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Gravitational lensing

In his theory of general relativity (GR), Einstein established that a massive object curves space–time and that photons move along geodesics of this curved space. Einstein's prediction was confirmed during the solar eclipse of 1919. This not only provided a decisive, quantitative proof of the validity of GR but also gave confirmation of the concept that electromagnetic waves do undergo deflections in gravitational fields.

Atmospheric lensing effects may lead to a distortion or to the formation of multiple images of a distant source, resulting in the perception of a 'mirage'. They sometimes literally deform our view of the surrounding areas. Similarly, gravitational lensing may perturb our view of the distant Universe and affect our physical understanding of various classes of extragalactic objects. The great interest in gravitational lensing comes from the fact that this phenomenon can be used as an astrophysical and cosmological tool. Indeed, gravitational lensing may help in deriving:

1. the distance scale of the Universe – via the determination of the Hubble constant H_0 – and possibly the values of other cosmological parameters (the cosmological density Ω_0 and the cosmological constant λ_0),
2. the mass distribution $M(r)$ of the lens,
3. the extinction law in the deflector, usually located at high redshift,
4. the nature and distribution of luminous and dark matter in the Universe,
5. the size and structure of quasars,
6. the size of absorbing intergalactic gas clouds,
7. upper limits on the density of a cosmological population of massive compact objects.

In this chapter we summarize some of the theoretical and observational evidence supporting these claims and show how space observations have significantly contributed in some of the areas listed above.

The chapter is organized as follows. We first review the historical background of gravitational lensing in Section 1. Unlike most other astrophysical discoveries made during the last century, the physics of gravitational lensing was understood well before the first example of a multiply-imaged extragalactic object was found.

In Section 2 we describe the basic principles and concepts of gravitational lensing. We first establish the exact form of the lens equation. By making use of the Einstein deflection angle, we derive the expression for the angular diameter of an Einstein ring, which is also the typical angular separation between multiply-lensed images when the conditions of perfect alignment between the observer, the lens and the source are no longer fulfilled. We then set up a sufficient condition for an observer to see an Einstein ring, or multiple images, of a distant source that is located behind a deflector, and go on to derive, for the case of a point-mass lens model, expressions for the expected image positions and their amplifications. Using wavefront and ray tracing diagrams, we introduce the important concepts of caustics and time delays. We then show how all the lensed image configurations observed in the Universe may be understood in terms of the relative location between the observer and the caustics associated with an asymmetric lens. Several outstanding

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examples of gravitational lens systems observed with the Hubble Space Telescope (HST) serve as illustrations.

In Section 3, we discuss the most remarkable astrophysical and cosmological applications of gravitational lensing. These include the independent determination of the Hubble constant H_0 based upon the measurement of the time delay Δt between the observed light curves of multiply-imaged quasars. The possibility of weighing the mass of lensing galaxies, galaxy clusters and intervening dark matter from the observation of multiply-imaged distant sources, arcs and arclets is also reviewed. We further discuss the possibility of using gravitational lensing to determine the cosmological density Ω_0 $(=8\pi G\rho_0/3H_0^2)$ and the reduced cosmological constant λ_0 $(=\Lambda c^2/3H_0^2)$ of the Universe, the cosmological density Ω_L of dark compact lenses, the size of intergalactic absorbing clouds, dust extinction laws in deflecting galaxies and the structure and size of quasars. We also present the status of optical searches for massive astrophysical compact halo objects (MACHOs) based upon microlensing, the formation of giant luminous arcs in galaxy clusters and the observation of 'weak lensing' in the Universe.

The anticipated contributions of ongoing and future space missions such as Chandra, XMM-Newton, MAP, FIRST-Herschel, Planck, NGST and GAIA are presented in Section 4.

1 HISTORICAL BACKGROUND

One of the consequences of the theory of GR is that light rays are deflected in gravitational fields. Although this prediction was made in the twentieth century, speculations that light rays might be bent by gravitation had been proposed much earlier. Indeed, considering that light is composed of elementary constituents, Isaac Newton suggested as early as 1704 that the gravitational field of a massive object could possibly bend light rays, just as it would alter the trajectory of material particles. A century later, Laplace independently made this same suggestion. Furthermore, the astronomer Johann von Soldner (1804) at the Munich Observatory found that, in the framework of Newtonian mechanics, a light ray passing near the limb of the Sun should undergo an angular deflection of 0.875″. However, because the wave description of light prevailed during the eighteenth and nineteenth centuries, neither the conjecture of Newton nor the result of Soldner were ever taken seriously. In 1911 Albert Einstein had re-derived the latter result on the basis of the equivalence principle, unaware of Soldner's work.

In the elaboration of his theory of GR, Einstein predicted that a massive object curves spacetime in its vicinity and that any free particle, massive or not (e.g. photons), will move along geodesics of this curved space. After deriving the full field equations of GR, he predicted in 1915 that a light ray passing near the solar limb should be deflected by an angle given by

$$\hat{\alpha} = 4GM/(c^2R) \ll 1 \tag{1}$$

where G is the gravitational constant, c is the velocity of light and M and R are the mass and radius of the Sun (or of any other compact lens), respectively. This deflection angle turns out to be exactly twice the value derived by Soldner and by Einstein himself in 1911; the factor of 2 merely reflects the metric curvature. Note that in Newtonian terms the Einstein deflection also follows if one assumes a refractive index n associated with the Newtonian gravitational potential U $(|U| \ll c^2)$ via the relation

$$n = 1 - 2U/c^2 \tag{2}$$

The analogy between atmospheric and gravitational lensing then becomes obvious. Note, however, that the bending of light rays in gravitational fields is predicted to be totally 'achromatic' (see eqn (1)).

Using photographs of a stellar field taken during the solar eclipse in May 1919, and six months apart, Arthur Eddington and his collaborators (Dyson *et al*. 1920) were able to confirm, within a 20–30% uncertainty, the deflection angle predicted by Einstein (Figure 1). This was the second correct prediction of GR – the successful interpretation of the advance of Mercury's perihelion being the first – and marked the full acceptance of the work of Einstein.

It seems that Eddington (1920) was the first to propose the possible formation of multiple images of a background star by the gravitational lensing effect of a foreground one (but see the finding by Renn *et al*. (1997)). Note, however, that Oliver Lodge (1919) had already characterized massive

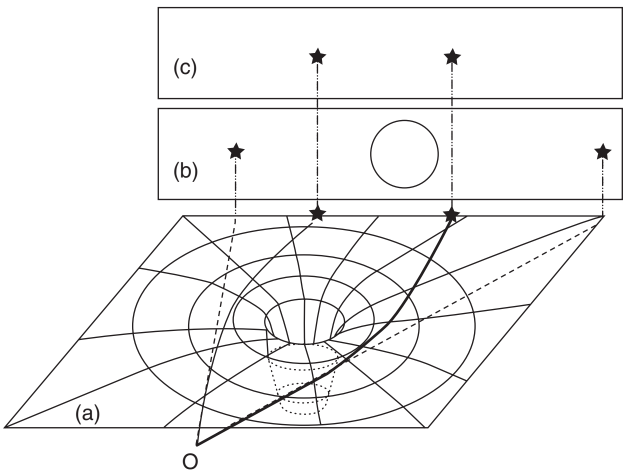

Figure 1 Curved spacetime around the Sun (a) and deflection of light rays from two distant stars as seen by an observer (O) during a solar eclipse (b) and six months apart (c).

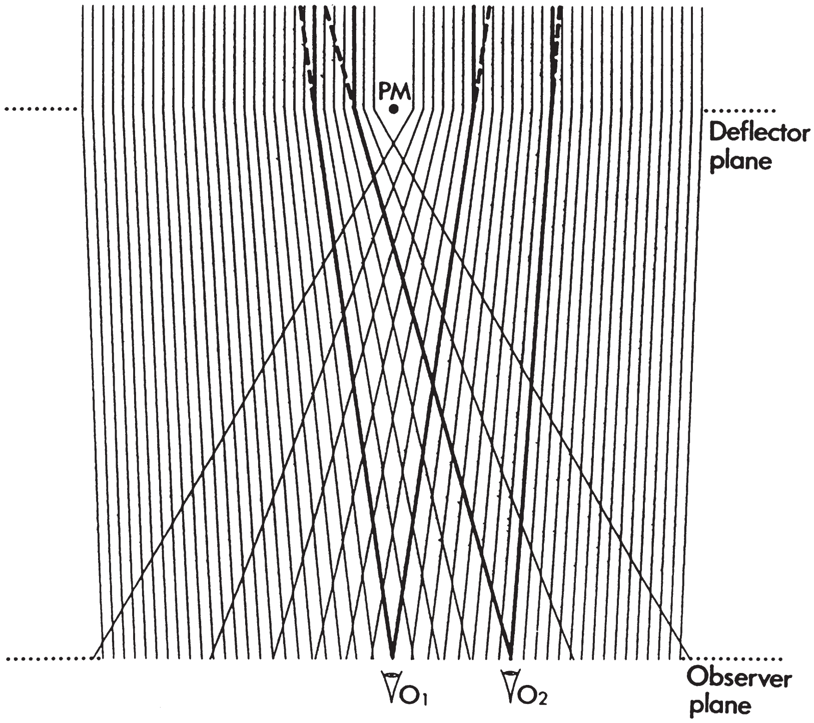

Figure 2 The paths of light rays in a point-mass (PM) lens model. In accordance with eqn (1), a set of parallel rays emitted from a distant source are deflected from their original paths as they cross the deflector plane. Different observer positions are represented from where an Einstein ring (O_1) or a double image (O_2) may be seen.

objects like the Sun as imperfect focusing lenses since they had no real focal length; the light from a background object being mainly concentrated along a focal line of 'infinite' length (Figure 2). In 1923, E.B. Frost, then director of the Yerkes Observatory, initiated a programme to search for multiple images of stars in the Galaxy, but it seems that these observations never really took place. Orest Chwolson (1924) suggested that, in the case of a perfect alignment between an observer and two stars located at different distances, the observer should see a ring-shaped image of the background star around the foreground one.

Independently, at the request of Rudi W. Mandl, a Czech electrical engineer, Einstein (1936) rediscovered the major characteristics (double images, the 'Chwolson' ring usually referred to as the 'Einstein' ring, and so on) of one star lensed by another, but he was very sceptical about the possibility of observing this phenomenon among stars, probably because the expected angular separations between the lensed images were so small. What seems remarkable is that Einstein had first established the whole theory of the formation of multiply-lensed images (the lensing equation, formation of double images by a point-like deflector, amplification of the lensed images, and so on) during the spring of 1912, three years before completing his theory of GR. This finding has recently been reported by Renn *et al*. (1997), who had examined some of Einstein's notebooks. It does therefore seem that by 1936 Einstein had totally forgotten his pioneering gravitational lensing work from 1912, as if he had already convinced himself that the idea was too speculative to have any chance of empirical confirmation.

Fritz Zwicky (1937a,b) was the first to realize the very high probability of identifying a gravitational lens mirage, (i.e. one composed of several distinct images of a single object) among extragalactic sources. He even proposed to use galaxies as natural cosmic telescopes to observe otherwise too faint and distant background objects. He also emphasized the possibility of determining the mass of distant galaxies simply by applying gravitational lens optometry and, in addition, to test the theory of GR. In 1937 Zwicky stated that 'the probability that galactic nebulae which act as gravitational lenses will be found becomes practically a certainty', and he was therefore very much surprised some twenty years later that no such lensing effects had yet been found with the 5 m (200-inch) Hale Telescope at Palomar (Zwicky 1957).

After several decades of little activity, interest in the theory of gravitational lenses was revived by Klimov (1963), Liebes (1964) and Refsdal (1964a,b, 1966a). Some of their proposed applications were particularly promising because of the recent discovery of quasars by Maarten Schmidt

(1963). It would indeed be much easier to prove the lensing origin of multiple QSO images rather than that of extended and diffuse galaxy images, since the former ones consist of very distant, luminous and star-like objects. (For more details on quasars, see Peterson (1997).) In 1964 Sjur Refsdal proposed to apply geometric optics in order to estimate the time delay between the arrival times of two parts of the same distorted wavefront at the observer; this proposal, which formed the second part of his master's thesis, was (erroneously) judged of uncertain quality by his supervisor. Nevertheless he succeeded in publishing his findings (Refsdal 1964a,b); the referee of these papers was Dennis Sciama! Refsdal finally, obtained his Ph.D. in 1970 on the basis of that controversial second part of his master's thesis.

On the basis of the strong similarity between the spectra of quasars and of the nuclei of Class 1 Seyfert galaxies, Barnothy (1965) proposed that high-redshift quasars could actually be the lensed images of distant Class 1 Seyfert galactic nuclei. Sanitt (1971) criticized this view on the basis of statistical arguments.

Theoretical work continued at a low level of activity through the 1970s. Refsdal (1965, 1970) and Press and Gunn (1973) discussed problems on lens statistics, Bourassa and Kantowski (1975) considered extended non-symmetric lenses (Bourassa *et al*. 1973) and Dyer and Roeder (1972) derived a distance–redshift relation for the case of inhomogeneous universes. In spite of clear theoretical predictions, the interest from observers was largely absent, and no systematic search for lenses was initiated.

Forty-two years after Zwicky's prediction, the first example of a distant quasar (Q0957 + 561) doubly imaged by a foreground massive lensing galaxy and its attendant galaxy cluster was serendipitously discovered by Walsh *et al*. (1979). This system consists of two lensed quasar images separated by approximately 6″. Good evidence that Q0957 + 561 A and B correspond to twin lensed images of a single quasar was provided by

1. the similarity between their spectra,
2. a simple lens model which could naturally account for the slight morphological differences detected between the optical and radio images of the quasar (Young *et al*. 1981),
3. the discovery of the lensing galaxy between the twin quasar images, made possible by the use of modern CCD imaging,
4. the observation of a time delay of 1.14 years, first reported by Vanderriest *et al*. (1989), between the light variations of the two quasar components.

In parallel with the discovery of several other multiply-imaged quasars, an even stronger interest in gravitational lensing studies developed with the first identification of giant luminous arcs in 1986, by two independent teams (Section 3.5). Since 1982 a group of French astronomers led by L. Nottale from Meudon Observatory had regularly submitted observing proposals with the Canada–France–Hawaii Telescope (CFHT) to search for such arcs in the centres of rich and compact galaxy clusters, among them Abell 370. However, the observing programme committees were not at all receptive to this kind of proposition. Although these predictions were entirely based on the theory of GR, and had been promoted several decades earlier by Zwicky, they probably still looked too revolutionary to conservative observing programme committee members. Furthermore, during the first international conference that was explicitly dedicated to the field of gravitational lensing, entitled 'Quasars and Gravitational Lenses' (24th Liège International Astrophysical Colloquium, 1983), some of the organizers were very surprised by the high degree of scepticism that was still present among a significant number of the participants. Probably half the audience still then considered gravitational lensing to be an unproved phenomenon, while many others thought that the proposed lensed monsters would remain a mere cosmic curiosity, with no further scientific interest. It also seems that until the 1980s, in some institutes gravitational lensing was not always regarded as an acceptable subject to study. Astronomers who wished to pursue the subject would not have received a research grant for work dedicated to gravitational lensing – nor would they be invited to deliver a seminar on the topic. We know from Refsdal, Nottale and many other pioneers that they had the feeling of being considered somewhat heretic by some of their colleagues.

Following the pioneering detections of multiply-imaged quasars and giant luminous arcs, the levels of observational as well as theoretical activities have increased dramatically. More than fifty multiply-imaged quasars and an even larger number of gravitational arcs have now been discovered, and more than 3100 scientific publications have been written over the past twenty years on the subject of gravitational lensing (Figure 3). Space observations, and in particular

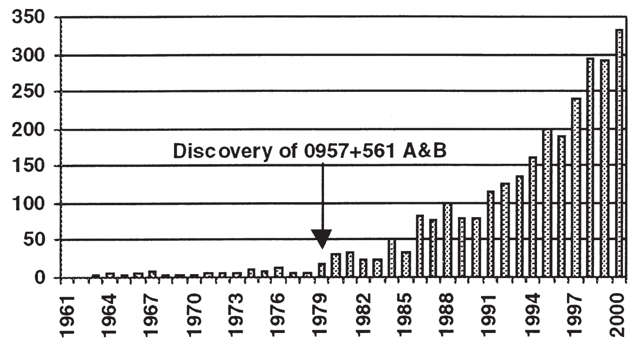

Figure 3 The number of scientific papers published annually on gravitational lensing over the past forty years. (Based on the gravitational lensing bibliography compiled by Pospieszalska-Surdej *et al*. (2000).)

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