GRAVITATIONAL LENSING

A Universal Astrophysical Tool

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Abstract. In the roughly 20 years of its existence as an observational science, gravitational lensing has established itself as a valuable tool in many astrophysical fields. In the introduction of this review we briefly present the basics of lensing. Then it is shown that the two propagation effects, lensing and scintillation, have a number of properties in common. In the main part various lensing phenomena are discussed with emphasis on recent observations.

1. The Basics of Lensing and Microlensing

The general geometry of a gravitational lensing situation is shown in Figure 1: the light path between observer O and source S is affected by a mass L between them. In a 'strong' lensing situation – lens and source are well aligned – two (or more) images S_1 and S_2 of the background source can be produced. They are separated by an angle which is proportional to the square root of the lens mass (see below). For typical galaxy masses this angle is of order arcseconds.

If the lens is a galaxy which consists partly of stars (and other compact objects), due to the graininess of the main lens, each of these (macro-)images consists of many micro-images, which are separated by angles of order microarcseconds, and hence unresolvable. However, due to the relative motion between source, lens and observer, the micro-image configuration changes with time, and so does the observable total magnification.

From Figure 1, one can easily derive the lens equation (all angles involved are small: $\alpha, \tilde{\alpha}, \beta, \theta \ll 1$):

$$\vec{\beta} \times D_S = \vec{\theta} \times D_S - \vec{\tilde{\alpha}} \times D_{LS}.$$

This relation reduces to $\vec{\beta} = \vec{\theta} - \vec{\alpha}$, where

$$\vec{\alpha} = (D_{LS}/D_S) \times \vec{\tilde{\alpha}} = (4GM/c^2)(\vec{\xi}/\xi^2) \propto (\vec{\theta}/\theta^2)$$

is the deflection angle for a point lens (G – gravitational constant; c – speed of light; $\vec{\xi}$ – impact parameter of light ray; M – mass of the lens; D_L, D_S, D_{LS} – angular diameter distances between observer-lens, observer-source, lens-source).

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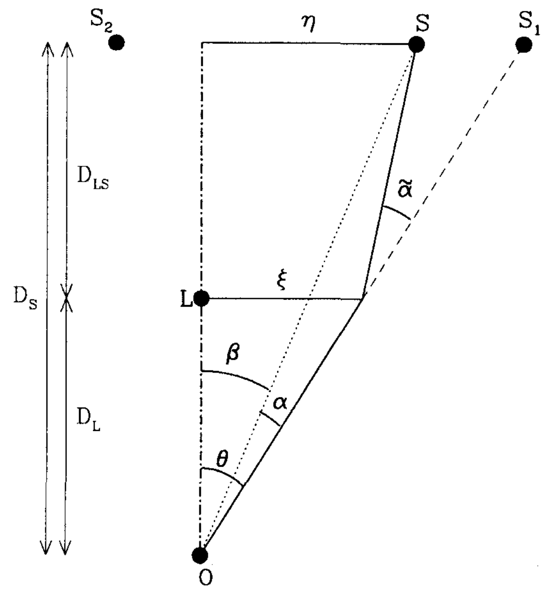

Figure 1. Basic setup of a gravitational lens situation. The lens L in the lens plane produces two images S_1 and S_2 of a background source S. If the lens has substructure (e.g., stars in a galaxy) each macro-image is split into many micro-images. Only the total magnification of all the microimages is observable. (The symbols are explained in the text.)

The positions of the images are the solutions of the quadratic equation for θ. For perfect alignment, i.e. $\vec{\beta} = 0$, the circular symmetric image has a radius of

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S}} \approx 2\sqrt{M/10^{12}M_\odot}\text{arcsec} \approx 2\sqrt{M/M_\odot}\text{microarcsec}.$$

This defines the relevant angular scale for gravitational lensing, the angular Einstein radius θ_E of the lens ('typical' lens and source redshifts of $z_L \approx 0.5$ and $z_S \approx 2.0$ were assumed for the numerical values on the right hand side).

This angular scale translates into a length scale in the source plane:

$$r_E = D_S \times \theta_E \approx 4 \times 10^{16}\sqrt{M/M_\odot}\text{cm} \approx 10\sqrt{M/10^{12}M_\odot}\text{kpc}.$$

The value on the right hand side is typical for galaxy masses. This type of 'macro'-lensing can be directly observed in form of multiply imaged quasars, with images separated by angles of order a few arcseconds.

Image splittings of microarcseconds corresponding to stellar mass lenses can obviously not be detected directly. What makes 'microlensing' observable anyway is the fact that observer, lens(es) and source move relative to each other. Due to this relative motion, the micro-image configuration changes with time, and so does the total magnification, i.e. the sum of the magnifications of all the micro-images.

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And this change in magnification over time can be measured: microlensing is a 'dynamical' phenomenon. There are two time scales involved: the standard lensing time scale t_E is the time it takes the source to cross the Einstein radius of the lens, i.e.

$$t_E = r_E/v_\perp \approx 15\sqrt{M/M_\odot}\,v_{600}^{-1} \text{ years},$$

where the same typical assumptions are made as above, and the effective transverse velocity v_{600} is parametrized in units of 600 km sec^{-1}. This time scale results in discouragingly large values. However, we can expect fluctuations on much shorter time intervals, due to the fact that the magnification distribution is highly non-linear, the sharp caustic lines separate regions of low and high magnification. So if a source crosses such a caustic line, we will observe a large change in magnification during the time it takes the source to cross its own diameter:

$$t_{cross} = R_{source}/v_\perp \approx 4 R_{15} v_{600}^{-1} \text{ months}.$$

Here the quasar size R_{15} is parametrized in units of 10^{15} cm.

2. Similarities Between Lensing and Scintillation

Gravitational lensing and interstellar scintillation are both propagation phenomena, and in fact these two physical effects have quite a number of aspects in common. This is graphically demonstrated in Figure 2. In both cases, a signal emitted by a distant source is affected by some intermediate medium, so that the observer receives a modified signal. The physical effect of the medium in both cases is the *deflection of electromagnetic waves* (restricted wavelength range in the case of scintillation), which causes

a) shift of image position,
b) apparent magnification or demagnification of a source (relative to the unaffected situation),
c) distorted image shape,
d) time variability due to relative motion of source, medium and observer, and
e) occasionally multiplicity of images.

Both lensing and scintillation can be used to better understand intrinsic properties of the source: size, structure, variability, as well as properties of the 'medium': size, mass, transverse velocity. The effect of the medium can be dominated by one relatively strong interaction (single screen), or by a sum of many uncorrelated weak effects (multi screen).

In Table I a selection of astrophysical fields in which gravitational lensing is important is listed. In order to stress the parallels to scintillation, it is also indicated whether in this particular field the 'object of desire' is the source or the medium.

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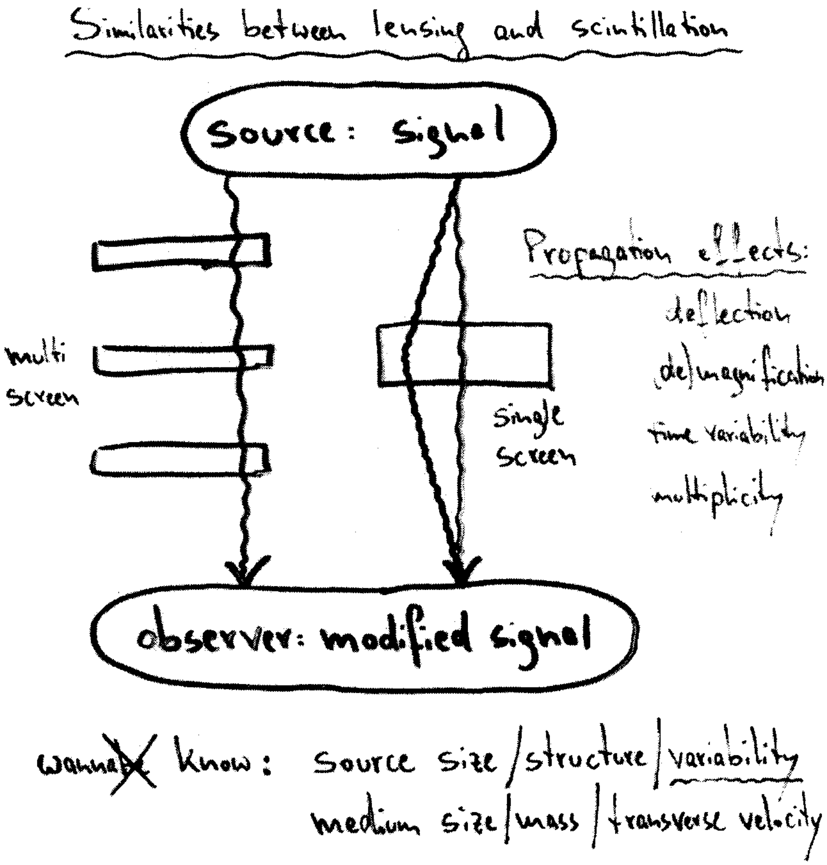

Figure 2. Similarities between gravitational lensing and scintillation as propagation mechanisms.

TABLE I

Goals of lensing and their relation to the propagation aspect

Phenomenon	Object of interest
search for dark matter	medium
cosmology: H_0, Ω_{matter}, Ω_Λ	medium
size/structure/physics of quasars	source
galactic structure	medium
evolution of galaxies	source/medium
search for extra-solar planets	medium

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TABLE II

Gravitational lens phenomena: number of cases, recent reference/review

Phenomenon	# of cases	Recent reference/review
Multiple quasars	> 50	CASTLES, Falco *et al.*, 1999
Time delays, H_0	≈ 6	Myers, 1999
Giant luminous arcs	≈ 100	Mellier, 1999
Einstein rings	≈ 10	CASTLES, Kochanek *et al.*, 2000
Quasar microlensing	> 5	Wambsganss, 2000
'Arclets', weak lensing	~ 200	Mellier, 1999
Galactic microlensing	> 500	Alcock *et al.*, 2000
Lensing by large scale structure/'cosmic shear'	a few	Bacon *et al.*, Kaiser *et al.*, van Waerbecke *et al.*, Wittman *et al.*, 2000

3. Lensing Phenomena

In Table II the most prominent gravitational lensing phenomena are given with the approximate number of detected cases and a recent reference or review. A more detailed discussion of the various phenomena with many examples can be found in Wambsganss (1998). An up-to-date version of the observational situation concerning lensed quasars is available at the CASTLES weg page (Falco *et al.*, 1999).

About 10% of the roughly 50 known multiply imaged quasars have a measured time delay. Together with a model of the lensing galaxy, this provides a determination of the Hubble constant. Myers (1999) has summarized the latest situation: values of the Hubble constant determined from gravitational lensing tend to be lowish (around 65 km s^{-1} Mpc). Uncorrelated fluctuations in multiply images quasar are interpreted as microlensing by stellar mass objects. It can be used to determine the structure of quasars and the mass of the lensing objects (Wambsganss, 2000).

Giant luminous arcs found in rich galaxy clusters provide strong support of large masses for these clusters, which means that they are dominated by dark matter. Even clusters at redshifts close to one still show (weak) lensing effects on background galaxies (Mellier, 1999).

Einstein rings – annular images due to perfect alignment between lens and source – are mostly known in the radio regime. Since they are 'extended', they provide many more constraints on the deflecting potential than a few point-images of quasars. Hence the lensing galaxies of Einstein rings are probably those with the most accurately determined masses and mass distributions (Kochanek, Keeton and McLeod, 2000).

The most recent development of gravitational lensing is the discovery of 'cosmic shear', the very weak lensing effect of large scale structure on background

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sources. In a kind of stimulated emission, four groups presented their uncorrelated detections within a few days this spring: Bacon, Refregier and Ellis (2000), Kaiser, Wilson and Luppino (2000), van Waerbecke *et al.* (2000), and Wittman *et al.* (2000).

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