EXPLANATIONS OF SUPERLUMINAL MOTION +

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It is a sobering thought that Blandford, McKee and Rees (1977) wrote a review on this subject 6 years ago and that we are still considering much the same range of possibilities. Observationally, five things are now firmly established that were either unknown or less clear in 1977:

a) Superluminal motion really does occur, and is very common (5 out of 7) among those sources that have been investigated. Of course the present sample is full of strong selection effects, which we shall never be able to define retrospectively.

b) Most VLBI sources (including all or nearly all the superluminals) consist of an unresolved self-absorbed part (the "core") and a steep-spectrum "jet" on one side only.

c) The motion relative to the "core" is reasonably uniform and always outwards. (Dr. Shaffer has just shown us an exception.)

d) Disappearance of the middle ground. Until last year one could believe that VLBI jets are highly relativistic but that they slow down somehow and have $v \lesssim 0.1c$ by the time they are many kpc long. Now you must go the whole hog: either you are for fast jets, or you are for slow jets, all the way. The reason is this simple observation: wherever there is a large-scale jet, there is a VLBI nucleus, and wherever that has been mapped the VLBI jet points towards the large-scale jet. Now suppose that VLBI jets have $\gamma \gg 1$ but large-scale jets have $v \ll c$. Then

(i) If VLBI jets are intrinsically one-sided, 50% of VLBI jets are relativistically beamed away from us, so the majority are invisible: we should observe many large scale jets with no VLBI cores.

(ii) If VLBI jets are intrinsically two-sided, the VLBI jet should point away from the large-scale jet in 50% of all cases.

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R. Fanti et al. (eds.), VLBI and Compact Radio Sources, 197–205.

In either case there is a contradiction with observation.

e) Low-frequency variability (at $\lambda \sim 1$m) really does occur, and is also fairly common among VLBI sources.

I also note that recently VLBI observers have used $H_o = 55$ km s^{-1} Mpc^{-1}, thereby doubling all the apparent velocities!

The fact that the motion is always outwards excludes primitive versions of the "Christmas tree" model, in which superluminal motion was simulated by a row of lights flashing at random times. My list of types of model (not a comprehensive list!) therefore begins with

1. "Computer-controlled Christmas trees, with $\sim$ isotropic lights".

This includes "lighthouse" models in which a beam of radiation or particles sweeps over a screen (at arbitrarily large speed) and excites it temporarily. It also includes models in which, say, a shock front crosses some linear feature at a small angle, and the crossing point radiates.

It is not easy to construct physically plausible models of this kind in which the source position always moves away from the core, but it can be done. The real downfall of most such models is that, when the source motion is not perpendicular to the line of sight, the apparent source velocity is often inward because of light travel time effect - as shown by the standard formula (1) (below) with $v > c$.

A model that escapes this criticism is the filament of matter excited by something (say a spherical shock front) propagating out from the central engine. For any shock speed and filament orientation, the total of shock travel time + light travel time has a minimum for some position on the filament, and as minima are flat, the two radiating spots appear to separate initially at infinite speed, decelerating gradually. This model has always been rejected on the grounds that the observed speed is constant; at this meeting the Caltech group have presented evidence against constant velocity in 3C345, but they find acceleration not deceleration. This simple model fails to account for the general rule that there is one heavily self-absorbed component at the end of the line.

2. Relativistic beaming

- in which the same radiating matter is seen at successive epochs and the apparent "superluminal" motion is all due to light travel time effects. For a jet of speed v, Lorentz factor γ, at angle θ to the line of sight, this yields an apparent speed given by the well-known formula

$$v_{app} = v \sin\theta/(1 - \frac{v}{c}\cos\theta). \tag{1}$$

This has been the favourite model ever since the one-sided VLBI structure (Item B) was discovered, and was worked out in considerable depth by Blandford and Königl (1979). Apparent speeds comparable with the maximum $\gamma v \cong \gamma c$ should occur only if $\theta \sim 1/\gamma$, i.e. for one source in several γ^2. Readhead and I (1979) pointed out that

(i) a very large fraction of radio quasars could be superluminal if the observed "core" were not really the stationary core at all, but the self-absorbed base of the relativistic jet itself. The strong selection effect in favour of small θ would then apply to the "core" emission too (slightly less strongly because of the flatter spectrum). While observational papers still refer to a "core" for lack of a better word, I think this hypothesis is now taken for granted in most discussions.

(ii) the model explains the strong apparent curvature in core-dominated sources as a projection effect. This had already been suggested earlier by the Caltech group, and has also become part of the conventional wisdom.

(iii) argument (i) cannot apply to optical and in particular to line emission. So, in a sample free from orientation bias, selected e.g. by optical line emission, only a fraction of the order of 1% should have strongly Doppler-boosted cores with $v_{app} >> c$. That would be compatible with observation if a substantial fraction of optically selected quasars were really fairly weak radio sources, well below the limits of most catalogues, and appeared strong only when $\theta << 1$. Item (iii) has been attacked vigorously from two directions.

On the one hand, there are statistically significant spectroscopic differences between radio-loud and radio-quiet quasars (see e.g. Osterbrock 1982 and Wills 1982). I think this is sufficient to establish that a large proportion of optically selected quasars are a physically distinct group of radio-quiet quasars; the spectroscopic differences would be hard to explain away as orientation effects.

On the other hand, Browne and others state that the superluminal sources are just the cores of ordinary double radio sources, on the grounds that all the core-dominated sources have some diffuse structure on both sides of the core if one looks hard enough. (The unique exception is 3C273.) In some sense they must be right. Even theoretically it would be astonishing if the radio jets vanished into the blue yonder without ever interacting with their surroundings. The questions at issue are not qualitative but quantitative: how powerful are the radio lobes associated with typical superluminals, and what distributions of Lorentz factor γ can occur in a sample of radio sources free from orientation bias, e.g. a sample selected by the flux in radio lobes alone. Orr and Browne (1982) find that the statistics of core fluxes are compatible with jets of $\gamma = 3.7$ in the 3C sample, while samples selected at higher frequencies (where the cores contribute more to the total flux) are compatible with $\gamma = 5$. I think there would be statistical trouble if the Lorentz factor were typically 7, and very severe trouble if it has to be 10 or 15, corresponding to putting $H_o = 55$ km s^{-1} Mpc^{-1} in the VLBI data.

Orr and Browne's samples are radio selected, and corrections have to be made for the selection effect due to the core contribution to the flux. Optically selected samples were considered by Strittmater et al. (1980) and Condon et al. (1981). They agree that the slow but inexorable increase in numbers with decrease in radio core flux, predicted by all relativistic beaming models, does not occur. Some quasars - particularly the optically very luminous ones - are radio loud, and the rest are very radio-quiet indeed. Lacking maps, we do not know how much of this flux comes from VLBI cores, but some of the brighter sources have flat radio spectra, and on the basis of these alone we should expect to see more of the quasars at the 10 mJy level. One escape route from this statistical threat is to note that the samples were selected largely by optical continuum flux, which should be contaminated with enough relativistically beamed optical flux from the jet to invalidate the statistics. The anticorrelation between the equivalent widths of broad emission lines and optical luminosity (Baldwin et al. 1978; Wampler et al. 1983) could be attributed to beamed optical continuum. If that is so, we must expect to see an excess of bright radio cores in a sample selected by optical magnitude. I have used the spectra published by Osmer and Smith (1980) to make rough estimates of C IV λ1549 equivalent widths of radio sources in their optically selected sample, in the range $1.8 < z < 2.4$, and magnitude brighter than 18.5, and compared them with flat-spectrum Parkes quasars at high flux densities, selected from a large area of sky but subject to the same magnitude and redshift limits: for a majority of these, equivalent widths and continuum fluxes have been measured by Baldwin et al. and Wampler et al. The statistics are very poor, and all I can say is that the data do not encourage the hypothesis that some of the optical flux is beamed along with the radio flux. However, we also have to remember that there is a positive correlation between intrinsic radio power and line strength (e.g. Hine and Longair 1979).

The statistical evidence mostly revolves around the flux densities of VLBI cores, whose own apparent jet speeds have not been measured. Crucial experiment No. 1, of monitoring the VLBI motion of a complete sample selected without orientation bias, has not been done. It was not possible before the routine operation of the Mk 3 VLBI because most of the cores are faint, and it may not be done convincingly till the VLBA is in action. The sample would have to be selected either by the radio flux of large-scale double structure or by optical, preferably line emission. Crucial experiment No. 2 is to look for superluminal motion in the VLBI jet of a source such as Cyg A, whose axis we have good reason to believe lies near the plane of the sky. In principle that can be done now, but in practice it seems that the core of Cyg A is peculiarly hard to map (Linfield 1981; Kellermann et al. 1981).

My reading of the statistical evidence is that we should look for mechanisms that can operate over a larger range of inclinations θ than the simplest beaming model. One hypothesis (mentioned by Rees 1981) is that the jet has angular width $> 1/\gamma$ but power that fades outwards on angular scales $\sim 1/\gamma$, so that we still see a one-sided structure. I have computed the appearance of such models, and find that they produce extremely fat jets (Fig. 1), so fat that I think this model is already excluded by existing VLBI maps. A variation is the "shotgun" model, in which the central engine ejects things along several distinct lines within a fairly narrow cone, and we see only that nearest the line of sight. However, as a majority of quasars have VLBI cores, we should have a good chance of seeing a few cases with two or more jets pointing in quite different (projected) directions.

3. Gravitational lenses

Splitting of a single source by a gravitational lens is excluded by the spectral difference between VLBI components (Fact B). However, a distributed mass, such as a galaxy, can magnify real motions and at the same time increases the observed flux ($\propto$ magnification^2) thus creating a strong selection effect in favour of magnified velocities.

As Dr. Subramanian will speak about this theory, I will only remind you of the traditional difficulties which I hope he will address. The difficulties are greatest for the nearest sources, 3C120 ($z = 0.032$), BL Lac ($z = 0.07$) and 3C273 ($z = 0.158$). The nearer the source, the stronger the gravitational lens must be (in the sense of mass per unit area) to achieve substantial magnification. But the probability of finding a galaxy along the line of sight to an object with $z \lesssim 0.15$ is exceedingly small, and, furthermore, no sign of an intervening galaxy has been found in these cases.

At this point I respectfully mention

4. Non-cosmological redshifts

- but say no more as I am not aware of any striking new developments in this field.

I do want to say something about

5. Computer-controlled Christmas trees with beamed lights

I know of only one published model in this class: the magnetic dipole model, proposed in original form by Sanders (1974) and elaborated by Bahcall and Milgrom (1980). It does not fit easily into current pictures of what goes on in quasar nuclei, and indeed, at a recent workshop at Jodrell Bank, Sanders himself demolished the model. Yet in one respect it is conspicuously successful, in that it predicts superluminal speeds over a large range of orientations θ, and furthermore the predicted speeds are never 1.1c or 1.5c but always > 4c, more or less as observed. These desirable features are not peculiar to the

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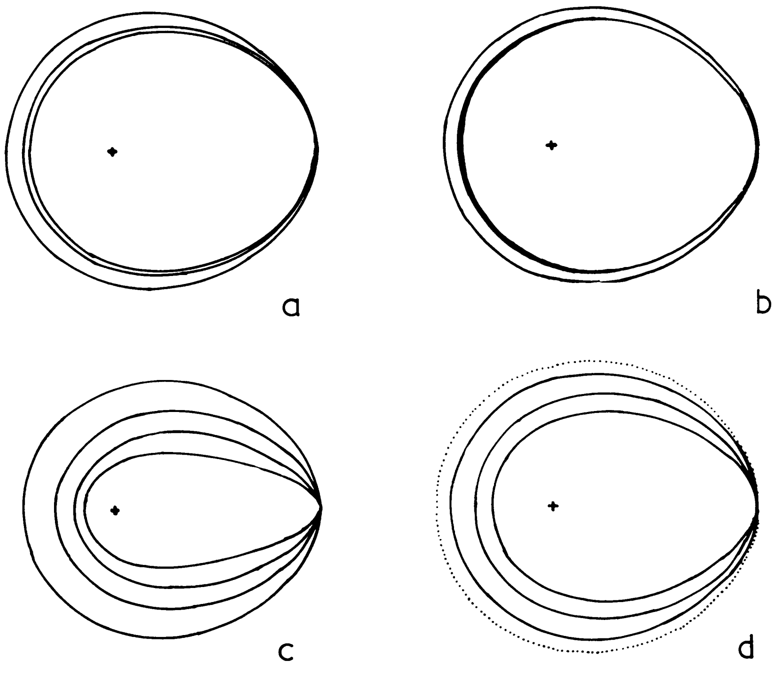
Fig. 1. How a non-uniform conical jet would look. Assume the axis of the cone makes angle θ with the line of sight, that the emitting material is ejected with uniform speed v, and that the emissivity varies as $r^{-n} \exp(-\sin\psi/\sin\psi_o)$ where ψ is the angle between the cone axis and the velocity of the emitting material, and r its distance from the core; n and ψ_o are parameters of the model. The r^{-n} dependence ensures that all isophotes have the same shape, given, in polar coordinates R,A on the sky by

$$R^{n-1} \propto \int_0^{\pi} \sin^{n-2}\chi \left(1 - \frac{v}{c}\cos\chi\right)^{-(2+\alpha)} \exp(-\sin\psi/\sin\psi_o)\,d\chi$$

where $\cos\chi \equiv \cos A \sin\theta \sin\chi + \cos\chi$; χ represents the angle between the velocity of an element of source material and the line of sight. The diagrams show isophote shapes for various θ, n and ψ_o, and $\gamma = (1 - v^2/c^2)^{-\frac{1}{2}}$.



In Figures (a),(b) and (c), n=3 and spectral index α=1; θ is least for the outermost isophote.

(a) has γ=10, ψ_o=5°; θ= 5°,10°,20°.
(b) has γ= 5, ψ_o=10°; θ=10°,20°,40°.
(c) has γ= 5, ψ_o= 5°; θ= 5°,10°,20°,40°.
(d) has γ=10, ψ_o= 5°; α=0.3; the full lines show n=3, θ= 5°,10°,20°; the dotted line, n=4, θ=5°.

geometry of a dipole magnetic field, and I think we can incorporate them in kinematic schemes that may have plausible underlying physics. What we need is bursts of high-γ ejecta travelling along a diverging bundle of trajectories. In the picture I want to consider (Fig. 2), the observer's line of sight makes angle θ with the x-axis, and sources of radiation move with speed $v \simeq c$ along curves that start off like $(y^2 + z^2)^{1/2} = Ax^n$. (For a dipole field line, n = 1.5). As in the dipole model, after a burst of high activity in the central engine, the observer sees ejecta travelling tangentially to his line of sight on different trajectories in quick succession. As in Scheuer and Readhead, the core flux is limited by self-absorption, so the base of the jet bundle is always visible at about the same place, but maxima of energy output appear to propagate along the optically thin jet at a speed which is straightforward to compute, and for which we can find explicit formulae in particular cases, e.g.

$$\frac{v_{app}}{c} = \tan\theta \;\{\frac{2c}{v}(\sec^3\theta - 1)\cos\theta \operatorname{cosec}\theta - 3 - 2\tan^2\theta\}^{-1} \text{ for } n = {}^3/2 \qquad (2)$$

$$\frac{v_{app}}{c} = \tan\theta \;\{\frac{c}{v}[\sec^2\theta + \operatorname{cosec}\theta \;\ell n(\tan\theta + \sec\theta)] - 1 - \sec^2\theta\}^{-1} \quad \text{for } n = 2 \qquad (3)$$

$$\frac{v_{app}}{c} = (1 - \cos\theta)(\frac{c}{v}\theta - \sin\theta)^{-1} \text{ for circular arcs} \qquad (4)$$

and, for $\gamma >> 1$, $\theta << 1$

$$\frac{v_{app}}{c} \sim \{\frac{n}{(n-1)2\gamma^2\theta} + \frac{n-1}{2n-1}\theta\}^{-1}, \text{ with a maximum value } \sim \gamma(1-1/2n)^{\frac{1}{2}}. \qquad (5)$$

In my picture (unlike the dipole model) the trajectories do not close up; in fact, their precise form at large θ is unimportant, since the expansion of the source material makes its luminosity unobservably small. For this reason we do not expect to see the far side of the jet, even if the jets are intrinsically two-sided, and we expect to see the jets feebly if at all when θ is really large (where 'really large' might mean 15° or 45°). Note that the apparent total luminosity of such a diverging jet does NOT vary in proportion to $(1+(v/c)\cos\theta/1-(v/c)\cos\theta)^{2+\alpha}$, like simple undirectional jets. It is expected to look much fainter at large θ, but in a manner which depends on the decrease in power of the source material as it spreads out at large θ, a manner which cannot be computed in any straightforward way because it depends on additional physical assumptions.

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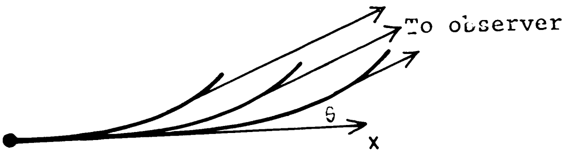

Figure 2. Thick lines represent the trajectories of emitting matter, which is observed when its velocity is directed within $1/\gamma$ of the line of sight.

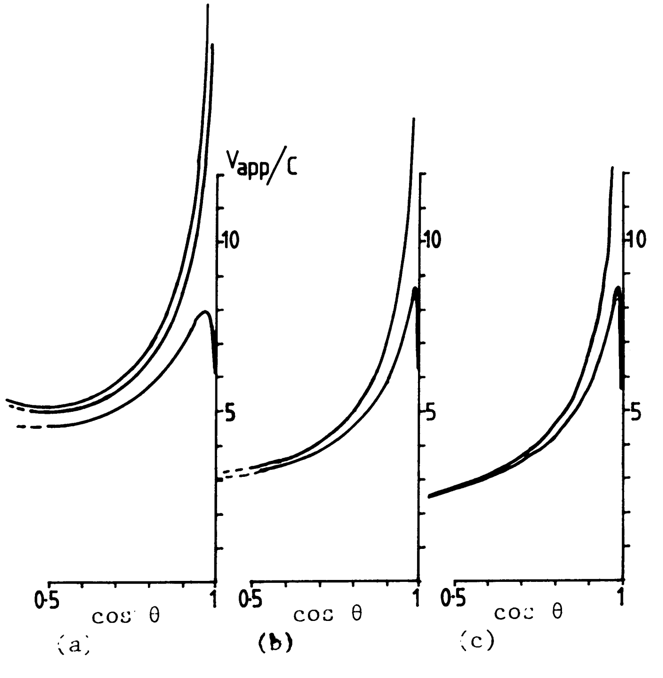

Figure 3. Apparent velocity versus cos θ, for models of the type illustrated in Figure 2, with trajectories of the forms: (a) $y = Ax^{3/2}$ (b) $y = Ax^2$ and (c) circular arcs. The top curve in each diagram represents emitting matter with v=c, the bottom curve represents emitting matter with $\gamma=10$, and the middle curve in Figure 3(a) represents $\gamma=20$.

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The apparent velocities shown in Fig. 3 illustrate that the results do not depend critically on the form of the trajectories. They are plotted against cos θ, to illustrate the distribution of velocities expected for a sample free from bias in orientation; a sample selected for strong core fluxes would of course crowd up towards small θ.

Such a model is quite flexible, literally as well as metaphorically. The trajectories could be twisted, resulting in a displaced and/or bent apparent jet, and the trajectories could themselves be moved by, say, pressures from a surrounding fluid. However, if the trajectories move too freely and too fast, there is a risk of generating apparent motion towards the core.

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