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GRAVITATIONAL LENSING AND LARGE-SCALE STRUCTURES

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ABSTRACT

The role of gravitational lenses as valuable tools for astrophysics and cosmology is highlighted.

I. INTRODUCTION

A manifestation of gravitational lensing arises when the gravitational field of an intervening deflector bends the paths of light rays from a remote object, in the process distorting the position, size, shape and luminosity of the background source. The phenomenon of gravitational lensing is a direct consequence of gravitational deflection of light. In fact, the bending of starlight grazing the solar limb was, indeed, measured during the total solar eclipse of 1919 to find its value of 1.75 arcsecond to be approximately twice the Newtonian value, in agreement with the prediction of Einstein's general theory of relativity. Zwicky (1937) applied the ideas of gravitational lensing in the context of extragalactic astronomy to recognize that the image-separations from the lensing action of galaxies would be of order ~ 1 arcsec and these should be resolvable by conventional telescopes. Zwicky also predicted that the lensing will allow a mass determination of distant nebulae and due to the magnification effects it could enable astronomers to have a deeper view of the cosmos.

The discovery of the first multiply-imaged quasar system, 0957+561 by Walsh, Carswell & Weymann (1979) gave a real boost to the field which has witnessed considerable progress over the past decade, in both its observational and theoretical aspects. The observed lens systems can be broadly classified into three image morphologies:

i) Multiply imaged QSOs: double, triple and quadruple images; ii) Ring-shaped images: complete or partial ring-like radio structures; iii) Arcs/Arclets: extended curved and linear features

We adopt the following criteria for designating an image configuration as a lensed system:

i) Morphology: Multiple images of a background compact source e.g. a quasar) with almost identical spectral characteristics and redshifts; ring-like images and arcs/arclets arising from a background extended source such as a galaxy being lensed by an intervening deflector (e.g., galaxy, cluster of galaxies)

ii) Flux-ratios: Similar flux ratios between images as the observing wavelength is varied.

iii) Lensing object: Presence of an intervenor near the sightline to the background source.

iv) Correlated variations: Source intensity, polarization, spectral variations reflected in various images with a time-delay.

The gravitational bending of light is insensitive to nature of the deflecting objects. The study of gravitational lens systems is, therefore expected to play an important role in inferring the nature and distribution of gravitating matter- both luminous and dark- lying en route to a distant source. The diverse image morphologies provide valuable tools to probe structures in the universe from planetary sizes to several tens of Mpcs. From the observed image configurations it becomes possible to infer the masses of lensing galaxies and galaxy-clusters, their core radii, ellipticities and density distribution. The cluster lenses can be profitably used as giant cosmic telescopes to provide a magnified view of the distant faint sources in a flux limited survey. It also becomes feasible to attempt cosmography with the help of lensing, specifically for estimating the Hubble constant.

The density distribution in lensing galaxies is not expected to be smooth and one can employ the graininess and granularity arising from individual objects like stars and black holes as microlenses to probe the intrinsic structure of background sources, such as angular sizes of continuum and emission line regions in quasars. The lensing events can furnish useful information about the sizes of intervening $Ly\alpha$ clouds, determine chemical abundance (e.g. presence of molecules like (H_2, CO) in deflecting systems, probe magnetic fields associated with the lensing galaxy or the cluster, and shed light on the size-evolution and redshift distribution of distant faint galaxies. Thus, gravitational lenses are expected to provide a distorted, but insightful, view of the Universe.

II. GRAVITATIONAL LENSING BY EXTENDED DEFLECTING OBJECTS

The action of an extended lens like a galaxy or a cluster of galaxies may be studied in the weak field approximation. In the linearized theory the gravitational bending angle has a negligible component along the light path when the source-observer distances are much larger than the impact parameter distance. This enables one to adopt the complex formalism due to Bourassa and Kantowski (1975) applicable to an elliptical lens. If one projects all positions onto the deflector plane taken orthogonal to the sightline, then the source and image positions, denoted respectively by complex numbers, $z_s = x_s + iy_s$ and $z_I = x_i + iy_I$ are related by the lens equation,

$$z_s = z_I - \frac{4GD_dD_{ds}}{c^2D_s}I^\star(z_I).$$

Here $I(z_I)$ is the complex scattering function which incorporates the requisite information about the lens properties like its density distribution, core-radius, ellipticity; D_s = observer-source distance, D_d = observer-deflector distances. D_{ds} = deflector-source distance. The object is to locate roots of this complex equation which give a configuration consistent with the observed separation of images and their intensity ratios.

Amongst the dozen or so confirmed gravitational lenses, the triple quasar 1115 + 080 discovered by Weymann et al (1980) is a relatively clean system which can be modelled satisfactorily. This is a canonical five-image configuration produced by a single-component; substantially eccentric ellipsoidal lens (Narasimha, Subramanian and Chitre, 1982). The predicted position of the lens galaxy of this model turned out to be in excellent good agreement with the HST observation of the lensing object (Crane, 1992).

The discovery of arcs/arclets and rings has highlighted the importance of lensing of extended sources by transparent deflector (Saslaw, Narasimha and Chitre 1985). The giant arcs in the cores of rich clusters of galaxies were first reported by Lynds and Petrosian (1986) and Soucail et al (1987). There are now dozens of such arcs and arclets detected and it is generally accepted that the arcs/arclets are manifestations of lensing phenomenon in the deep gravitational potential associated with a galaxy-clusters, generating a largely tangentially amplified image of an extended background galaxy (Paczynski 1987; Grossman & Narayan 1988, Narasimha & Chitre 1988). An interesting image configuration in this category is the extended linear features near the cluster-centres. (Pello et al 1991; Melnick et al 1993). Such a large linear structure results from the marginal lensing of a source galaxy by a foreground galaxy-cluster, when the surface mass density, Σ of the lensing cluster just marginally exceeds the critical surface density, $\Sigma_c = \frac{c^2 Ds}{4\pi G D_d D_{ds}}$. In fact, a detailed spectroscopic study of the arcs will be highly desirable for mapping the velocity field and brightness distribution of the background galaxy. Equally, the morphology of these linear features should be valuable in constraining the surface mass distribution and gravitational potential of the lensing cluster.

Some half a dozen image configurations of partial or near-complete ring-like images with angular extent $\leq$ arcsec have been detected. Such a morphology results when distant radio sources are lensed by a radio-quiet intervenor in the form of a galaxy (cf. Hewitt et al 1988; Langston et al 1989). Thus, for the radio ring 1634 + 1346, the source-structure could be the central high redshift ($z = 1.74$) quasar which is singly imaged, while one of its radio lobes is imaged into a ring-like morphology by the lensing action of a low redshift ($z = 0.254$) galaxy en route. The Ooty radio ring 1830-211 is an unusually strong ($\sim 10Jy$) flat-spectrum double radio source, with $\sim$ *arcsec* dimension. In this system the source could be a dominant compact core with a highly bent arcsecond-size jet, lying largely in a three-image region bounded by a radial caustic (Nair, Narasimha and Rao 1993).

III. ASTROPHYSICAL APPLICATIONS

Gravitational lenses provide a powerful tool for locating dark matter (baryonic and non-baryonic) in the Universe on galactic as well as cluster, scales. The lensing events are sensitive to the total gravitating mass distribution and are, therefore, useful in mapping both the luminous and dark matter present in the deflecting objects. Thus, the baryonic dark matter candidates may include sub-solar mass dwarfs ($10^{-4} - 10^{-1} M_\odot$), very massive compact objects ($10^4 - 10^6 M_\odot$) which could be responsible for microlensing events reported by MACHO, OGLE, DUO, EROS projects (cf. Paczynski 1996)

There are a host of relatively large-separation quasars images (cf.2345+007, 1635+267) with remarkably similar spectral characteristics (Weedman et al 1982; Dgorgovski and Spinrad 1984). Some of these multiple image configurations are likely to be manifestations of the phenomenon of dark matter gravitational lensing (Turner et al 1988; Steidel & Sargent 1991). There are also compelling theoretical considerations to invoke the assistance of an additional mass-component around the lens galaxy either in the form of a dark halo or as yet undetected compact core of a galaxy-cluster to reproduce the observed large-separation image configurations (cf. Narasimha and Chitre 1989). It is proposed that massive underluminous galaxies with dark halos are probably responsible for lensing action in some of the systems where the intervening objects are being elusive. In fact, there may be present such large-size, high-mass ($\geq 10^{12} - 10^{13} M_\odot$) low surface brightness (LSB) galaxies in the universe at moderate redshifts which may serve as dark lenses and which could be detected by their gravitational influence on distant background source. The large quantities of neutral hydrogen gas in such lensing galaxies is liable to generate a copious amount of radio emission at 21 cm with a ratio flux of a few tens of mJy. A definitive signature of a dark lens would be substantial amount of 21 cm emission in the frequency range of 500 to 1400 MHz (for z=0.5-1.5) and Lyα absorption at the same redshift.

The study of giant luminous arcs like Abell 370 generated by the phenomenon strong lensing can furnish valuable information about the core radii, masses, ellipticity of rich clusters and the amount of dark matter present in their cores. The existence of several faint arcs/arclets is an indication of weak lensing reinforcing the idea that the distribution of dark matter is perhaps spread as far as the outskirts of clusters to scales of hundreds of Kpc. The dark matter is thus not necessarily clustered around galaxies, but rather there is also a diffuse component of dark matter distributed throughout the cluster. It seems unlikely that dark matter is clumped only around massive galaxies in cores of clusters, for otherwise extended arcs detected in cluster lenses would have been broken up on several arcsec scales and would necessarily form around cluster members (Tyson et al 1990).

The linear features (e.g. Abell 2390, 2236-04) are valuable for mapping the velocity field and brightness distribution in the background spiral galaxies which might be the sources lensed to generate the straight morphology. It would then be feasible to use the surface brightness and rotation velocity measured from these features to test the Tully-Fisher relation for distant ($z \geq 1$) spirals (Narasimha and Chitre 1993).

A direct consequence of the lensing action due to an intervening deflector en route is that if the intensity, polarization or any spectral feature of the background source varies with time, these variations will not manifest in all the images simultaneously, but rather with a relative time delay between different images. This is a combination of delay contributed by different geometrical light paths and by different gravitational potential wells sampled by the photons, and may be expressed as

$$\Delta t = \frac{1}{H_0} F(z_L, z_s, \text{Lens Model, Cosmology})$$

The dimensionless function, F has a weak dependence on the cosmological parameters like the deceleration parameter and cosmological constant. (Refsdal 1964; Cooke and Kantowski 1975). The effective time-delay which is inversely proportional to the Hubble constant, H_0 has the largest uncertainty resulting from the underlying lens model.

The gravitational lens system 0957+561 has been monitored, both in the optical and radio wavebands, to give a time-delay, Δt_{AB} between the components $A, B = 510 \pm 40$ days. This gives a value of H_0 ranging from 50 to 80 km/sec Mpc. The time-delay measurements for this system, however, suffer from the disadvantage of different statistical methods adopted for irregularly spaced data. There is also the complication arising from possible contamination due to microlensing and more importantly, contributions from multiple lensing objects, namely, giant elliptical + clusters, adding to the uncertainty of the lens models.

The triple quasar 1115 + 080 is a relatively clean lens system with a well-defined image geometry and centroidal position of the lensing galaxy. Recently, Schechter et al (1996) have reported two time-delays from this system: $\Delta t_{BC} = 23.7 \pm 3.4$ days and $\Delta t_{AC} = 9.4 \pm 3.4$ days. The time-delay measurements suggest a value of $Ho \simeq 65$ km/secMpc (Narasimha, private communication).

The radio ring 0218+357 offers an attractive possibility for inferring the Hubble constant from the evidence for radio variability and highly variable polarization characteristics of the two compact flat-spectrum components. The measured time-delay for this system is $\Delta t = 12 \pm 3$ days. With the lens redshift, $z_l = 0.68$ and the source redshift, $z_s = 0.91$, the value of the Hubble constant falls in the range 50 to 70 Km/secMpc.

An exciting possibility is to search for a supernova event in a distant galaxy that is being lensed by a foreground rich cluster. There will appear a twin-supernova event in the arc-like morphology of the lensed galaxy, but with a time-delay of the order of several months. With a reasonable idea about the cluster mass distribution and its distance, it should be feasible to obtain the value of H_0.

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