IMAGING WITH A GRAVITATIONAL LENS

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Abstract. The basic ideas of gravitational microlensing are discussed. Particular attention is given to the use of a gravitational lens as a (non-standard) telescope, to probe the very small scale structure of extragalactic sources. The recovery of information from a gravitational lens telescope is discussed, as well as the unique contribution which can be made by imaging with a gravitational telescope.

1. Introduction

Usually when we consider very high angular resolution imaging of extraterrestial objects, we think in terms of interferometric measurements of the source using a multi-element array or perhaps compensation for the smearing induced by the Earth's atmosphere. An alternative technique, which might provide very high resolution information on extragalactic objects, is microlensing. Microlensing is the term used to describe the gravitational lensing of background sources by compact foreground objects such as stars, planets or black holes. Since the angular separation of multiple images from gravitational lensing by a mass M is $\theta \sim (M/10^{12}\,\mathrm{M}_{\odot})^{\frac{1}{2}}$arcsec, the separation of multiple images due to lensing by stars is $\sim 10^{-6}$arcsec, much smaller than can be resolved at any wavelength by more conventional techniques. Clearly then, it is not possible to resolve the structure of such configurations of lensed images; however there are two associated effects which are observable – the magnification of the background source, and the effects of timedelay between different images.

2. Basic Ideas of Microlensing

Gravitational lensing is the term used to describe the effects of a non-homogeneous mass distribution on the passage of light through space. There are a number of different formalisms which can be used to describe the propagation of light from a distant source. The full details of these formalisms will not be repeated here, since they are well-described in a number of books and review articles: Narayan and Wallington (1992), Schneider, Ehlers and Falco (1992) and Blandford and Kochanek (1987).

One simple way to understand the effects of an inhomogeneous mass distribution is to consider the shape of the wavefront as it passes over local inhomogeneities. Consider a source which emits a pulse of radiation; in a region of smooth mass distribution, at a time δt later, the wavefront can be depicted as a sphere of radius $c\delta t$. When part of the wavefront enters a region of higher gravitational potential, the wavefront is delayed, and that part of the wavefront is deformed. If the observer is sufficiently distant from the region of increased gravitational potential, then the wavefront develops a fold. The location where the fold develops is somewhat analogous to the focus of a glass lens, although gravitational lenses rarely have a point of perfect focus. The focus of a gravitational lens depends on the distribution of the

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mass in the lens, and will only be a point-like for a mass distribution of constant surface density.

Even though the wavefront develps a fold, it remains continuous, except in the case where the mass is not transparent (*e. g.* a star) or where the gravitational potential becomes infinite (*e. g.* a black hole). The number of images seen by the observer can be determined by the number of times the now deformed wavefront crosses the observer's location, and the direction of each image will, of course, be perpendicular to the wavefront. By determining the radii of curvature of the wavefront, the observer can also determine the amplification of the source. In gravitational lensing, surface brightness is conserved, so that the apparent brightening of the source means that the observer is actually 'seeing' a greater solid angle of the source. Also, by the equivalence principle, photons of different wavelengths are all effected similarly by a gravitational lens. Thus the spectrum of light from one specific part of the source will be unchanged by gravitational lensing. However a source may be differentially amplified, changing the observed spectrum.

For high resolution imaging studies, we are interested in the effects of a compact objects on the propagation of the light beam. For this mass distribution, the light is focussed to a line, the extension of the line joining the source and the compact object. An observer on this line will see a luminous ring, usually referred to as the Einstein ring. The angular radius of the ring is given by:

$$\theta_E = \left(\frac{4GM}{c^2 D}\right)^{\frac{1}{2}} = 1.7 \times 10^{-6} \left(\frac{M}{\mathrm{M}_\odot}\right)^{\frac{1}{2}} \left(\frac{10^{3.5}\mathrm{Mpc}}{D}\right)^{\frac{1}{2}} \mathrm{arcsec} \quad (1)$$

where M is the mass of the compact object and D is the effective distance given by $D = D_{ol} D_{os} / D_{ls}$ where the D's are angular diameter distances and the subscripts refer to observer, lens and source respectively. If the microlens is closer to either the source or the observer, then the radius of the ring increases, but the probability of a close alignment between observer, microlens and source decreases.

In order to observe the effects of microlensing, either part of the source must vary, or there must be relative motion between source, lens and observer. In the first case, the variations in the source are observed at different times, corresponding to different images, by the observer. The timedelays between different images are simply the sum of the path differences and the differences in gravitational potential. If the source position, in the absence of a lens is θ_s, then it is possible to describe the time delay surface in some particular direction with respect to an unlensed ray, as

$$t(\theta_i) = (1 + z_d)\left(\frac{D_{os} D_{od}}{2cD_{ds}}(\theta_i - \theta_s)^2 - \frac{2}{c^3}\int \phi(\theta_i D_{od}, s) ds\right) \quad (2)$$

ϕ refers to the Newtonian potential of the lens. Then the timedelay between two images is $\delta t = t(\theta_i) - t(\theta_j)$. In the second case, the relative motion causes successively different parts of the source to be highly amplified. It is common practice to map the caustic structure due to the microlenses into the source plane (*e. g.* Schneider, Ehlers and Falco, 1992). By then determining the relative source motion, it is possible to calculate the expected light curves caused by ensembles of microlenses of different masses and optical depths. The transverse velocity projected into the source plane is given by

$$\mathbf{v}_t = \frac{1}{1+z_s}\mathbf{v}_s - \frac{1}{1+z_l}\frac{D_{os}}{D_{ol}}\mathbf{v}_l + \frac{1}{1+z_l}\frac{D_{ls}}{D_{ol}}\mathbf{v}_o \quad (3)$$

where the velocity vector of each part of the system is that component perpendicular to the line-of-sight.

In order to image by microlensing, the background object must be observed through a field of stars, for example a galaxy. The optical depth to microlensing for a particular geometry and star density can be determined by calculating the fraction of the lens plane which is covered by the Einstein rings due to each individual star. This is equivalent to the ratio of the smoothed surface density due to stars, to the critical surface density. The latter is defined as the constant surface density which would exactly focus the light from the source at the observer, for the particular geometry in question.

3. Probing the Structure of Quasars

Resolution of features of extragalactic objects depends on a number of criteria. For a particular compact object, the Einstein ring is a good measure of the region which might be amplified. If the region subtends an angle ξ_s, much greater than θ_E, then the microlens will have little effect on the observed flux from that part of the source. Thus $\xi_s \lesssim \theta_E$ for observable effects. It is difficult to disentangle the intrinsic variability effects of the source from the effects of microlensing. Presently the only way we can do this is to observe quasars which are macrolensed. With some knowledge of the timedelay, the effects of intrinsic time variability can be separated from microlensing effects by observing the variability in different images. Grieger *et al.*(1988) have proposed using a parallax method with two widely separated telescopes, to detect microlensing in a single source. Use of this method must await the availability of space observatories at distances > 100AU.

Microlensing by a solar mass object will amplify a region of size $\sim \theta_E D_{os} \sim 2.4\times10^{-2}h_{100}^{-1}$pc. For a cosmological configuration, typically $v_t \sim 10^3$km/s. Thus the typical timescale for crossing the caustic structure caused by a solar mass is about ten years. Both these values scale like $M^{\frac{1}{2}}$. Variations on shorter timescales will be measured if regions of the source are smaller than the above value. If the lensing geometry is atypical, and the lens is either very close to the source or the observer, then these scales might change; in particular in the case of quasar 2237+0305, the expected timescale for variability is reduced by a factor of ten.

We still only have rough ideas about the structure of an image of a quasar. However, from variability arguments, both the continuum and the emission line region might be small enough to be effected by microlensing by solar-sized objects.

4. Results to Date

The lens system Q2237+0305, which has four images of a quasar at redshift $z = 1.7$, around the nucleus of a low redshift ($z = 0.04$) barred spiral galaxy, is the first system in which microlensing variations have been convincingly detected. This system is an excellent candidate for microlensing: it is relatively easy to distinguish intrinsic variations in the quasar from microlensing variations, since the former will occur on timescales of a few days, the timescales of the variability are expected to be foreshortened by a factor of ten compared to a more typical lens, since the lensing galaxy is at such a low redshift, and the images are known to traverse regions where the optical depth to microlensing is of order 0.5.

A compilation of the direct imaging data taken in good seeing up to the end of 1989 (Corrigan *et al.*1991), showed that several changes in the brightness (of $\sim 0.3m$) of one of the images had taken place over periods of 27-50 days. Since the coverage of the observations is poor, these estimates of the timescale of the changes are at best upper limits, however the photometry is accurate to about $0.05m$, so there can be little doubt that the variations are real.

Any rise or fall in the light curve can be used to estimate the size of the region which emits the flux at the observed wavelength, since each rise or fall is caused by the source crossing a region of high amplifcation. A reasonable estimate of the transverse velocity for Q2237+0305 is $\sim$ 6000km/s. Thus a conservative estimate of the continuum source size is $< 6 \times 10^{-4}$pc.

Rauch and Blandford (1991) have used this estimate of the source size to argue that the putative accretion disk which is thought to emit the optical continuum observed in an AGN, cannot be optically thick. The argument is a simple one: suppose that the continuum emission is emitted from gas in the accretion disk which is emitting as a black body. The observed flux of the quasar, with appropriate allowance for the gravitational lensing magnification, provides an estimate of the luminosity. They find that the accretion disk would need to be at least 3 times larger than the rather conservative value deduced from the observations to produce the required luminosity. Another way of stating this, is that the brightness temperature would need to be $> 2 \times 10^5$K, or ten times greater than the temperature of a thermal disk required to account for the observed flux. Other possible models are also considered, but they fit the data just as poorly. They therefore deduce that the emission must be non-thermal, and the accretion disk optically thin.

To date there have been systematic observations of only one multiply-imaged quasar, 0957+561, and in this case there is only weak evidence for microlensing. In two other cases, where microlensing might more readily be observed, unconfirmed observations provide additional glimpses of the data which might be obtained from regular monitoring programs. For 2237+0305, Fillipenko (1989) found that the width of the MgII emission line varied by 20% between the two brighter images. If this effect were due to microlensing, then this would provide some information about velocity distribution of the emitting material as a function of its spatial position. For the same quasar, Corrigan *et al.*(1991) found weak evidence for colour changes in one image as a function of amplification. Such observations might provide information about the spectral profile of the continuum source. For the BAL quasar, 1413+117, Angonin *et al.*(1990) found evidence for differences in structure of the absorption troughs in different images. These might be due to either variability in the source or to differential amplification of different parts of the source.

5. Concluding remarks

Gravitational microlensing can resolve structure in extragalactic sources on much smaller scales than any other know technique, *i. e.*microarcsecond scales. However this is a telescope over which we have no control – we are not able to chose our sources, nor our microlenses. In particular, we cannot chose the mass distribution in the lens, and must work not only with the imperfect focus that a compact object provides, but usually with the complex network of caustics realised from an ensemble of compact objects. Deconvolution techniques for the light curves are still in their infancy. Nevertheless, signficant progress has been made, and we might expect that consistent monitoring of selected objects both by direct imaging and spectroscopy, might provide a wealth of information, particularly on the structure of quasars.

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