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Relativistic beams, thick accretion disks and active galactic nuclei

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Abstract. We review recent analyses of observations of radio galaxies and quasars that support the relativistic beaming models and appear to produce values for the Lorentz factors of the radiating material in the nuclear jets. Thick accretion disk models for active galactic nuclei seem to yield comparable values for the Lorentz factors, and this coincidence may be taken as support for these models.

Key words : radio galaxies—quasars—active galactic nuclei—accretion disks

1. Introduction

Apart from explaining the observed phenomena of superluminal expansion and rapid radio variability in the cores of compact radio sources, the relativistic beaming models of Scheuer & Readhead (1979) and Blandford & Königl (1979) also suggested a unified interpretation of compact and extended double radio sources. In these models both types of sources are intrinsically similar but appear different due to the different orientations of their jet axes to the line of sight. Viewed from a direction close to the jet axis the radio emission from the core is strongly enhanced owing to the relativistic beaming in the approaching jet and tends to mask the emission from the extended lobes which do not move relativistically. In contrast, a normal double source has its jet axis well away from the line of sight and the core appears weak in camparison with the lobes.

Although Scheuer & Readhead (1979) also attempted to unify the radio-quiet quasars in their model, recent radio observations of samples of optically selected quasars appear to be inconsistent with this aspect of the model (*e.g.* Strittmatter *et al.* 1980; Condon *et al.* 1981). Considerable support for the basic model has however been found from the samples of radio-selected quasars. It has been shown by Orr & Browne (1982; see also Browne & Orr 1982) for instance, that the observed proportion of flat spectrum quasars in flux-limited samples selected at different radio frequencies, and the flux density counts of flat-spectrum quasars in high frequency

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surveys, are entirely consistent with the beaming interpretation. More recently, Kapahi & Saikia (1982), from an analysis of a sample of 78 well-observed double quasars selected from low frequency catalogues, conclude that the fractional flux density in the compact central component shows an inverse correlation with the projected linear size of the extended double structure. This fractional flux density also shows positive correlations with (a) the apparent misalignment of the hot-spots in the lobes from collinearity with the central component and (b) the ratio of separations of the hot spots from the central component. All these correlations are in the sense expected if the fractional flux in the core is a statistical measure of the source orientation as predicted by the beaming model.

2. Estimates of Lorentz factors

The Lorentz factor, $\gamma = (1 - \beta^2)^{-1/2}$, of the nuclear jets is an important parameter of the beaming model, but is not easy to determine. The known cases of superluminal motion require values of γ in the range of about 3 to 10 (*e.g.* Cohen & Unwin 1982). The typical values may in general be smaller because the strong Doppler boosting of the flux of compact sources can bias the observations in favour of sources with the highest values of γ. For a group of well resolved double quasars in the 3CR sample, Scheuer & Readhead estimated an average value of $\gamma \lesssim 2$ from the observed distribution of the ratio, R, of the core flux density to the flux density of the extended structure. A similar value of $\gamma \lesssim 2$ was suggested by Hine & Scheuer (1980) to explain the temporal and spectral variations in the core of the radio galaxy 3C 111 as arising from an incoherent synchrotron radiation mechanism.

Orr & Browne (1982) have argued recently that Scheuer & Readhead's estimate of γ may be incorrect becuase they did not include the compact core-dominated 3CR quasars in their distribution of R. By including such sources, Orr & Browne infer typical values of γ between 4 and 5. The larger values have also been found by them to be required to explain the observed counts of flat-spectrum quasars on the unified interpretation of compact and extended sources.

The plot of projected linear size *vs* fraction of flux density in the central component (emitted at 8 GHz) shows that most of the large separation (> 300 kpc) sources have a central component producing less than 15 per cent of the total flux density while the large core-fraction sources have smaller separations (Kapahi & Saikia 1982). Fitting an upper envelope to the data points indicates that $\gamma = 2$ is sufficient to explain most of the data points, but the distribution of γ must extend to larger values to fit the small number of core-dominated double sources. Larger values of γ are required also to explain the asymmetric D2 type quasars that usually have more than 50 per cent of the flux density in the core (Kapahi 1981). Recent observations of compact flat-spectrum quasars found in high frequency surveys indicate such one-sided extended components to be fairly common (*e.g.* Perley *et al.* 1980, 1982; Browne *et al.* 1982; Moore *et al.* 1981).

Radio galaxies are in general known to have less prominent cores as compared to quasars (*e.g.* Riley & Jenkins 1977), and it is possible that the typical values of γ are smaller for galaxies than for quasars. Saikia (1981) has pointed out that there is a noticeable difference in the spectral index *vs* luminosity ($\alpha - P$) relation for the steep spectrum cores of radio galaxies and quasars. While the galaxies show a strong

$\alpha - P$ correlation (Bridle & Fomalont 1978; Fomalont *et al.* 1980) there is a much larger scatter in the quasar data. The scatter in the correlation for galaxies implies an upper limit of $\gamma \sim 2$ in their nuclear jets.

At this point it therefore seems safe to conclude that $\gamma \lesssim 5$ for the vast majority of quasars and $\gamma \lesssim 2$ for the lower luminosity radio galaxies.

There are also possible counter examples to the beaming model which should be mentioned. Porcas (1981) has discovered superluminal motion in 3C 179, a normal double quasar (with a strong core) and notes that this does not easily fit the Scheuer & Readhead picture. Also, Saikia & Wiita (1982) and Linfield (1982) have shown that the beaming model cannot account for the asymmetrical nuclear jets in the galaxy Cygnus A. However, the evidence in favour of some form of relativistic beaming is strong enough to support its use as an organizing hypothesis.

3. Thick accretion disks

Turning now to the theoretical side of the problem, we note that accretion disks around supermassive blackholes have long been popular models for the power houses of active galactic nuclei (Lynden-Bell 1969). If the viscosity in the disk is low, the disks can become flat near the blackhole, with a pair of vortices or funnels existing along the axes (Lynden-Bell 1978; Paczyński & Wiita 1980). These funnels provide a natural way to produce accelerated and collimated beams. Starting from models for perfect fluid rings around blackholes (*e.g.* Fishbone & Moncreif 1976), and applying a global energy balance condition to the disk, Paczyński & Wiita (1980) constructed disks where the half-thickness, flux per unit area, total luminosity L, and accretion rate $\dot{M}$, are determined by the mass of the blackhole and a prescribed non-Keplerian angular momentum distribution, $l(r)$. As reasonable physical limits on $l(r)$ exist, the properties are not too sensitive to it, and mainly depend on the ratio of the outer to the inner radius of the disk (Jaroszyński *et al.* 1980; Abramowicz *et at.* 1980).

These models can produce luminosities up to some 20 times $L_{\rm Edd}$ ($= 1.3 \times 10^{38}\ M_{\rm BH}/M_\odot$), normally considered the maximum luminosity, although the efficiency $\eta (= L/\dot{M} c^2)$ typically drops as $L/L_{\rm Edd}$ increases. The first attempt by Abramowicz & Piran (1980) to calculate the degree of collimation and the terminal velocity imparted to optically thin matter flows within the funnels indicated that total opening angles of between 12° and 18° and γ factors between 1.5 and 2.4 were produced for astrophysically acceptable models.

However, Sikora (1981) and Sikora & Wilson (1981) essentially agree on the opening angles, but conclude that ordinary matter beams could rarely exceed $\gamma = 1.1$, although γ's from 3 to 4 are possible for $e^+ e^-$ beams. Although the latter works appear to be more complete, the exact disk structures used differ, and both gravitational redshifts and the swallowing of radiation by the blackhole are neglected. If these effects were included, a lower luminosity should reach a distant observer, and one would naively expect still lower velocities. But because these effects are most important close to the blackhole, where the radiation field is essentially isotropic and exerts a drag on the particles, they would also serve to lower the height at which effective acceleration could begin within the funnels, thus probably allowing for higher terminal velocities. Similar fairly detailed calculations by Abramowicz &

Sharp (1982) produce ordinary plasma beams with terminal γ's near 2, while electron-positron beams achieve γ's between 4 and 6. At this time it is unknown where the discrepancies between these results arise. It is clear that more precise calculations are needed, and they should be extended to optically thick flows as well. Still, assuming that the conclusions of Abramowicz & Piran and Abramowizc & Sharp are correct, we have an interesting coincidence between the above analysis of observational data and a powerful theoretical model. The results for ordinary plasma beams agree with the lower range for γ values obtained from the observations while those for $e^+ e^-$ beams agree with the upper range. Obviously this kind of *agreement* is akin to having one's cake and eating it too, but we note that no other picture of beam formation has been carried to the point where it predicts any particular value for γ, and most appear to be indifferent to the Lorentz factor attained.

It must be admitted that the current thick disk models are inadequate to explain many of the observations concerning quasars and other active galactic nuclei. Most importantly, the typical peak temperatures are only slightly higher than for standard thin disk models, *e.g.* $\sim 10^6$ K around a blackhole of $\sim 10^7 M_\odot$ needed to produce the requisite $\sim 10^{46}$ erg s^{-1} total luminosity (Wiita 1982). This is far less than needed to explain the hard x-ray emission, but it is certainly possible to consider Comptonization in a corona around the disk (Liang & Thompson 1979) which may be able to yield enough hard photons (Wiita 1983). The current models also seem to demand that the disk's mass exceed the hole's mass if $M > 10^7 M_\odot$ (Wiita 1982), but there is no reason that more complex, fully self-consistent, models cannot include the disk's selfgravity and allow for this possibility. Finally, the questions concerning the stability of such disks (Abramowicz *et al.* 1982) and the detailed effects of magnetic fields upon them (Dadhich & Wiita 1982; Wiita *et al.* 1982) demand further scrutiny. If all of these questions can be resolved favourably, in terms of a more refined model, then thick accretion disks may well be the answer to the question: "What powers active galactic nuclei?" The coincidence discussed above appears to be a piece of evidence in their favour.

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