dark matter at all scales.

Indeed, the determination of the amount and the nature of matter present in the Universe is an important problem for contemporary astrophysics and cosmology. 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 radio telescopes. The most recent studies lead to the conclusion 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 (Perlmutter *et al.*, 1999).

Important evidence for the existence of large quantities of dark matter comes from the measured rotation curves of several hundreds of spiral galaxies, 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 Zwicky (Zwicky, 1933). Since then, much effort has been put into the search for dark matter, the nature of which is still largely unknown.

The field of gravitational lensing is growing very rapidly and almost daily there are new results, therefore we give here only a summary of the main results. For more details see the book of Schneider et al. (1992) and the references therein.

2. HISTORICAL REMARKS

Today we know that light is bended by the presence of gravitational fields. This phenomenon is a consequence of the general relativity theory as formulated in its final version by Einstein in 1915. Within Newtonian gravity theory, since the light is massless, the trajectory of light is not affected by gravity and thus remains unchanged. Nonetheless, long before Einstein's general relativity several people thought about the possibility that light would be affected by gravity. Already, Newton in his book on Optics, published in 1704, in his first Query wrote: “Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action (caeteris paribus) strongest at the least distance?”.

Various scientist, afterwards, made thoughts on light rays bending by massive bodies. Assuming that light has a mass one can easily compute within Newtonian mechanics how much it gets deviated by a massive body, as for instance the Sun. Moreover, it turns out that the deflection angle does not depend on the mass of the light as it drops out. Clearly, the so obtained result is only right as long as light has a mass, even if tiny. As is found using classical mechanics, a particle starting with velocity v at a large separation from the gravitating mass M is deflected by an angle α given by (assuming small deflection angles):

$$\alpha \simeq \frac{2GM}{v^2 r} \ . \tag{1}$$

From this equation, assuming that the result also holds for massless light, one obtains the “Newtonian” value for the light deflection by setting $v = c$. In particular, a light ray that grazes the surface of the Sun should be deflected by $0.''85$, as can be found by setting $r = R_\odot$ ($R_\odot$ being the radius of the Sun) and $M = M_\odot$ ($M_\odot$ being the mass of the Sun). Indeed, in 1804 the astronomer Soldner published a paper in which he computed the error induced by the light deflection on the determination of the position of stars. To that purpose he used the Newtonian theory of gravity assuming that the light is made of particles. He also estimated that a light ray which just grazes the surface of the Sun would be deflected by a value of only $0.''85$. Within general relativity this value is about twice as much, more precisely $1.''7$. The first measurement of this effect has been made during the solar eclipse of 29 May 1919 and confirmed the value predicted by general relativity (Dyson *et al.*, 1920). These observations were then repeated during following solar eclipses, in particular the ones which took place in 1922 in Australia, 1929 in Sumatra, 1936 in Russia and Japan, 1947 in Brazil and 1952 in Sudan. All results were in agreement with the prediction of general relativity.

In 1936 Einstein published a short paper in Science in which he computed the light deflection of light coming from a distant star by the gravitational field of another star (Einstein, 1936). He mentioned that if the source and the lens are perfectly aligned the image would be a ring. If instead the alignment is not perfect one would see two images with, however, a very small separation angle. Einstein also wrote: "Of course, there is no hope of observing this phenomenon". Actually, it has been found recently that Einstein made most of the calculations presented in that paper already in 1912 as can be seen on some pages of his notebook (Renn *et al.*, 1997). 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 the following year 1937 the swiss astronomer Zwicky wrote two short articles in Physical Review suggesting to consider galaxies as sources and lenses rather than stars as mentioned by Einstein (Zwicky, 1937). He came to the conclusion that such a configuration would have much higher chances to be seen, since the typical mass of a galaxy is several billion times higher than the mass of a single star. He argued that such configurations must almost certainly be seen. Moreover, he gave also a list of possible applications among which the possibility to better determine the total mass of galaxies, including their dark matter content.

The first gravitational lens has been discovered in 1979, when spectra were obtained of two point-like quasars which lie only about 6 arc seconds away. The spectra showed that both objects have the same redshift and are thus at the same distance. Later on also the galaxy acting as lens has been found, making it clear that the two objects are the images of the same quasar, which is lensed. Since then many other examples have been found, and in 1986 the first lensing case with a galaxy acting as source was discovered. The galaxy appears then distorted as one or more arcs. Many such systems have since then be discovered, some thanks to the Hubble space telescope.

In 1993 the first galactic microlensing events were observed, in which the source is a star in the Large Magellanic Cloud or in the galactic bulge. In the former case the lens is a compact object probably located in the galactic halo, whereas in the later case the lens is a low mass star in the galactic disk or in the bulge itself.

3. BASICS OF LENSING

The propagation of light in a curved space-time is in general a complicated problem, however, for almost all relevant applications of gravitational lensing one can assume that the geometry of the universe is described in good approximation by the Friedmann-Lemaître-Robertson-Walker metric. The inhomogeneities in the metric can be considered as local perturbations. Thus the trajectory of the light coming from a distant source can be divided into three distinct pieces. In the first one the light coming from a distant source propagates in a flat unperturbed space-time, nearby the lens the trajectory gets modified due to the gravitational potential of the lens and afterwards in the third piece the light travels again in an unperturbed space-time till it gets to the observer. The region around the lens can be described

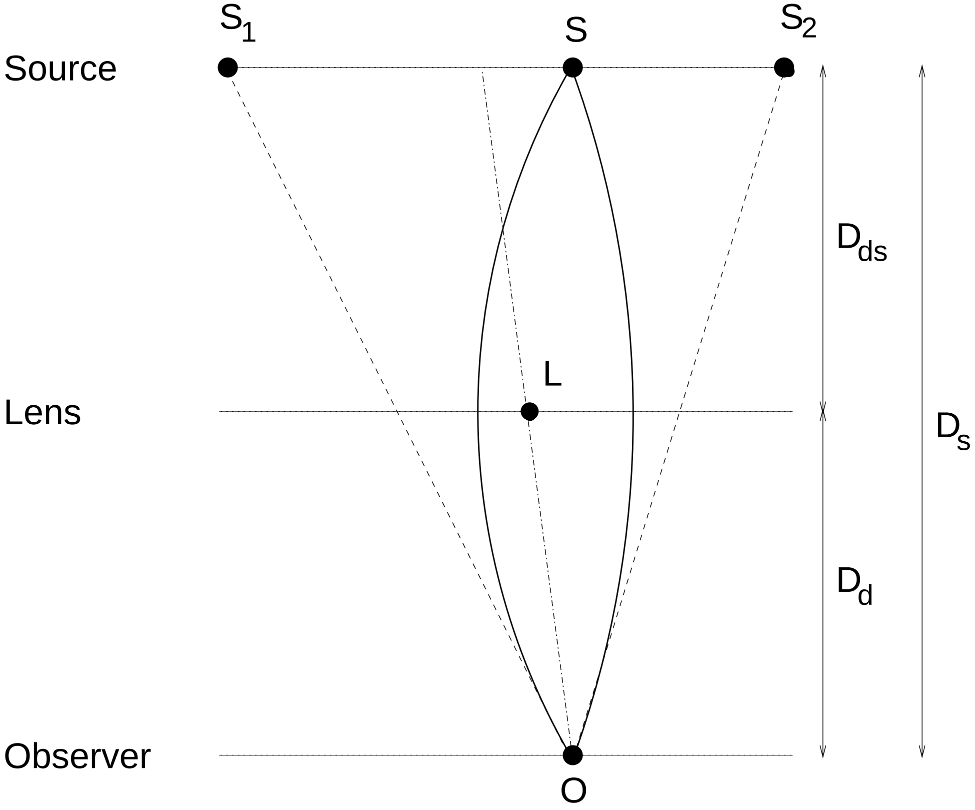

Fig. 1. Setup of a gravitational lens situation: The lens L located between source S and observer O produces two images S_1 and S_2 of the background source. D_d is the distance between the observer and the lens, D_s between the observer and the source and D_{ds} between the lens and the source.

by a flat Minkowskian space-time with small perturbations induced by the gravitational potential of the lens. This approximation is valid as long as the Newtonian potential Φ is small, which means $\mid \Phi \mid \ll c^2$ (c being the velocity of light), and if the peculiar velocity v of the lens is negligible as compared to c. These conditions are almost always fulfilled in all cases of interests for the astrophysical applications. An exception, for instance, is when the light rays get close to a black hole. We will not discuss such cases in the following.

With the above simplifying assumptions one can describe the light propagation nearby the lens in a flat space-time with a perturbation due to the gravitational potential of the lens described in first order post-Newtonian approximation. The effect of the space-time curvature on the light trajectory can be described as an effective refraction index. One can thus derive a lens equation purely geometrical optics with an effective refraction index given by:

$$n = 1 - \frac{2\Phi}{c^2} \ . \tag{2}$$

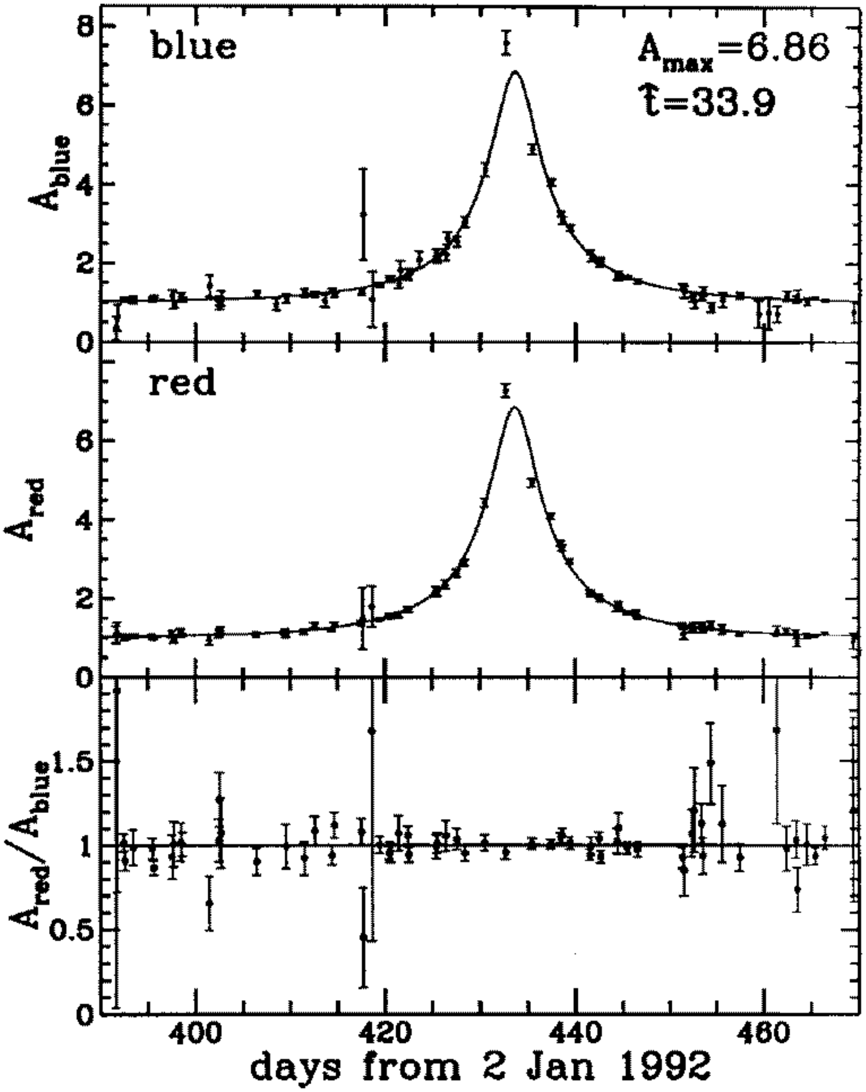

Fig. 2. Microlensing event observed by the MACHO collaboration in their first year data towards the LMC. The event lasted about 33 days. The data are shown for blue light, red light and the ratio red light to blue light, which for perfect achromaticity should be equal to 1 (from (Alcock *et al.*, 1993)).

4. MICROLENSING

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

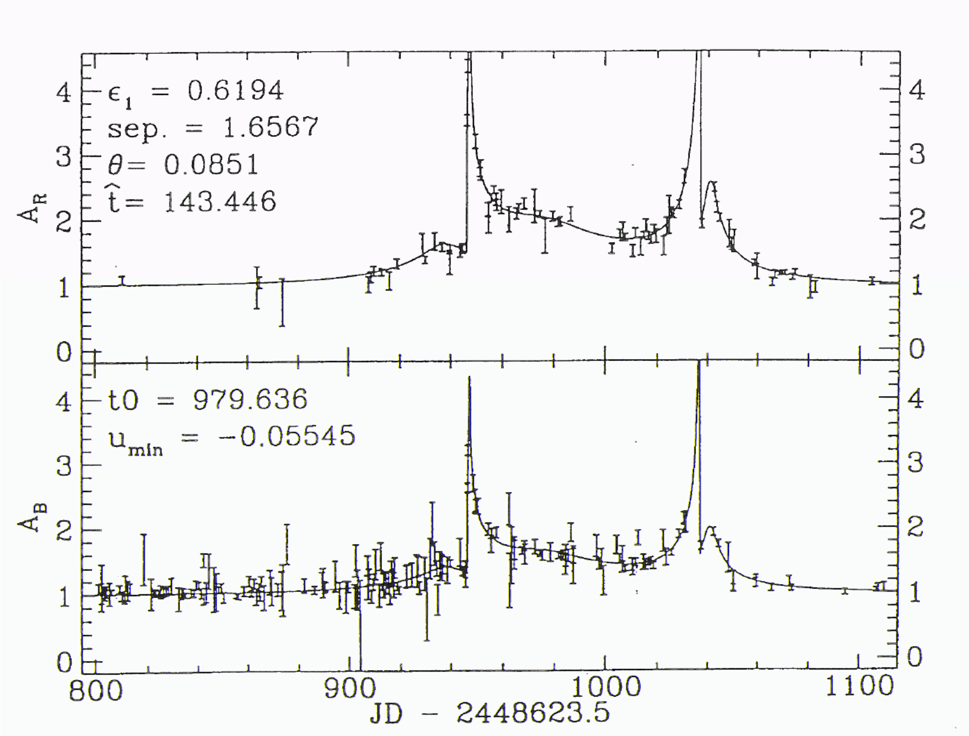

Fig. 3. Binary microlensing event towards the LMC by the MACHO collaboration (taken from the web page http://darkstar.astro.washington.edu). The two light curves correspond to observations in different colors taken in order to test achromaticity.

to each other, this can be detected as a time-variable brightness. This behaviour is referred to as gravitational microlensing, a 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.

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 (1986). Since then the field has grown very rapidly, especially since the discovery of the first microlensing events at the end of 1993 and many new applications have been suggested, including the detection of Earth like planets around stars in our Galaxy.

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, several hundreds of events have been found. The still few observed events towards the LMC indicate that the halo dark matter fraction in the form of MACHOs is at most of the order of 20%, assuming a standard spherical halo model.

4.1. Microlensing towards the LMC

Microlensing allows the detection of MACHOs located in the galactic halo in the mass range $10^{-7} < M/M_\odot < 1$ (De Rújula *et al.*, 1991; De Rújula *et al.*, 1992), as well as MACHOs in the disk or bulge of our Galaxy (Paczyński, 1991; Griest *et al.*, 1991).

In September 1993, the French collaboration EROS (Expérience de Recherche d'Objets Sombres) (Aubourg *et al.*, 1993) 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 (Alcock *et al.*, 1993) by monitoring several millions of stars in the LMC (see Fig. 2).

The MACHO team went on to report the observation of 13 to 17 events (one being a binary lensing event; see Fig. 3) by analysing their 5.7 years of LMC data (Alcock *et al.*, 2000). The inferred optical depth (which is a measure for the probability to detect a microlensing event) is $\tau = 1.2^{+0.4}_{-0.3} \times 10^{-7}$ with an additional 20% to 30% of systematic error. Correspondingly, this implies that about 20% of the halo dark matter is in the form of MACHOs with a most likely mass in the range 0.15 - 0.9 $M_\odot$ depending on the halo model. 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 as well as the fraction of halo dark matter in form of MACHOs have to be treated with care (Mancini *et al.*, 2004).

One of the events discovered 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 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 (see Fig. 3).

EROS has also searched for very low mass MACHOs by looking for microlensing events with time scales ranging from 30 min to 7 days (Renault *et al.*, 1997). 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 (Alcock *et al.*, 2000). A few events have also been discovered towards the Small Magellanic Cloud.

4.2. Microlensing towards other targets

To date, the MACHO, EROS and OGLE (Optical Gravitational Lensing Experiment) collaborations have found more than thousand microlensing events towards the galactic bulge, which also imply the presence of a bar in the galactic centre. They also found several events by monitoring the spiral arms of our Galaxy. These results are important for studying the structure of our Galaxy (Grenacher *et al.*, 1999). Microlensing observations towards the galactic centre turns out to be also a very powerful way to detect planetary systems in our Galaxy. In particular it allows to find planets with a mass comparable to the Earth's mass. Recently, a planet with a mass of only about five times Earth's mass has been found this way (Beaulieu *et al.*, 2006).

Microlensing searches towards the Andromeda galaxy (M31) have also been proposed (Crotts, 1992; Baillon *et al.*, 1993; Jetzer *et al.*, 1994). 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, however it allows to use M31 and other objects as targets. For information on the shape of the dark halo, which is presently unknown, it is important to observe microlensing in different directions. Several groups performed such observations and preliminary results suggest that about 20% of the halo dark matter could be in form of MACHOS (Calchi Novati *et al.*, 2005), however more data is needed in order to confirm this result. Such efforts are under way and possibly in few years this issue will be solved.

Fig. 4. Giant arc in Cl2244-02 (image from CFHT). The lensing cluster is at $z = 0.329$ and the source of the arc is a very distant field galaxy at $z = 2.238$. (Courtesy of G. Soucail, Obs. Midi–Pyrénées, ESO Messenger 69, September 1992.)

5. GALAXY CLUSTERS AS LENSES

When dealing with cosmological lenses one has to interpret all distances as *angular diameter distances*. Galaxy clusters similarly to galaxies can act as gravitational lenses for more distant galaxies (see Figs. 4 and 5). One classifies the observed lensing effects due to clusters into two types.

1) Rich centrally condensed clusters produce sometimes a giant arc (Fig. 4) when

a background galaxy turns out to be almost aligned with the cluster (*strong lensing*).

2) Every cluster produces weakly distorted images of a large number of background galaxies (*weak lensing*).

Both these cases have been observed and allow to get important information on the distribution of the matter in galaxy clusters. For the analysis of giant arcs, we have to use parameterized lens models which are fitted to the observational data. The situation is much better for weak lensing, because there now exist several parameter–free reconstruction methods of projected mass distributions from weak lensing data.

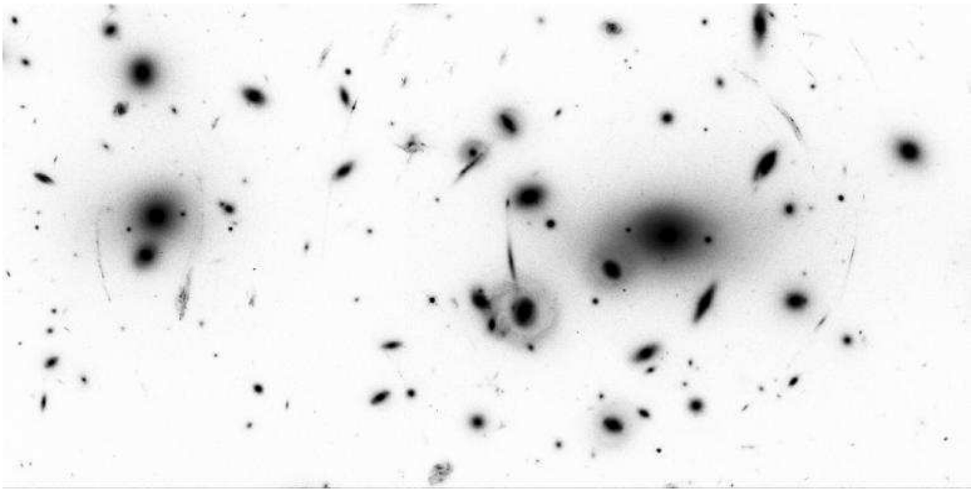

Fig. 5. Setup of a gravitational lens situation: Hubble Space Telescope image of the cluster Abell 2218. Beside arcs around the two centers of the cluster, many arclets can be seen (NASA HST Archive).

5.1. HUBBLE CONSTANT FROM TIME DELAY

As first noted by Refsdal in 1966 (Refsdal, 1966), time delay measurements can yield, in principle, the Hubble parameter H_0. Unfortunately, the use of this method requires a reliable lens model. This introduces systematic uncertainties.

Measuring the time delay is not an easy task, nonetheless for several lens systems one could get reliable observations. For instance for the double lens quasar QSO0957+561 it could be determined and turned out to be: $\Delta t = 417 \pm 3$ days. Modelings lead then for this case to a best estimate of $H_0 \simeq 61$ km s^{-1} Mpc^{-1}. For this example there are constraints for modeling the lens, nevertheless it is difficult to assess an error for the value of H_0.

Besides having the above mentioned problems, the determination of H_0 through gravitational lensing offers also some advantages as compared to the other methods. It can be directly used for large redshifts (~ 0.5) and it is independent of any other method. Moreover, it is based on fundamental physics, while other methods rely on models for variable stars (Cepheids), or supernova explosions (type II), or empirical calibrations of standard candles (Tully–Fisher distances, type I supernovae).

Finally, we notice that lensing can also lead to bounds on the cosmological constant Λ. The volume per unit redshift of the universe at high redshifts increases for a large Λ. This implies that the relative number of lensed sources for a given comoving number density of galaxies increases rapidly with Λ. This can be used to constrain Λ by making use of the observed probability of lensing. Various authors have used this method and came up with a limit $\Omega_\Lambda \leq 0.6$ for a universe with $\Omega_0 + \Omega_\Lambda = 1$. It remains to be seen whether such bounds, based on lensing statistics, can be improved.

6. Conclusions

Although being rather young observational techniques, gravitational lensing and microlensing, which had their beginning in observations made during the 1919 solar eclipse, have already enabled us to make substantial progress on various topics such as dark matter and the search of planets in our Galaxy. The prospects for further contributions to solve important astrophysical problems look very bright.

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