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Faster-than-Light Motion in Quasars

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Abstract. Over the past fifteen years, observations of some quasars with the techniques of very-long-baseline interferometry have shown that the angular separation between pairs of radio-emitting regions in their cores is increasing year after year. If the quasars are indeed as far away as implied by Hubble's law, then these angular motions translate into linear speeds several times the speed of light. Several theoretical scenarios have been proposed to show that the observed motions are illusory. The leading contender in this field—the relativistic beam model—and an alternative offered by the concept of a gravitational screen are described and compared in the light of recent observational data.

Key words: quasars—superluminal motion—relativistic beaming—gravitational screen

1. Introduction

The first hint of apparent faster-than-light motion in quasars came from a series of transpacific observations made between 1967 and 1969, of the sizes of variable components in quasars 3C 273 and 3C 279 (Gubbay *et al.* 1969; Moffet *et al.* 1972). More direct evidence for such motions came in 1971 which indicated a double structure, with the two components having separated with a linear velocity 5 to 10 times the speed of light over a period of a few months (Knight *et al.* 1971; Cohen *et al.* 1971; Whitney *et al.* 1971). Although the early data could be partially discounted on the grounds of ambiguity, imperfect resolution and single baseline observations, later studies extending over the past decade or so with increasingly more sophisticated techniques of very-long-baseline interferometry (VLBI) have confirmed a *prima facie* case for superluminal separation of pairs of radio emitting regions within quasars(Cohen & Unwin 1984, and several other papers in Fanti, Kellermann & Setti 1984). The observational results are summarized in Table 1.

While the astronomical scenarios subject the fundamental laws of physics to far more stringent tests than ever possible in the terrestrial laboratory, theoretical astronomers by and large tend to be conventional in outlook, relying as far as possible on the laws of physics *known* at the time of observation. This attitude can be justified by invoking Occam's razor, although one cannot help wondering why the universe should choose to reveal at any given time only that much of its storehouse of mysteries as is understandable in the framework of the physics known at that time.

Following the above attitude we rule out the conclusion that the observed motions are both superluminal and real; for such a conclusion would hit at the very basic tenets

Table 1. Superluminal sources (H_0 = 50 km s^{-1} Mpc^{-1}).

Source*		Redshift	V/c
3C 120	A	0.033	4.2
	B		8.2
	C		7.4
	D		5.2
BL Lac		0.069	3
3C 273	C1	0.158	10.6
	C2		14.1
	C3		10.6
3C 279		0.538	6.8
3C 345	O	0.595	18
	I		13
3C 179		0.846	8.5
NRAO 140		1.258	10.8

* A, B, C . . . *etc.* refer to the separating components; it is observed that some components fade away to be replaced by others (kellermann & pauliny-Toth 1981)

of special relativity. The observed features of quasar radiation do not suggest anything so extraordinary about the radiating particles that one has to appeal to tachyons.

There is another way of resolving the difficulty of superluminal motions. Since all the observations relate to measurements of angular separations, their conversion into linear motions requires the knowledge of the distances to the objects. In deriving the separation velocities of Table 1 it has been assumed that the quasars are at cosmological distances implied by their redshifts. There are some astronomers who question the validity of this assumption and argue that quasars are in fact considerably closer than implied by Hubble's law (Burbidge 1978; Arp 1983). If this turns out to be, the case then the observed motions are *not* superluminal after all. Indeed, one wonders if this phenomenon had been found in the early days of the discovery of quasars, whether it might have swayed the majority opinion towards the view that quasars are local objects!

Nevertheless the majority of astronomers today would like to assume that quasars are as distant as implied by Hubble's law. In that case there is only one recourse left: to argue that the observed motions are illusory and do not correspond to actual physical motions. In the remaining part of this article we take a stock of theoretical attempts to explain the superluminal motions as illusions, although our main emphasis will be on two scenarios.

2. Relativistic beaming

Even before the discovery of the phenomenon of superluminal motion, some quasars had given indications of fast bulk motions, through the rapid time variability of their luminosities both in radio and optical wavelengths (Burbidge & Burbidge 1967). If τ is the characteristic timescale of variability then special relativity imposes an upper limit

$c\tau$ over the linear dimensions of the object. To get out of this stringent upper limit Rees (1966) proposed an ingenious model. If the quasar is expanding relativistically with speed $v \simeq c$, then a remote observer will see its projected boundary expand at a rate $\gamma v \simeq \gamma c$ where

$$\gamma = \frac{1}{(1 - v^2/c^2)^{1/2}} \cdot \tag{1}$$

This effect arises because the light rays reaching the observer at any given time do not all start at the same time from the boundary of the expanding object.

Fig. 1 illustrates this concept when adapted to the superluminal separation of the VLBI components of a quasar. Here, component A is fixed in the rest frame of the observer O, while component B is beamed with speed $v \simeq c$ *almost* along the line of sight OA, towards the observer. In Fig. 1 the angle OAB = θ is supposed to be small so that $|\sin \theta| \ll 1$. Then the projected separation perpendicular to OA will be seen to grow at a rate

$$V = \frac{v \sin \theta}{1 - \frac{v}{c} \cos \theta} \cdot \tag{2}$$

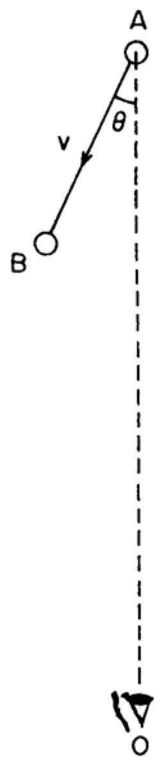

Figure 1. In the beam model schematically shown here A is the stationary component and B is the component beamed at the observer O. For apparent superluminal motion to manifest, the angle θ has to be very small.

This expression reaches a maximum value $V_{\max}$ when $\theta = \theta_{\max}$, where,

$$\sin \theta_{\max} = \gamma^{-1}, \quad V_{\max} = \gamma v \simeq \gamma c. \tag{3}$$

Though this conclusion is similar to that for the original Rees model, there is one important difference. In the Rees model the quasar was a spherical object and therefore θ spanned the entire range from 0 to π, with the maximum expansion occurring for its value given by (3). In Fig. 1 we have a linear system and to achieve the large value of γ, θ ($\simeq \sin \theta$) has to be *chosen* to be finely tuned to the value γ^{-1}. We will return to the question of how probable this is, later.

The beam model also predicts that the intensity of blob B is enhanced by a factor

$$f = \left[\gamma \left(1 - \frac{v}{c} \cos \theta \right) \right]^{-(3+\alpha)} \tag{4}$$

due to the Doppler effect, where α is the spectral index of the radiating source (Cohen *et al.* 1971). Thus in cases of interest $\theta \simeq 0$, $v \simeq c$ and $\alpha \simeq 1$, f is expected to be ~ 10.

The beam model starts with the advantage that the underlying idea existed in literature before the phenomenon was discovered. It makes a clever use of the kinematic effect due to narrow, relativistic beaming at the observer. The model received further theoretical support in terms of the twin exhaust model of Blandford & Rees (1974) which provided a scenario for highly collimated beams issuing in opposite direction along the axis of rotation of a massive system such as a galaxy. These jets are supposed to impinge on intergalactic clouds to produce the observed hot spots. It was natural to think of the core beams producing the superluminal motion on the VLBI scale, as part of the largescale phenomenon of the extended jets which produce the hot spots.

The VLA data do show radio jets on extended scales of several tens of kiloparsecs and these findings have led to a general belief in the existence of jets in radio sources, whether on the small scale of a few parsecs seen in VLBI or on the larger scale of the extended radio sources. Against this background the hypothesis of relativistic beaming appears (at first sight) to provide a natural expalnation of the observed superluminal motions in quasars.

With all these attractive features; however, the beam model is not without its difficulties when confronted with certain observational details. For instance, take the formula (4). If both blobs A and B were comparable in luminosity in their respective rest frames, then B should appear brighter (by a factor ~ 10) in the observer's rest frame. Had this turned out to be the case, it would have been a striking demonstration of the beaming effect. In reality the brightness of B is not significantly different from that of A as seen by O. To explain this result one has to assume that B is intrinsically fainter than A. Indeed, the stronger the beaming effect ($\cos \theta \simeq 1$) the larger is this difference in luminosity. By making a comparison with the radio sources which are not beamed at us, Browne *et al.* (1982) placed a lower limit on the beaming angle θ for the various superluminal quasars. They found that these values are not small enough to explain the superluminal effect unless the Hubble constant is increased from 50 km s^{-1} Mpc^{-1} to 100 km s^{-1} Mpc^{-1}. (An increased value of the Hubble constant brings quasars closer and reduces the transverse speed of separation of A and B. This way out of the difficulty is thus closer in spirit to the resolution offered by the local hypothesis of quasars.)

One of the early expectations of the twin exhaust model was that the smallscale (VLBI) structures of radio sources would be aligned with the extended lobes. We will refer to this as the 'alignment property' in all future discussions here. While initial observations lent some support to the alignment property, discrepancies began to appear in later studies. For example, the VLBI jets in a number of super-luminal sources are found to be inclined at angles of a few tens of degrees to the largescale jets (Readhead *et al.* 1978). More recently, Schilizzi & de Bruyn (1983) have looked at these objects from another angle. If the VLBI and largescale structures were aligned, then, using the angle θ given by Knight *et al.* (1971), one can estimate the linear sizes of the extended structures. Schilizzi & de Bruyn find that these linear sizes are significantly larger than for sources which are not beamed at us, implying that their inclination to the line of sight is considerably larger than θ. Clearly the two structures then cannot be aligned.

To get out of this difficulty it is argued that obstructions due to inhomogeneities cause knots in the relativistic jets (Fomalont 1983). The kinks so caused are magnified by the kinematic effects of $v \simeq c$ and hence the position angles of smallscale jets are found to be different from those of extended jets.

We may mention an added difficulty arising from the breakdown of the alignment property. Most quasars so far seen show only one jet instead of two. In their paper on twin exhaust, Blandford & Rees (1974) had argued that the issue of central plasma as a single jet is basically unstable and that a counterjet must develop. Why do we not see two jets in reality? The explanation offered by the Doppler hypothesis of Narlikar & Subramanian (1983), that ram-pressure of the intergalactic medium stops the exhaust in the forward direction cannot be invoked in the cosmological hypothesis of quasars. So it was argued that there are two jets but we see only the Doppler boosted one beamed at us. However, with a misalignment of the extended jet and the VLBI jets it is not possible to argue that both are being beamed at us.

In the Blandford–Rees model the magnetic field in the jet was supposed to be oriented largely perpendicular to the outflowing relativistic plasma. Recent observations of the optical emission from the extended radio source Coma A by Miley *et al.* (1981) suggests the alignment of the magnetic field along the direction of the jet.

Optical spectroscopy of the beam fluid indicates that the motion is nowhere near relativistic speeds. In fact there is a certain amount of evidence (Heckman *et al.* 1982) that the jets associated with low-luminosity radio galaxies such as 3C 305 have velocities characterizing the bright regions of the emission line gas more like $\sim$ 300 km s^{-1}. By examining the correlation between the optical and radio emission in radio sources in general, Strittmatter (1984) has argued that relativistic beaming is unlikely to be taking place in the extended sources. Scheuer (1983) also has given arguments to show that the jet velocities in both the VLBI and extended sources must have the same characteristic of being either relativistic or nonrelativistic.

Finally, it should be remarked that the existence of intervening beams carrying material from the central source to the outer lobes was utilized in the earlier studies to emphasize the formation of outer lobes as a result of plasma impinging upon the intergalactic medium. In the light of the resolution and dynamic range available at the time the relativistic beams themselves were not expected to be observed which is probably why their observable features were not particularly stressed. The beams were later revealed from the radio maps on the VLBI and the extended scales.

These arguments suggest that although the relativistic beaming hypothesis is the best sell theory today, it is not manifestly the best buy theory. For it to have the latter property it is necessary to examine what alternative hypotheses exist in literature today.

3. Alternative scenarios

There have been a number of ingenious proposals advanced to explain the phenomenon of apparent superluminal motion.

(a) *Christmas-tree model* (Dent 1972) involves independent flares erupting at random in various locations of the source and these could mimic a regular superlight motion. However, it was soon realized (Cohen *et al.* 1977) that the observed motion was highly systematic and only superlight expansions were generally observed.

(b) *Light echo model* (Lynden-Bell 1977) attributes the superluminal motion to an outward-propagating signal like a relativistic blast wave which causes a progressive brightening of the source region of increasingly large size. Such a signal directed in opposite directions along an axis making a small angle with the line of sight can result in a superluminal expansion. Clearly, the model is not compatible with the observed core–jet structure of these sources.

There are a number of other suggestions: dipole field model, synchrotron opacity model, kinematic illusions caused by the finite time of propagating signals. We shall not discuss them here, but refer to the reviews by Marscher & Scott (1980), and Kellermann & Pauliny-Toth (1981).

4. The gravitational screen model

The gravitational screen model (Chitre & Narlikar 1979; Chitre & Narlikar 1980) was proposed by us as an explanation of superluminal separation a few months *before* the discovery of the twin quasar 0957 ± 561 A, B and the consequent popularity of gravitational lens in quasar astronomy. Fig. 2 illustrates schematically how this model operates. A, B are two radio blobs in a source S which is 'screened' by an intervening massive object D which defects the light rays from A and B *en route* to the observer O. As a result of deflection, O sees the virtual images A′, B′ of A, B. While A and B separate from each other at subluminal speed, is it possible for O to see A′, B′ separate superluminally? This is the question we set out to investigate, and the outcome is summarized below. It is worth pointing out at the outset that this model is different from the earlier models of Barnothy (1965; see also Barnothy & Barnothy 1971) or the work of Gott & Gunn (1974) all of which invoke gravitational bending in one form or another.

First we note that a typical gravitational screen like a galaxy causes differential gravitational bending as the impact parameter α of the light ray increases. In a spherical galaxy, $a = 0$ for a ray passing through the centre and the bending angle $\Delta\,(a) = 0$. As a increases, $\Delta\,(a)$ rises sharply and then falls slowly outwards. For a galaxy of mass M and radius R, $\Delta\,(a)$ equals the Einstein value

$$\Delta\,(r) = \frac{4GM}{c^2 r} \quad \text{for } r \geqslant R. \tag{5}$$

In the central regions of the galaxy $\Delta\,(a)$ could be significantly higher than $\Delta\,(R)$. [Both $\Delta\,(a)$ and $\Delta\,(R)$ in weak-field general relativity turn out to be twice the respective values in Newtonian gravity.]

Denote by x_D, x_{DS} and x_s the distances between the observer and the deflector, the

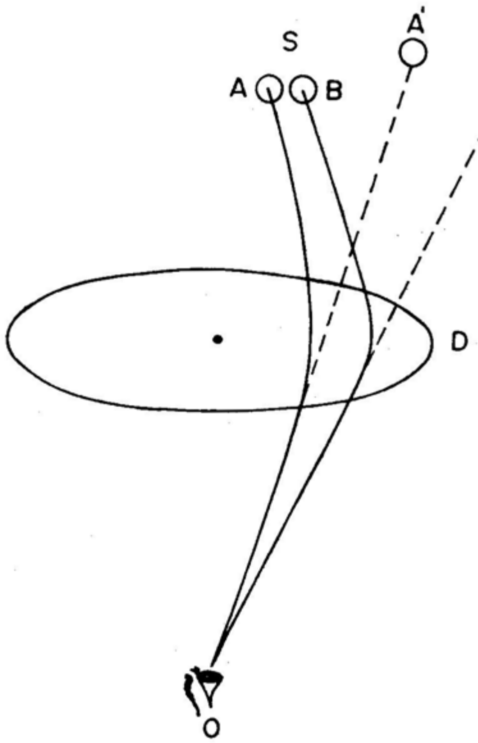

Figure 2. Source S has two components A and B which are separating subluminally. The images A′ and B′ formed by the gravitational deflector D under certain circumstances appear to the observer O to separate at superluminal speeds.

source and the deflector and the observer and the source, respectively. Let $v_\perp$ denote the transverse speed of separation between A and B relative to the direction OS. Then the apparent separation velocity as seen by O is

$$V = \frac{v_\perp}{1 - x_D \dfrac{x_{DS}}{x_S} \Delta'(a)}. \tag{6}$$

From this we see that a large magnification of velocity is possible if $\Delta'(a) > 0$ and the denominator of (6) almost vanishes, *i.e.,*

$$\Delta'(a) = \frac{1}{x_D} \cdot \frac{x_S}{x_{DS}}. \tag{7}$$

For this condition to be satisfied, the source and the observer should be at conjugate positions with respect to the deflector. How probable is such a situation? Again, we defer the computation of probabilities to the end.

In essence, therefore, apparent superluminal speeds will be seen provided a suitable gravitating mass intervenes between the source and the observer at a suitable intermediate point. Intervening galaxies have been invoked to account for absorption-line redshifts in quasars, and more recently, for explaining very similar closely spaced multiple quasars as gravitationally lensed images. Thus the supposition of an intervening deflector for producing superluminally separating images is no more or no less implausible against the current backdrop of theoretical ideas. The best 'proof' of the correctness of the screen model lies of course in the detection of an actual screen. We will consider evidence of this kind shortly. First we outline some observable effects in the screen model and compare its performance with the beam model.

(i) A significant feature of lensing is that the amplification produced is not uniform in all directions perpendicular to the line of sight. Thus the image of a straight line or a straight path may appear distorted. These effects will be confined to the VLBI features which are influenced by the magnification formula (6), but will be negligible in the extended features. It is therefore expected that the VLBI jets will be misaligned with respect to the extended features, especially in quasars which show superluminal motion. (It is worth recording that when the screen model was first proposed in 1978, a referee of our paper pointed this property as a *drawback* of the model since it was then believed that the alignment property holds!)

(ii) Since gravitational deflection is independent of wavelength, the superluminal separation is expected to be the same at all wavelengths of observation.

(iii) The apparent velocity of separation in 3C 345 seems to show an increase from 7.5 c to 12.2 c ($H_0 = 50$ km s^{-1} Mpc^{-1}). This superluminal acceleration appears to be genuine (Moore, Readhead & Baath 1983), but is hard to understand in the simple beaming model. In the screen model, accelerations (and decelerations) of this kind are artifacts of changes in the magnification as the light rays encounter varying density regions with changing Δ (a). This effect is expected to be large when the source and the observer are near conjugate points. Besides, smallscale inhomogenities in the deflector are expected to produce short-term changes in V (of duration $\sim$ 1 yr), thus making the plot of angular separation against time a jagged curve with a linear trend.

(iv) If the optical object coincides with the core where superluminal separation is being observed, the lensing phenomenon will lead to an amplification of the apparent optical luminosity of the quasar. We will discuss an explicit example of this circumstance in the next section. A similar effect is not expected in the beam model.

(v) A testable prediction of the screen model is the likely existence of super-luminal separation in those quasars which are believed to be lensed by intervening galaxies or clusters. For example, the twin quasars 0957 + 561 A, B where the lens system has been detected, should show a magnification of velocity by a factor ~ 2–3. Hence, provided the source components are separating at speed $v \lesssim c$ we should see apparent separation speed $V \lesssim 3c$.

(vi) It should be recognized that in the screen model the probability measure of two images of a single source can be larger than for a single bright image. The double imaging would therefore be expected to occur in many of the super-luminal sources, although none have been detected so far. This may be due to a selection effect which favours a single bright image over a couple of less bright images. It would be worthwhile undertaking high-resolution studies with a view to look for multiple imaging in superluminal sources.

5. The quasar 3C 273

3C 273, the first quasar to be detected has the redshift $z = 0.158$ and an apparent magnitude 12.8. It is not only abnormally bright optically, but is in fact the brightest quasar in the sky at optical, X-ray and γ-ray wavelengths. Further, the strength of the emission line region of this quasar also makes it a unique object (Rees 1984). It is perhaps significant for the screen model (but not for the beam model) that the radio component 3C 273B which coincides with the optical object contains the core with superluminally separating components. The extended optical jet in the source is misaligned by about 20° with the direction of the VLBI jet.

Let us consider 3C 273 in both scenarios, that of relativistic beaming and of screening by an intervening galaxy. For H_0 = 50 km s^{-1} Mpc^{-1} we have $V \simeq 10c$. The best, case of Equation (3) requires $\gamma = 10$. However, to avoid the criticism of choosing the 'best' as 'typical' we assume that the beaming in a direction $\theta \neq \theta_{\max}$. A straightforward calculation shows that for $\gamma > 10$, a small range of values of θ around $\theta_{\max}$ can generate $V \geqslant 10\ c$. The probability of beaming in this range is given by

$$P(\gamma) = \frac{1}{1 + V^2/c^2}\left(\frac{\gamma^2 - 1 - V^2/c^2}{\gamma^2 - 1}\right)^{1/2}. \tag{8}$$

For the limit $\gamma = \infty$, $P = \theta^2_{\max} \simeq 10^{-2}$. However, $\gamma = \infty$ gives clearly an upper limit on P. For $\gamma = 10.1$, the value is $\sim 10^{-3}$. However, we should multiply this value by a further rarity factor $\sim 10^{-2}$ to include the abnormal brightness of 3C 273 in the optical and X-rays as well its strong emission line region (Rees 1984). Thus the probability comes down to $P \sim 10^{-5}$. [The brightness of the emission-line region could not be explained as a beaming effect since there is no evidence for a relativistic motion of the emission-line gas (Kellermann & Pauliny-Toth 1981; Heckman *et al.* 1982).]

We shall now demonstrate that the exceptional features of 3C 273 can be accounted for in a natural manner by postulating a gravitational screen at an intermediate distance along the line of sight to the quasar.

First we note that studies of the nebulosity around 3C 273 by Tyson, Baum & Kreidl (1982) furnish possible support for the screen hypothesis in the following way. These authors have argued that the isophotal distribution of the nebulosity resembles that of the brightest elliptical galaxy in a cluster. Earlier, Wycoff *et al.* (1980) had found that the redshift of the galaxy is very nearly the same as the redshift of the quasar, thus implying that the quasar is being hosted in the nuclear region of the galaxy. There are two anomalous features, however, which are found from the work of Tyson, Baum & Kreidl (1982). At apparent magnitude of 16 the supposed galaxy is considerably brighter than other galaxies similarly hosting quasars in their nuclei (W. A. Baum, personal communication). Further, the quasar is not exactly at the centre of the galaxy but is off-set by about 1 arcsec to the east of it. Both these anomalies could be explained if there were an intervening galaxy which is fainter than the nebulosity by ~ 2–3 magnitudes. We show that such a galaxy can also explain the abnormal brightness of the optical (and X-ray) object in 3C 273 as well as the superluminal motion ~ $10c$.

A typical solution with a spherical lens galaxy located at a redshift of 0.07 and core-radius r_c = 1 kpc has a mass ~$10^{11}\ M_\odot$, line-of-sight velocity dispersion $\sigma \sim 187$ km s^{-1} and yields a linear magnification ~ 10 and an intensity magnification ~ 22. The details of various screen models are given elsewhere (Chitre *et al.* 1984). We may add that these solutions are also able to explain the misalignment ~ 20° between the extended jet and the VLBI jet which alone is subjected to the dominant gravitational influence of the screen. Furthermore, the models are by no means unique, but typical ones. It is possible to generate other sets of values for the screen at different intermediate redshifts with a scaling that holds the parameter

$$\mu = \frac{4GM\, x_D x_{DS}}{c^2 r_c^2 x_S} \tag{9}$$

fixed. (r_c = radius of the core producing the bending.)

Finally we compare the probability of such a scenario with that computed earlier for the beam model. For this purpose we adopt the luminosity function ϕ (L) for galaxies given by Schechter (1976) and assume the Faber–Jackson (1976) relation between the luminosity L and the line of sight velocity dispersion σ. The probability of finding intervening galaxies with a velocity dispersion in the range (σ, $\sigma' + \mathrm{d}\sigma$) and permitted redshift range (z_{min}, z_{max}) in the $q_0 = 0$ Friedmann universe is given by

$$\mathrm{d}P = \frac{1}{2}\left(\frac{c}{H_0}\right)\left[(1+z_{max})^2 - (1+z_{min})^2\right] A^{3/2} f(\Delta\theta)\Sigma(\sigma)\phi(L/\sigma)\mathrm{d}\sigma. \tag{10}$$

Here ϕ (L/σ) is the Schechter function convolved with the Faber–Jackson relation, Σ (σ) is the cross section for bending required to produce the large superluminal speed, F ($\Delta\theta$) is the probability that the position angle of the major axis of the lens galaxy yields the desired configuration and A is the flux amplification factor. The net probability so computed comes out $\gtrsim 6.3 \times 10^{-5}$. The > sign allows for deflectors which are not in galactic forms. If the existence of unseen mass in the universe is confirmed, then it is not unreasonable to suppose either that the bending masses used in models are underestimates or that faint objects with large mass-to-light ratio exist in the universe over and above the galaxies used in ϕ (L).

We mention in passing that the optical object associated with 3C120 (another VLBI superluminal case) also presents another likely case of superposition of the line-of-sight screen galaxy with the galaxy hosting the radio source. The optical studies of Arp (1975) and Baldwin *et al.* (1980) suggest a two-component system, one with the axis of symmetric gas motion aligned with the radio axis and the other made of star distributions whose isophotal ellipses have major and minor axes pointing in altogether different directions. Could the latter system be a screen for the former?

6. Conclusion

As the VLBI techniques continue to improve in the future we may very well encounter further cases of superluminal motions in quasars. While the beaming model has several attractive features it has difficulties also, and it may be worthwhile having more than one theoretical basket to store our eggs of speculation. We believe that the screen model which offers yet another striking application of gravitational lensing phenomenon can be one of these additional baskets.

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