RELATIVISTIC BEAMING MODELS AND VLBI OBSERVATIONS OF A COMPLETE SAMPLE OF RADIO SOURCES

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1. INTRODUCTION

We have conducted a systematic study of the milliarcsecond structure of a complete, flux-density limited sample of strong radio sources selected at 5 GHz. We have made 5 GHz maps at two epochs of the 45 compact sources in the sample, and third-epoch observations are in progress. Our intention was to explore the full range of morphologies exhibited by compact radio sources, to search for new superluminal sources, and to determine how widespread such phenomena as parsec-scale jets, alignment of parsec-scale and kiloparsec-scale jets, and superluminal motion are. In addition, we hoped to use this well-defined sample for statistical tests of the beaming theories.

We have found that superluminal motion is common. Thus far it has been observed in all classes of object except the compact doubles, which comprise less than 10% of the objects in our complete sample (Pearson, Readhead and Barthel 1987). Examples of superluminal sources in our sample are the compact flat-spectrum objects 3C 345 and BL Lac, the compact steep-spectrum object 3C 216, and the extended triple sources 3C 179 and 1928+738. At least nine of the 65 sources in the complete sample are superluminal, and we can place subluminal limits on two of the compact double objects (0710+439 and 2021+614). In order to detect superluminal motion high quality observations at many epochs are needed. Based on the number of superluminal objects already detected in this survey, it seems likely that it will be only a matter of time and effort before superluminal motion is detected in 90% of the remaining sources.

The results of this survey will be discussed fully elsewhere. We concentrate here on some implications that these results have for relativistic beaming models.

2. THE SIMPLE BEAMING HYPOTHESIS

We make no attempt at a complete review of beaming theories here. There are a number of excellent recent discussions in the literature (Phinney 1985; Blandford 1987; Scheuer 1987) to which the reader is referred for the details of the arguments. However our observations of a complete sample do cast some interesting light on the subject, as discussed below.

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In its simplest form the beaming hypothesis makes the following assumptions:

i. Material is ejected from the nuclei of active galaxies with relativistic bulk velocity v, corresponding to Lorentz factor γ.
ii. This velocity is constant from the innermost region of the jet to the outer lobes.
iii. The velocity is the same for all active nuclei.
iv. The velocity is parallel to the axis of the jet, so that the emission cone has opening angle $\sim 1/\gamma$.
v. The jets are narrow (opening angle $< 1/\gamma$).
vi. The jets have very small intrinsic curvature over their entire length.
vii. The range of the ratio, R_i, of the intrinsic flux density (i.e., the flux density in the rest frame of the emission region) of the core to that of the outer lobes is much smaller than the variation of the observed ratio, R_o.
viii. The observed motions in the nuclear radio regions are causally connected, and are not simply pattern speeds.
ix. There is no orientation bias in the selection of optical quasars.

Of these assumptions (iii) is commonly dropped in beaming models and a range of velocities, which applies to all classes of active nuclei, is assumed.

There are five significant successes of the simple beaming models:

I. There is good evidence, based on three independent arguments, for relativistic motion in compact objects (superluminal motion, variability timescales and low X-ray luminosities of some compact objects; see e.g., Cohen and Unwin 1984).
II. Misalignments between the central components and outer components are greater in the core-dominated sources than in the lobe-dominated sources (Readhead *et al.* 1978).
III. The apparent velocities of extended double sources are lower than those of compact sources (Hough and Readhead 1987; Zensus and Porcas 1987).
IV. In powerful objects with both kpc-scale and pc-scale jets, the jets lie on the same side of the nucleus or they are connected (over 25 cases).
V. Classical triple objects with one-sided jets show less Faraday depolarization on the side coincident with the large-scale jet (about a dozen cases; Laing, private communication).

It has been clear from the start that this model is too simplistic (Scheuer and Readhead 1979; Blandford and Königl 1979), and the evidence against this simplest form of the model has increased steadily over the last decade:

A. The shape of the radio luminosity function is inconsistent with the predictions of simple beaming models, and there are too few radio quiet quasars or extended radio sources to account for the numbers of compact radio sources (Strittmatter *et al.* 1980; Phinney 1985; Kellermann *et al.* 1986).
B. The overall sizes of superluminal sources are too large if they are deprojected by the geometrical factor derived from the superluminal speeds (Schilizzi and de Bruyn 1983; Barthel *et al.* 1986; Browne 1987; Barthel, these proceedings).
C. Few, if any, two sided jets are observed in powerful radio sources.

3. IMPLICATIONS OF THE SURVEY FOR BEAMING THEORIES

It is clear that at least one of the assumptions—that the jets are narrow, with small emission cones, small intrinsic curvature over their entire length and that there is no orientation bias in the selection of optical objects—must be incorrect.

One of the most powerful arguments against the simplest model is that of the large deprojected sizes. However, it is difficult to discriminate between the alternative models on the basis of deprojected sizes alone. It has long been recognized that the observed differences in position angles provide a potentially powerful test. The first VLBI maps showed that there is a significant difference between the alignment of the inner and outer regions in core-dominated and lobe-dominated objects (Readhead *et al.* 1978). The direction of the superluminal motion is likely to be along the jets that we have already detected in many of these objects, and we can therefore use the present observations, together with VLA, MERLIN and WSRT observations of larger-scale structure, to measure variations in the apparent orientation of the jet axis.

We have looked at the change in position angle between the inner and outer components in the core-dominated objects in our sample, and the first significant result is that 1/3 of these objects, almost all of which have asymmetric milliarcsecond structure, have no detected large-scale structure at all. These have < 0.3 mJy in compact components within 6 arc seconds of the core (Perley 1982). Thus, although lower resolution VLA observations may reveal some weak extended features which were resolved out in Perley's observations, it appears that R_o exceeds 10^3 for these objects. Two of these objects (0212+735, 0454+844) have been the subject of very sensitive 20 cm VLA observations (Antonucci *et al.* 1986), and found to have $R_o > 2700$ and 1500, respectively. The lowest values of R_o are observed in double-lobed radio galaxies, where they can be as small as 10^{-3}. Thus we have to accommodate a total range in R_o of at least six orders of magnitude. One of the attractions of beaming models is that they can easily account for two to four orders of magnitude in R_o.

The second significant result is that we observe substantial misalignments in a number of objects (e.g., 3C 216, 0945+408, 1749+701, 1803+784, 1823+568).

Our results on position angle differences between small-scale and large-scale structure are shown in Figure 1 where we show the largest change in angle observed between the central component and features in the outer jet. We choose to plot the largest PA difference observed in each jet since it is the maximum curvature which should be used in any estimates of the deprojected length. Our distribution is broader than those obtained by Rusk and Rusk (1986) and Browne (1987), reflecting the fact that there is curvature along the large-scale jets.

Browne concluded, on the basis of the paucity of large misalignments in a sample of superluminal sources, that the intrinsic misalignment angles are rarely larger than the angle made by the core motion to the line of sight. His results showed that fewer than 20% of the sample had misalignments of greater than 90°. In Figure 1 41% of the objects have misalignments of greater than 90°. The results of Figure 1 can be tested against the simple beaming model (Moore *et al.* 1981; Readhead *et al.* 1983; Rusk and Rusk 1986). The chi-square test shows that simple beaming with an assumed intrinsic bend of 10° and $\gamma = 10$ cannot be ruled out, but that there is only a 13% probability of exceeding the value of chi square which obtains with an assumed bend of 11° and $\gamma = 5$. We wish to emphasize that for many of the objects included in Figure 1 only one or two comparatively

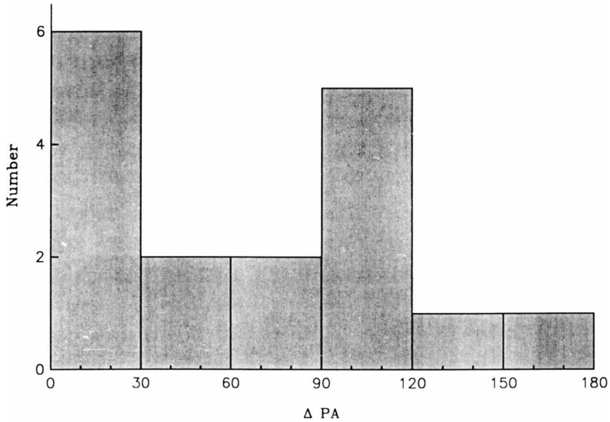

Figure 1 Histogram of the largest position angle differences ΔPA between the large-scale and small-scale features observed in the sources in the sample.

bright regions in the large-scale jet are visible. Higher dynamic range observations will likely reveal a larger fraction of the underlying jet, and some of these regions will show greater misalignments than we have observed thus far. Thus the misalignments plotted in Figure 1 are lower limits, and higher quality data are likely to be harder to reconcile with the simple beaming model. Furthermore, the tests assume that we have a complete sample, based on the core flux density, and as mentioned above, 1/3 of the objects are not included—these are the objects with high R_o which are expected to show the greatest curvature.

Since the observed misalignments are only marginally consistent with the simple model and we expect the evidence for misalignments to increase, we must consider alternatives to the simplest beaming models defined above.

If we admit intrinsic bends of order 30° in these objects is this alone sufficient or do we need, in addition, a broad ejection cone and/or a broad cone of emission at each position along the jet? Large intrinsic bends alone appear insufficient for the following reasons.

(a) A very large fraction of core-dominated objects are asymmetric core-jets. If intrinsic bends alone were responsible for increasing the overall emission cone angle in these objects we would expect to see a significant fraction of disembodied jets, i.e., jets with no flat-spectrum core at one end, and such objects are exceedingly rare. We would therefore be forced to postulate that the initial jet direction is closely aligned with the line of sight, and this leads to the problems with the luminosity distribution and relative numbers of faint objects mentioned above.

(b) Very large variations in the surface brightness of large-scale jets are not observed, although these would be expected on some models near bends in the jets. This expectation is relaxed if the emission cone is comparable in width to the intrinsic changes in jet direction.

We next consider whether broad ejection cones alone can explain the observations. Rees (1981) suggested a model with a broad ejection cone. In his model the "specific discharge" and/or the bulk velocity drops monotonically with angle from the axis of the jet. This ensures that the dominant superluminal effects are on one side of the core and appear in projection aligned with the approaching side. This model does not ensure that successive components follow the same path, and in addition, it is difficult to reconcile with the sharp decrease in surface brightness at the edges of the jets (see the map of M87 by Biretta *et al.* in these proceedings). Furthermore we would expect to see some components of brightness comparable to the main jet components moving at random angles relative to the jet axis. For all these reasons, a narrow ejection cone with a wide emission cone, caused by bulk motions at significant angles to the jet axis, seems to be favored by the observations.

It therefore appears that these objects must have both significant intrinsic curvature and broad emission cones. A promising approach is one in which shocks and instabilities in the jets give rise to a rather wide range of bulk speeds and directions of motion (Norman, Winkler and Smarr 1983; Blandford 1984; Lind and Blandford 1985; Phinney 1985), and therefore there is beamed emission over a much wider cone angle than the opening angle of the jet. On purely physical grounds this is an attractive possibility, and it is worth pursuing since, even in those objects for which the misalignment is large (e.g., 3C 216, 3C 309.1, 1823+568), the nuclear jets do join up with the larger-scale jets, often after bending through more than 90°. This fact, together with the fact that successive ejecta appear to follow the same path, suggests that the ejection cones in these objects are narrow ($\sim 1/\gamma$).

4. LARGE-SCALE COUNTERJETS

Until a few years ago no large-scale counterjets had been observed. However this is no longer the case. Simon *et al.* (1987) have published a map of 1928+738, a core-dominated double-lobed superluminal quasar which does have a counterjet, and in an ongoing program of mapping 3C quasars at the VLA Bridle and a large group of collaborators have recently found large-scale counterjets in 3C 9, 3C 68.1 and 3C 334 (private communication). Indeed, there are features in the Cygnus A map of Perley and Dreher (private communication) which look suspiciously like a counterjet.

The present incomplete statistics of large-scale counterjets argue against the beaming hypothesis (Wardle and Potash 1984; Barthel 1987 and these proceedings), and we may therefore be missing quasars with axes near the plane of the sky. This argument is strengthened if we admit large emission cones and intrinsic bends into the model since in some objects with symmetry axes near the plane of the sky there will be regions of the counterjet at angles significantly less than 90° to the line of sight. However the statistics are incomplete and we must await the results of VLA observations of complete samples.

5. CONCLUSIONS

We have summarized the arguments and presented some new evidence which suggest that significant modifications to the simplest beaming theories are required. In particular, it appears that all of the observations can be explained in terms of a model with a narrow ejection cone and large intrinsic curvature of the jet, in which some material moves at significant angles to the axis of the jet.

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