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Testing the lensing hypothesis for compact double radio sources and other milli-lensing candidates

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Abstract. Condensed objects of $\approx 10^6\ M_\odot$ could manifest themselves via their lensing action on the radio cores of background quasars, thus giving rise to compact double sources, or more complex small-separation lenses, on the milli-arcsecond scale. Such compact bodies could be dense cores of small galaxies or remnants of pregalactic stars which have been postulated as a candidate for the dark matter in the universe. Search for examples of milli-arcsecond scale lensing, either due to such remnants or dwarf galaxies, forms a central objective of several new VLBI projects which has already revealed a good candidate. Here we point out that the milli-lensing of superluminal cores of quasars/blazars, when it occurs, can lead to substantial changes in the apparent orientation, flux ratio and velocities of the image components over periods *as short as a year*. This is essentially because the proper motion of the sub-components of such cores is comparable to the image splitting scales. Hence VLBI monitoring programmes can provide a fairly simple test of the milli-lensing hypothesis.

Key words: gravitational lensing – dark matter – galaxies: jets – galaxies: active – quasars: general – radio continuum: galaxies

1. Introduction

VLBI observations have led to the discovery of radio sources that appear to be miniature versions of classical double radio sources like Cygnus A. Extended on the scale of only $\simeq 10 - 100$ pc, these sources are designated as 'compact doubles' (CDs) and usually marked by a spectrum peaked in the frequency range 1 to 10 GHz (Phillips & Mutel, 1982). Such objects form a significant fraction of powerful flat-spectrum radio sources (Wilkinson, 1995). They are a subset of the so called 'Gigahertz-peaked-spectrum (GPS)' sources (Gopal-Krishna, Patnaik & Steppe, 1983; Spoelstra, Patnaik & Gopal-Krishna, 1985; O'Dea, Baum & Stanghellini, 1991). According to one view, CDs are progenitors of the $\simeq 10^3$ times larger classical double radio sources (e.g.,Phillips & Mutel, 1982; Carvalho, 1985; Hodges & Mutel, 1987; see also, Wilkinson, 1995; Fanti et al., 1995; Readhead et al., 1995). On the other hand, it has also been argued that many CDs could be cases where the jets are 'frustrated', or 'smothered' by a dense medium (e.g., van Breugel et al., 1984; Baum et al., 1990; Stanghellini et al., 1993; Carvalho, 1994; Gopal-Krishna, 1995).

In a radically different approach, some CDs are envisioned to be twin images of a single compact radio source gravitationally lensed by a compact body of mass around $10^6\ M_\odot$ (Ostriker, 1995; also, Press & Gunn, 1973). Objects having such masses could be small galaxies of high surface brightness, such as M32 (cf. Faber 1973) or the postulated $\approx 10^6 M_\odot$ remnants of a generation of pregalactic objects (Carr et al., 1984). Current observations limit the mass density in such remnants to be $\lesssim 10\%$ of the critical density (needed to close the universe) (Blandford & Narayan, 1992) although the limit will be much stronger if they are made of baryons (Carr 1994). So the possibility that supermassive remnants may constitute a non-negligible fraction of the dark matter in the universe is not yet ruled out. Searches for such objects would not only be important for assessing their cosmological role and significance, but also serve as an important guide for interpreting the ongoing extensive programmes to search for small separation (1-100 milliarcsecond) lenses using VLBA (e.g., Patnaik et al., 1995; Wilkinson, 1995).

Since the individual components of CDs are found to have sizes of ≈ 1 msec, the lensed object is likely to be the radio core of a quasar/blazar. Blandford & Konigl (1979) have identified such cores with radio emission originating from the base of a relativisitc jet pointed roughly in our direction. Usually, with increasing angular resolution, VLBI observations of such cores resolve them into a jet-like structure dominated by one or more emission knots which appear to separate at superluminal velocities of typically 5-10c from a 'nucleus' close to the jet's origin (e.g., Vermeulen & Cohen, 1994). The 'stationary' nucleus could be the optically thick portion of the base of the approaching jet, anologous to a (stationary) photosphere. Alternatively, it could be the base of the counter-jet, which is not strongly Doppler de-boosted since, due to light travel time ef-

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Send offprint requests to: Gopal-Krishna fects, it is viewed at an early and, hence presumably, a highly opaque stage (Kellermann, 1994). In either of these scenarios, the observed core emission is likely to arise not only from a stationary nucleus but also, in substantial measure, from the Doppler boosted superluminal knot(s) within the approaching nuclear jet.

VLBI measurements of quasar cores suggest a typical bulk Lorentz factor of $\gamma \simeq 8$ for the knots (e.g., Vermeulen & Cohen, 1994), which corresponds to a characteristic proper motion of ~ 0.5 msec yr^{-1}, taking an angular-diameter distance of 1 Gpc (i.e.,$z \simeq 1$, for $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_o = 0.5$). *Since such a displacement is comparable to the source-lens offset inferred for the small separation lenses, including any lensed CDs (see below), significant changes in the image can be expected over a period as short as a year, and could be detected by VLBI monitoring*. Here we present an estimate of such temporal effects which may serve as a signature of the lensing action. (It is worth emphasizing that such an independent test of the postulated lensing origin of CDs is valuable since finding nearly identical spectra for the two components does not *per se* exclude its being a genuine CD). A brief report on our study has been presented recently (Gopal-Krishna & Subramanian, 1995: Paper I). Earlier, we have pointed out the possibility of ultra-rapid flux variations arising from 'superluminal microlensing' of the relativistic jets of quasars (Gopal-Krishna & Subramanian, 1991; Subramanian & Gopal-Krishna, 1991), and their low-frequency flux variability resulting from 'superluminal refractive scintillations' imposed by the *intergalactic* plasma (Gopal-Krishna, 1991).

2. Estimating the temporal effects for milli-arcsecond scale lenses

Consider a compact superluminal source being multiply imaged by a forground lens (Fig. 1). For the purpose of our idealized treatment we assume the lens to be a point-like object of mass M. The lensing would give rise to two images (+,–) whose angular positions, α, measured from the lens (which is the origin of our co-ordinate system) are related to the source position β by (Refsdal, 1964; Schneider et al., 1992):

$$\alpha^2 - \beta\alpha - \theta_L^2 = 0. \qquad (1)$$

Here

$$\theta_L = 5\mathrm{msec}(\frac{D_{LS}}{D_L})^{1/2}(\frac{D_S}{1000 Mpc})^{-1/2}(\frac{M}{3\times10^6 M_\odot})^{1/2} \qquad (2)$$

is the Einstein ring radius, where D_S, D_L and D_{LS} are respectively the source, lens and lens-source angular-diameter distances in a Robertson-Walker universe. The separation between the two images is simply $\Delta\alpha = [\beta^2 + 4\theta_L^2]^{1/2}$, while the amplification factors for the two images are:

$$A_\pm = (2 \pm u^{1/2} \pm u^{-1/2})/4, \qquad (3)$$

where $u = [1 + 4\theta_L^2/\beta^2]$. For a $3 \times 10^6 M_\odot$ lens located roughly midway between us and a source $\sim$ 1000 Mpc away (see Sect. 1) the image separation $\Delta\alpha \sim 2\theta_L \sim$ 10msec, which is characterestic of CDs (e.g., Carvalho, 1985). Another characteristic is the flux density ratio, R, of their components $\sim$ 1 to 2. This obtains in the lensing picture if the source is nearly aligned with the lens with $\beta \simeq \theta_L/5$.

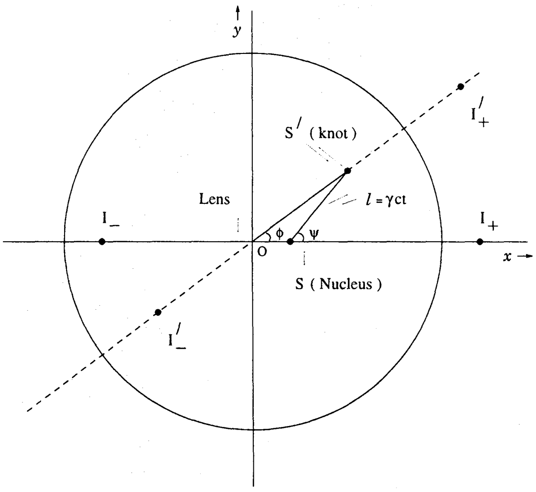

Fig. 1. Schematics of the lens (O), nucleus (S) and the superluminal knot (S′). The circle describes the Einstein ring. $I_\pm$ are the twin images of S, while $I'_\pm$ are the images of S′.

Now consider the effects of superluminal motion of the source (i.e., the emission knot; see Sect. 1) at an apparent velocity γc. This amounts to a proper motion of

$$\dot\theta = 0.5 \quad \mathrm{msec\ yr}^{-1}(\frac{\gamma}{8})(\frac{D_S}{1000 Mpc})^{-1} \qquad (4)$$

Such a proper motion of the source over a year or so would become comparable to the misalignment β of the true source direction from the lens. Hence, significant changes could ensue in the image properties, such as the flux ratio of the two images and, more dramatically, in their position angle.

To illustrate this, let us orient our co-ordinate system such that the emission knot initially coincides with the nucleus S located on the $x - axis$, with $x = x_A$, measured from the lens at the origin O (Fig. 1). Suppose that the knot moves with an apparent velocity γc at an angle ψ to the x-axis. Then, after time t the source position from the lens satisfies the equation $\beta^2(t) = x_A^2 + 2lx_A \cos\psi + l^2$, where $l = \dot\theta t = \gamma ct/D_S$. The twin images are separated by (see above):

$$\Delta\alpha(t) = [\beta^2 + 4\theta_L^2]^{1/2} = [x_A^2 + 2x_A l cos\psi + l^2 + 4\theta_L^2]^{1/2} \qquad (5)$$

and the flux ratio of the two images would be:

$$R(t) = \frac{|A_+|}{|A_-|} = \frac{(2 + u^{1/2} + u^{-1/2})}{(u^{1/2} + u^{-1/2} - 2)} \qquad (6)$$

The position angle, $\Phi(t)$, of the line joining the two images relative to the x-axis varies as:

$$\tan\Phi(t) = \frac{l sin\psi}{x_A + l cos\psi} \qquad (7)$$

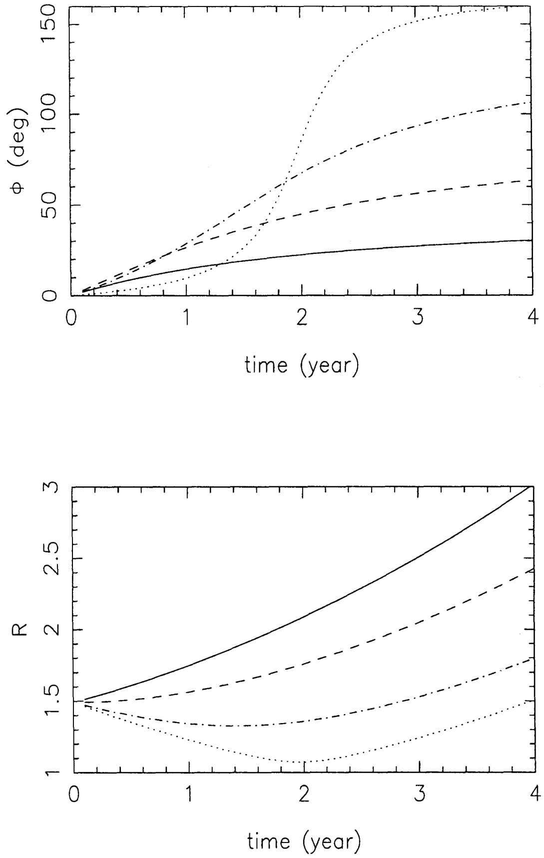

Fig. 2a and b. Evolution of position angle $\Phi(t)$ (top panel) and flux ratio R(t) of the superluminal knot's two images, for several ejection directions; $\psi = 45^o$ (solid line) $\psi = 90^o$ (dashed) $\psi = 135^o$ (dash-dotted) and $\psi = 170^o$ (dotted).

Fig. 2 illustrates the computed time evolution of the position angle (PA), $\Phi(t)$ and the flux ratio $R(t)$ of the knot's two images for a range of ejection directions $\psi = 45^o, 90^o, 135^o$ and 170^o, assuming that the ejected knot moves 0.5 msec per year (Eq. 4.). Here the Einstein ring radius has been taken to be 5 msec (Eq. 2.) and the knot is assumed to coincide initially with the nucleus at $x = x_A = \theta_L/5 = 1$ msec. For these adopted parameters the two images of the knot will, to begin with, have a separation of 10 msec and a flux ratio $R = 1.5$ which is characteristic of known CDs (see above).

While from Eq. (5), the angular separation between the two images is found to change negligibly over 3-4 years ($\lesssim 5\%$) for the typical parameters assumed here, large changes can arise in both the PA (i.e. Φ) and R of the image pair. Fig. 2a shows that changes of a few tens of degrees or more can occur in PA within about a year for all but small values of ψ. On the other hand, for such small values of ψ, the flux ratio R would change quite substantially ($\sim 25\%$) (Fig. 2b). Thus, at least one of these two parameters, PA or R, is expected to vary substantially within about a year, for almost any ejection direction ψ.

Note that image configurations more complex than simple doubles are expected to arise if the core contains a prominent nucleus in addition to one or more superluminal knots. Infact, in blazar cores, individual knots are seen to emerge from the nucleus typically on a timescale of months to a few years, and then gradually fade away in a couple of years. Thus the core will usually consist of two or more compact components. The lensed image of the core would, however, show multiple image pairs, displaying a complex pattern. Further, as the knot(s) move out superluminally, the image configuration could undergo dramatic changes mainly due to rotation of the image pairs, and their tangential stretching, thereby simulating a *gravitational kleidoscope*. We broadly illustrate this by considering the simple case of lensing of a core made of a nucleus and one superluminal knot, both having equal pre-lensed flux and radii of 0.1 msec. In Fig. 3a we plot the expected image configurations at four successive years as the knot separates from the nucleus along a straight line, at $\psi = 60^o$, with a constant proper motion of 0.5 msec yr^{-1}. (All the other parameters have the same values as in Fig. 2). The corresponding image configurations for $\psi = 120^o$ are shown in Fig. 3b. The images of both the nucleus and the knot appear as thin arclets, with their sizes proportional to their respective amplification factors. On actual maps, these individual images would normally appear more circular due to finite angular resolution. It is strikingly evident from Fig. 3 that even for the simple source structure considered here, the image shows a rapidly evolving quadruple configuration. For instance, the apparent motion of the knot during the first two years, is about 2.5 msec yr^{-1} for $\psi = 120^o$, amounting to an apparent separation velocity of 40c from the nucleus! Even more dramatic changes could arise for larger values of ψ corresponding to a closer flyby of the knot to the point mass lens. Subsequent to its closest approach to the lens the knot will appear to slow down. Eventually, when the knot has receded from the lens by a distance $\gtrsim \theta_L$, it will exibit its normal (pre-lensed) superluminal velocity along a straight line (the ejection direction), with a greatly de-amplified counter image. Some aspects of the possibility of the apparent velocity being amplified via gravitational lensing have been discussed by Chitre & Narlikar (1978) and Chitre et al. (1984), in an attempt to explain the observed superluminal motion in quasars as being entirely an artifact of relativistic motion magnified due to lensing. Chitre & Saslaw (1989) have also noted the possibility of structural variations caused due to relative motion of the lens and source, though in the contexts considered by them, the time scales for such variations were found to be a couple of orders of magnitude longer than those predicted here.

3. Discussion

In this work we have used the standard theory of point mass lenses to arrive at some interesting, observationally verifiable predictions pertaining to milli-arcsecond scale lensing candidates. A few highly promising indicators of the putative millilensing, emerging from the present analysis, are the rapidly changing position angle, Φ, flux ratio, R, of the image components, the structural complexities and velocity patterns within the core region. As seen from Figs. 2 and 3, very substantial vari-

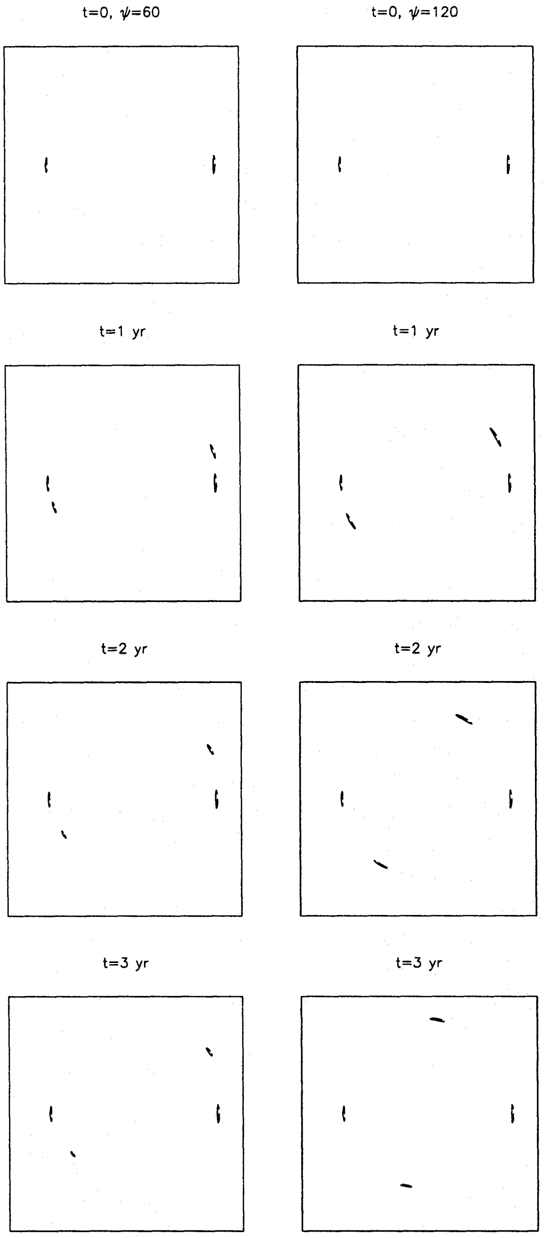

Fig. 3. Computed snapshots of the expected image configurations at 4 successive years. Each frame is 7 × 7 msec^2 with the lens at the centre. The two stationary features on the x-axis are the images of the nucleus, while the other two are the images of the superluminally moving knot ejected from the nucleus at $t = 0$ at an angle ψ (given at the top) from the x-axis. Radii of both the knot and the nucleus are assumed to be 0.1 msec.

ations in these parameters could occur, if indeed an observed small-separation source, or CD has arisen from gravitational milli-lensing of a blazar. For a wide range of initial conditions, the expected changes should be readily measurable with the VLBA and other VLBI arrays even in the course of a year or so. Moreover, in the context of the ongoing VLBA searches for lenses on the scale of just a few milli-arcsec (e.g., Patnaik et al., 1995; Wilkinson, 1995), even more dramatic variations can be expected. It should be pointed out that all the *different components of a multiply imaged core (Fig. 3) need not have identical spectra or light curves*. This is because such an image can arise from the lensing of *both* a nucleus and the moving knot(s), whose intrinsic spectra can differ substantially. This contrasts with the situation for arc-second lenses, where the core is multiply imaged as a whole. Note that these broad conclusions should hold even if the lens is not strictly a point mass (as assumed here).

Indeed, in the aftermath of Paper I, we learnt (M. Garrett, private communication) that using VLBA Patnaik et al. have found a promising milli-lensing candidate, 0223+341. It consists of a pair of compact sources separated by about 10 msec, each showing a jet-like extension with the two 'jets' pointing in very different directions. The origin of this offset can be readily understood in the lensing picture, as being the difference in the parities of the two images of a single core (nucleus + jet). If future VLBI observations can resolve the individual 'jets' into knot(s), one should be able to identify the lensed pairs of the knots, based on their correlated flux variations (see below) and orientations of their polarization vectors (which are expected to be parallel). If the lens were a point-like mass, it would be located at the intersection of the line joining the two imaged nuclei and those joining the lensed pair(s) of knots. Also, in this case we would predict that this point of intersection remains unchanged as the (relativistic) knots recede from the nucleus, accompanied by large changes in the position angle and flux ratio of their images. The lensing hypothesis for the system can thus be verified by monitoring it periodically over a couple of years.

Image distortions resulting from milli-arcsecond lensing have been emphasized in some previous studies. It was pointed out that the absence of double imaged radio cores on milli-arcsecond scales, or the absence of uncorrelated distortions in the milli-arcseond jets of the twin quasar images can be used to constrain the number density of lenses of mass $\approx 10^6 M_\odot$. (Kassiola et al., 1991; Wambsganss & Paczynski 1992) (Note however that Kassiola et al. have not considered the possibility of some compact doubles being cases of lensing). In contrast, the aim of the present work is not to constrain the density of milli-lenses, but rather to devise ways of testing the reality of milli-lensing candidates via the prediction of strikingly rapid temporal evolution in the image properties.

In the context of milli-lensing the expected differential time delay for the two images is only of the order of seconds and therefore any variations in the source will be almost simaltaneously reflected in the lensed images (unlike the case for arcsecond lenses). Secondly, the predicted rapid structural variations would be still more conspicuous in the polarimetric VLBI images, where the (superluminally moving) knots usually outshine the nucleus (cf., Gabuzda et al., 1994).

As mentioned above, when a knot traverses close to a tangential caustic (in this case the origin), enormous appapernt velocities, >> 20c (e.g., Fig. 3) accompanied by a steep rise in the image flux can result, followed by a rapid deceleration and fading of the knot as it recedes away from this region. Conceivably, this could explain the highly anomalous superluminal properties of the complex VLBI images of, for example, the quasar 3C 454.3 which showed extremely rapid ($> 30c$) and irregular apparent motion of some of its components (Pauliny-Toth et al., 1987). Thus, to conclude, we propose that a powerful test of whether a given CD, or a more complex VLBI image, is merely an illusion caused due to milli-lensing can be carried out by monitoring its structure $\approx$ 1 year apart with VLBI arrays, preferrably equipped with polarimetric capability.

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