GRAVITATIONAL LENSING AND RECENT CONTRIBUTIONS FROM RADIO STUDIES

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1. INTRODUCTION

1.1 Preamble

The year 1979 saw the discovery of the first example of "gravitational lensing" in the form of multiple imaging of a background quasar by a foreground galaxy (or group of galaxies), and the fulfilment of an implicit prediction of Einstein's general theory of relativity over sixty years before. Before 1970, the subject produced a few papers per year in the astronomical literature. Since then, the literature has grown considerably with the discovery and interpretation of many more lens systems. It is difficult to tell how much effect the discovery had, as the beginning of the rise depends on whether the number of papers is plotted on a linear *[Refsdal, 1993]* or log scale *[Press, 1996]*.

Lens systems are a uniquely powerful astrophysical tool in that they allow the masses and mass distributions of cosmologically distant objects to be determined independent of the light they emit. They are thus crucial in constraining "dark matter" on scales from stellar masses to the largest scales in the universe. Moreover, lensing observations have brought within our grasp some of the great prizes of cosmology. These include the determination of the Hubble constant, which relates distance to redshift and fixes the age and scale of the universe, and of the cosmological constant which, if it exists, causes the acceleration of the expansion of the universe. The cosmological constant corresponds to a universal vacuum energy, and confirmation of its existence would virtually guarantee the ultimate fate of the universe as an everlasting dimming and expansion. In all lens studies, from the first gravitational lens discovery onwards, radio observations have played a vital role due to their routinely high resolution and to the ability of radio waves to pass unobscured through dusty regions of the universe which have extremely high optical depths to shorter-wavelength visible light.

The standard reference work for gravitational lensing studies is the monograph by *Schneider, Ehlers & Falco [1992]* which contains a comprehensive description of lensing theory and a complete summary of the observational status as of 1992. Other major reviews have been written by *Blandford & Narayan [1992]* on the cosmological implications of lensing, by *Refsdal & Surdej [1994]* on the theory of lensing and by *Paczynski [1996]* on lensing by stars. More recent reviews include *Narayan [1998]*, on general astrophysical results from gravitational lensing, and *Schechter [2001]* who gives a sceptical review of Hubble constant determinations from lensing studies. In addition, IAU Symposium 173

(1996, eds. *Kochanek & Hewitt*) contains a comprehensive range of papers on all aspects of lensing.

The aim of this review is to give an overview of current developments in the subject, and in particular of lensing by galaxies and what radio observations can contribute. The review starts with a concise introduction to lensing (Section 1) and a description of lens searches to date (Section 2). In Section 3 we describe the mass models used to characterise lens systems, concentrating on the galaxy-mass lensing systems most accessible to radio interferometers and in particular to developments in the last three years. In Section 4 we describe the efforts made to derive cosmological parameters from lenses, in particular from radio-selected gravitational lenses which we argue give the cleanest samples. Section 5 is a review of some new fields which are currently being opened up by radio observations of microlensing and of the Faraday depths of lensing galaxies. Finally, in Section 6 we describe the future prospects for lensing studies using the new generation of instruments – in particular the Atacama Large Millimetre Array (ALMA) and the proposed Square Kilometre Array (SKA). Throughout we concentrate on the major developments in lensing since 1998, when the last major reviews were written.

1.2 Basic geometry of lensing

If a ray of light passes close to a point mass M, it is deflected by the gravitational field of the mass through a small angle

$$\alpha = 4GM/bc^2$$

where b is the impact parameter. This is a standard result of general relativity, and also one of the first to be tested. Eddington in 1919, during an expedition to a total solar eclipse, measured the predicted small gravitational deflection of light (of about $2''$) from stars passing close to the line of sight to the limb of the sun during the eclipse.

Measuring very small deflections is not easy. A light ray passing through the solar system at an impact parameter similar to the radius of the Earth's orbit will be deflected by only $0''.01$ by the Sun's gravitational field. Whole galaxies often produce more significant deflections; the same light ray would be deflected by about $1''$ by the Galactic gravitational field during its whole passage through the plane of our Galaxy.

For any given system in which a background light source is subjected to gravitational deflection by a foreground massive object, we can work out the appearance of the background source to the observer by use of Fermat's principle: the path followed by a ray of light must be an extremum (i.e. a maximum, minimum or saddle point). In the case where no lens is present, the problem is of course very simple; the path actually followed is a Fermat minimum, corresponding to a straight line. If a lensing mass is introduced, however, a compromise must be made between a straight path, which involves an extra time delay due to the traversal of a deep gravitational potential well (the "Shapiro time delay"), and a path deviating considerably from a straight line, which incurs a time penalty corresponding to the extra path length. In between these extremes there will be a path corresponding to a Fermat minimum, and an image of the background source will therefore be seen, but offset from the line of sight that would be obtained if no lens were present. In the completely symmetric case, where lens and source are precisely aligned,

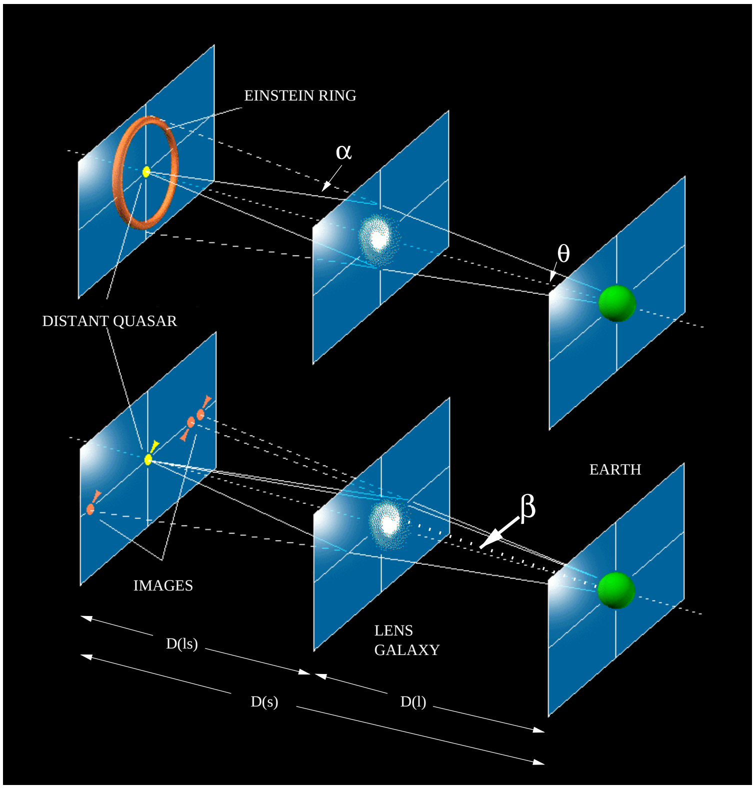

Figure 1: The formation of gravitationally lensed images. At the top is shown the formation of an Einstein ring of a distant quasar by a foreground galaxy directly along the line of sight. The light rays are deflected by an angle α, and the apparent separation of the galaxy and lensed images from the observer's point of view is θ. The bottom panel shows the formation of images from a quasar by a galaxy which is offset by a small angle β from the line of sight to the quasar. The picture also gives the definitions of the distances D_l, D_s and D_{ls} discussed in the text. [A colour version of this figure appears in the CD-ROM version of this chapter].

a ring image will be seen – known as an "Einstein ring" in honour of Einstein's general-relativistic prediction of its radius for a given mass of deflector. In the more general case, there will be multiple Fermat extrema in the field of the lensed system, and multiple images will be produced.

The radius of the Einstein ring can be calculated using simple theory. Consider the diagram shown in Figure 1. If we write θ for the apparent separation of the lens and lensed image, D_l and D_s for the distances[1] to the lens and source, respectively, and D_{ls} for the separation of lens and source, simple geometry shows that

$$\theta - \beta = \alpha D_{ls}/D_s$$

(the so-called *lens equation*), where β is the angle on the sky, in the absence of lensing,

[1]To be precise, these are what is known in cosmology as "angular size distances", defined such that the angle θ subtended by unit length within an object is given by $\theta = 1/D$. They are different by a factor of $(1+z)^2$, where z is the redshift, from the "luminosity distance" which relates absolute and apparent brightness. Consult any cosmology text, for example *Peacock [2000]* for further details.

separating the lines of sight to the source and lens. For an Einstein ring to be seen, $\beta = 0$ and, since $b = \theta D_l$, we can combine the two equations with Einstein's original equation for the deflection angle in terms of the impact parameter b to obtain

$$\theta = \sqrt{\frac{4GMD_{ls}}{c^2 D_l D_s}}.$$

For typical galaxy masses, $M \sim 10^{11}$–$10^{12} M_\odot$, at cosmological distances, one obtains Einstein radii of about $1''$. For typical stellar masses, Einstein radii are of the order of a few microarcseconds at cosmological distances, or about a milliarcsecond at distances of $\sim 1\,\mathrm{kpc}$ within our galaxy; with current technology, such small splittings are difficult to observe in the optical, although such "microlensing" events are recognisable by increases in magnification. However, most of this review will concentrate on arcsecond-scale lensing by galaxies, as this is the area in which most progress has been made by radio techniques, though radio observations are just beginning to be made of stellar-scale "microlensing" events and will be discussed in some detail in section 5. Lensing on larger scales, by clusters of galaxies, is also possible. This gives information on mass distributions in clusters of galaxies and large-scale structure We mention this only briefly, in section 6.2 on the SKA, but an extensive review is given by *Mellier [1999]*.

1.3 Observables in real systems

In order to get an idea of what might actually be observed, we make some plausible assumptions. First, real lensing galaxies normally lie at redshifts of $\sim$0.5. At this distance, most of a typical galaxy's stellar light subtends an angle of about $1''$ or less. Therefore measuring the light distribution requires the Hubble Space Telescope or at least adaptive optics on ground-based telescopes. But what really matters in gravitational lensing studies is the *mass* distribution in the lensing galaxy and here our lack of knowledge becomes embarrassing. It has been known for some time that galaxies contain a large amount of "dark matter" over and above that which can be accounted for by normal luminous stars (see *Rubin [2000]* for a recent review). There is evidence for dark matter existing on many scales, from within galaxies themselves, in which dynamical studies indicate much more mass than is observed as luminous mass, to clusters, where the dynamics of the galaxies within the cluster are dominated by dark matter. How this mass is distributed is not clear, although recent simulations of galaxy formation have begun to illuminate this area (e.g. *Navarro, Frenk & White [1996]*).

Knowledge of the mass distribution is required for gravitational lensing studies because the lens equation (which relates θ and α) simply states the geometrical conditions for images to be seen. In order to make further progress with physical modelling we need a relation between θ and α peculiar to the mass distribution we are considering. Einstein's original relation does this for a point mass, but this is not a particularly realistic representation of a galaxy! In section 3 we discuss the impact on lensing studies of galaxy mass models; here we examine the general properties of such models.

In Figure 2 the lens equation (the dotted straight line) and the variation of α with θ for different galaxy mass models are plotted. Lensed images occur only when both equations are satisfied simultaneously, and it can be seen that three images may be produced,

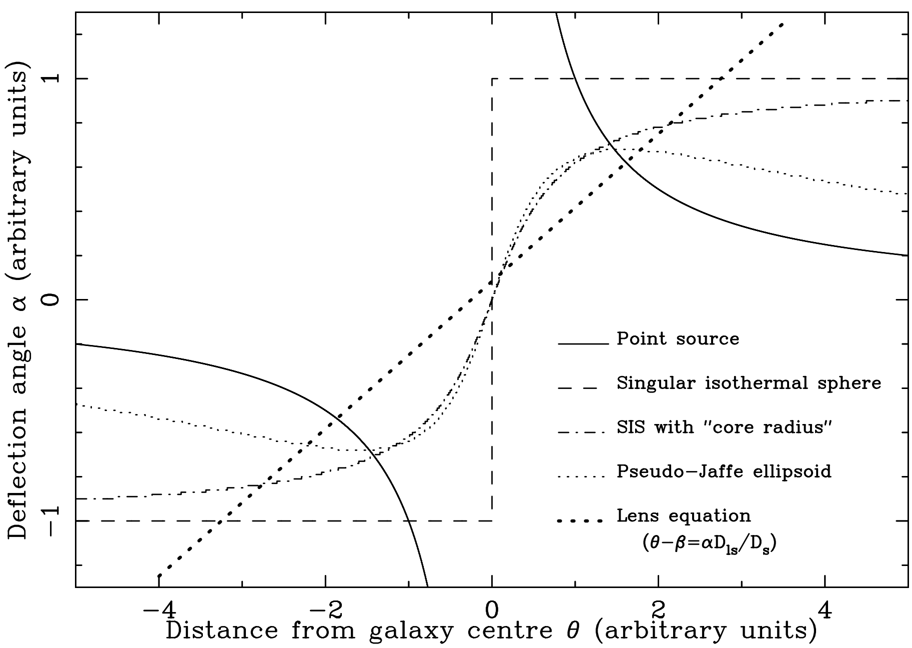

Figure 2: "Bend angle diagram" for a gravitational lens. This shows the deflection suffered by a ray of light as a function of impact parameter from the centre of the lensing galaxy. For a point mass, this is given by $1/b$. Three other, more plausible, mass distributions in common use for lens modelling are also plotted, including a variant of the *Jaffe [1983]* model. In addition, a straight line corresponding to the Lens Equation is also plotted. For any mass distribution, images will be formed when the bend-angle line crosses the lens equation line. *Keeton [2001]* summarises many other mass distributions.

provided that β is small enough. This latter condition of course corresponds to the lines of sight to lens and source being close enough to each other. Another condition is also necessary; the slope of the $\alpha - \theta$ relation must be sufficiently high in the central region to allow three intercepts rather than one. Since the deflection angle α is related to the projected gravitational potential ψ by the equation

$$\alpha = \nabla\psi$$

this introduces the additional requirement that the potential well should be sufficiently deep, steep or both to allow multiple-image lensing to occur. It can be shown that this condition corresponds to having a surface mass density exceeding a critical value (Σ_{crit}, which at cosmological distances is about 1 gram cm^{-2}). Objects with less than this critical density may distort and magnify background objects, but they will not generally produce multiple images. In practice, massive galaxies often possess central mass densities such that $\Sigma > \Sigma_{crit}$ by factors of a few, and stars by factors of many thousands. Clusters of galaxies can fall below this surface mass density limit, although many do produce multiple images.

There are situations in which more than three images of the background object will be seen. First, the above analysis has been done in one dimension (see e.g. Figure 2). Proper analysis in two dimensions shows that for small enough impact parameters and non-circularly-symmetric potentials, five images, not three, will be produced (the reader is referred to standard texts such as *Schneider, Ehlers & Falco [1992]* for the full details; see also Fig. 3). Secondly, it is a standard result of geometrical optics that lenses, including gravitational lenses, produce distortion (changing areas and shapes) of background objects during the imaging process yet always conserve surface brightness. The production of larger or smaller images with constant surface brightness therefore corresponds to production of images which have larger or smaller flux densities than the original image. Most of the images in a gravitational lens are magnified by the lensing, by factors of up to 10 in typical galaxies. However, the central image, which is always produced near the centre of the lens, is demagnified, usually by factors of a few hundred, to the point where it falls below detection thresholds. This results in typical galaxy-mass lens systems having either two or four detectable images[2], depending on the mass of the lensing galaxy and the size of the impact parameter.

In Figure 3 we illustrate the configuration of images formed as a source approaches the line of sight to a lensing galaxy. Far from the line of sight, only one image is formed although it is in general slightly magnified and distorted. As the source crosses the outer caustic, a second faint image appears close to the lensing galaxy, corresponding to the appearance of an extremum in the Fermat surface of the system. As the line of sight moves closer, the source crosses the inner caustic. At this point another extremum appears, which splits into two producing two highly magnified, distinct images which gradually separate as the source moves closer in. This four-image configuration, with two close, bright images and two more distant images, is characteristic of lensing systems. To search for gravitational lenses one therefore looks for the characteristic two- or four-image configurations within any sample of interest.

[2]In fact, more than four images can in principle be generated for complicated deflectors such as multiple galaxies. *Keeton, Mao & Witt [2000]* discuss such systems, and one has actually been found *[Rusin et al., 2000; Rusin et al., 2001]*