Relativistic Motion in Lobe-dominated Quasars

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Abstract
Sensitive VLBI and VLA surveys of a complete sample of 25 3CR lobe-dominated quasars have revealed evidence of relativistic motion on scales ranging from parsecs to tens of kiloparsecs. VLBI internal proper motion studies of the nuclei in eight objects at 8.4/10.7 GHz have identified four superluminal sources with apparent speeds of $\sim 1-4c$ ($H_0 = 100$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$). One superluminal source exhibits acceleration and non-radial motion of components. In 24 of the objects, VLA and MERLIN images have detected kiloparsec-scale jets (or jet candidates). In all eleven cases where both parsec- and kiloparsec-scale jets are seen, both jets lie on the same side of the most compact VLBI component. VLA deep imaging of thirteen sources at 5 GHz shows a strong correlation between the prominence of the nucleus and the prominence of the *straight, inner* segments of the kiloparsec-scale jets. The significance of this correlation is enhanced by the addition of data available for nine other sources. Taken together, the results to date are generally consistent with some type of relativistic beaming model, although departures from its simplest form are indicated. Yet on the simple beaming model, the superluminal results and nuclear-straight jet prominence correlation suggest a typical Lorentz factor $\gamma \sim 5$ in the nuclear jets and hint at a *possibly* lower value ($\gamma \sim 2-5$) in the straight segments of the kiloparsec-scale jets.

1 Introduction

Relativistic motion in some form undoubtedly plays a large role in the energy transport processes of powerful extragalactic radio sources, and it may well be a key ingredient to unification of a wide variety of quasars and active galactic nuclei (*e.g.* Scheuer and Readhead 1979; Blandford and Königl 1979; Orr and Browne 1982; Impey 1987; Barthel 1989). To ascertain its role in the most powerful and distant extragalactic radio sources, long-term VLBI and VLA imaging surveys of a complete sample of 25 3CR lobe-dominated quasars with minimal orientation bias have been undertaken (*e.g.* Hough and Readhead 1989; Hough, Vermeulen, and Readhead 1993; Bridle *et al.* 1993, 1994). This paper reports on the status of these surveys and presents evidence that relativistic motion occurs on scales from parsecs to tens of kiloparsecs in the lobe-dominated quasars. Throughout this paper, $H_0 = 100$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ are assumed.

2 The VLBI Survey

A VLBI survey to map the parsec-scale structure in the nuclei of the 25 3CR lobe-dominated quasars was initiated in 1981. Observations have been made at 8.4/10.7 GHz using the

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Mark III system (Rogers *et al.* 1983) with wideband recording (28-56 MHz). Telescopes of the NASA Deep Space Network, European VLBI Network, U.S. VLBI Network, and VLBA have been used, and processing has been performed at both Haystack Observatory and the Max-Planck-Institut für Radioastronomie. The typical resolution and noise level of the maps are ~0.5 mas and ~0.3 mJy/beam, respectively. Twenty objects have been observed to date: two "case studies" with observations spanning a decade, six with two-epoch maps, four with first-epoch maps, and eight with detections during brief pilot observations. This list includes all but one of the objects with a nuclear flux density at 5 GHz >10 mJy.

The two "case studies" involve the nuclei in 3C 245 (Hough and Readhead 1987; Hough *et al.* 1994) and 3C 263 (Zensus, Hough, and Porcas 1987; Hough, Zensus, and Porcas 1994), which have been both unusually cooperative and blessed with a decade of good observations. They offer a contrast in that 3C 245 has a small projected linear size and strong nucleus (as measured relative to extended emission), whereas 3C 263 is a large source with a nucleus of moderate strength; thus on the assumption that size and nuclear strength are orientation indicators, 3C 245 may be oriented significantly closer to the line of sight than 3C 263. Analysis of proper motions for two components in 3C 245 is consistent with their both having a constant apparent transverse velocity $v_{app}{\sim}3c$. For 3C 263, observations of one component from 1982 to 1984 yielded $v_{app}{\sim}1.3c$, but from 1982 to 1991 the *average* $v_{app}{\sim}2.5c$. These results suggest acceleration of this first component. Further, a second component emerged in 1989 at a different position angle (by $5° - 10°$) than the first, but then it appeared to align with the first by 1991.

Six nuclei have been mapped at two epochs, permitting a measurement of v_{app} or setting an upper limit thereto in five cases. The results are: 3C 47 at $\sim 3.7c$ (Vermeulen *et al.* 1993); 3C 204 at $\leq c$ and 3C 205 at $\leq 3c$ (Hough *et al.* 1993); 3C 207 at $\leq c$ (preliminary – Vermeulen, private communication); and 3C 334 at $\sim 1.6c$ (Hough *et al.* 1992). Zensus and Porcas (1987) observed 3C 268.4 in their Jodrell Bank quasar program and report structural variations that may indicate superluminal motion.

Four nuclei have first-epoch maps that, by virtue of the source structure and/or limitations of the observations, did not display distinct jet components at the observing epoch: 3C 208 and 3C 351 (Hough, unpublished); and 3C 212 and 3C 249.1 (Hough 1986). Note that insufficient closure phase data were available to determine jet sidedness in 3C 351. Future outbursts may well make these sources good candidates for multiple-epoch mapping.

Eight nuclei have been the subjects of brief pilot observations that seem to indicate resolved structure in virtually every case: 3C 175 and 3C 215 (Hough *et al.* 1993); 3C 181, 3C 270.1, and 3C 336 (Vermeulen, private communication); 3C 190 and 3C 191 (Hough, unpublished); and 3C 275.1 (Hough 1986).

To summarize, all twelve sources that have been mapped exhibit typical "core-jet" morphology. The eleven objects whose maps allow determination of the small-scale jet direction show it pointing toward the large-scale jet, suggesting the same cause of jet asymmetry on both size scales. Four objects have been classified as superluminal, and three have had limits set on their motion. The apparent speeds of $\sim 1 - 4c$ are consistent with relativistic beaming assuming a Lorentz factor $\gamma{\sim}5$ and random orientations. These speeds are also consistent with unification of lobe-dominated and core-dominated quasars, since the latter objects tend to exhibit speeds of $\sim 5 - 10c$. Further, there is a reasonably good correlation between apparent transverse velocity and nuclear strength, as expected on relativistic beaming models. However, 3C 47 seems to buck this trend: it is the largest and most strongly lobe-dominated superluminal in the sample, yet it exhibits the largest value of v_{app}. This may necessitate an above average Lorentz factor in 3C 47 (Vermeulen *et al.* 1993). Further, 3C 207 would also fail to follow the trend if its preliminary result is confirmed: it is a small source with a strong nucleus, yet it may have among the lowest values of v_{app}. The acceleration and non-radial motion observed in 3C 263 also do not conform to a simple model of unidirectional, constant velocity flow.

3 The VLA Survey

Bridle *et al.* (1993, 1994) present deep 5 GHz VLA images of thirteen of these quasars: 3C 9, 3C 47, 3C 68.1, 3C 175, 3C 204, 3C 208, 3C 215, 3C 249.1, 3C 263, 3C 334, 3C 336, 3C 351, and 3C 432. This list includes all the objects with projected linear size >100 kpc. The images have typical resolution and sensitivity of ~0.35 arcs and ~20 μJy/beam. They describe these images in great detail and provide a lengthy discussion of the implications of several new trends that have emerged upon proper dissection of the source structures. Note that with their work and that of others given in the references to Table 1 of Hough and Readhead (1989), 24 of the 25 sources in the complete sample have been reported to contain large-scale jets or jet candidates (3C 181 is the exception).

Perhaps foremost among the new trends is the discovery of a marked correlation between the (logarithmic) prominence of the nucleus and that of the *straight, inner* segments of the kiloparsec-scale jets (98% confidence level). Their specific prominence measure is the ratio of a feature's flux density relative to that of the extended emission on the jetted side of the source, at 5 GHz in the quasar rest frame. Note that this common normalization of the nuclear and jet flux densities could introduce some false correlation between the prominences, so the confidence levels quoted here, and below, are not those from normal statistics but from simulations as prescribed by Bridle *et al.* (1994). The straight jet segment is defined as the length over which there is a deviation of less than one jet radius from the mean jet axis. They suggest relativistic beaming on *both* size scales as an explanation for this correlation, and note that it is possible to estimate the Lorentz factor in the straight kiloparsec-scale jet segments from the slope of the relationship. For the thirteen sources they discuss, a tentative conclusion is drawn that if the nuclear Lorentz factor is typically $\gamma{\sim}5$, then the straight kiloparsec-scale jet segments typically have $\gamma{\sim}2$.

Informed by their approach, it is possible with hindsight to make somewhat crude measurements off lower quality existing images of other sources in the complete sample. When this is done for nine additional sources that lend themselves to appropriate dissection, the prominence relationship can be tested for 22 out of 25 sources in the complete sample of 3CR lobe-dominated quasars. The data for the nine additional sources – 3C 191, 3C 205, 3C 207, 3C 212, 3C 245, 3C 268.4, 3C 270.1, 3C 275.1, and 4C 16.49 – are taken from the references to Table 1 of Hough and Readhead (1989). The result is a confirmation of the correlation found by Bridle *et al.* (1993, 1994), but at a confidence level that certainly exceeds 99% for the linear correlation coefficient $r = 0.73$ (see Figure 1). It should be made clear that the nuclear and straight jet segment prominences show utterly no dependence on redshift ($r = -0.19$ and -0.12, respectively). Note also that the VLA/MERLIN flux densities have been used for the features here, with no attempt to redistribute intermediate-scale emission (~10 – 100 mas) from the nuclei to the straight jet segments, as was presented

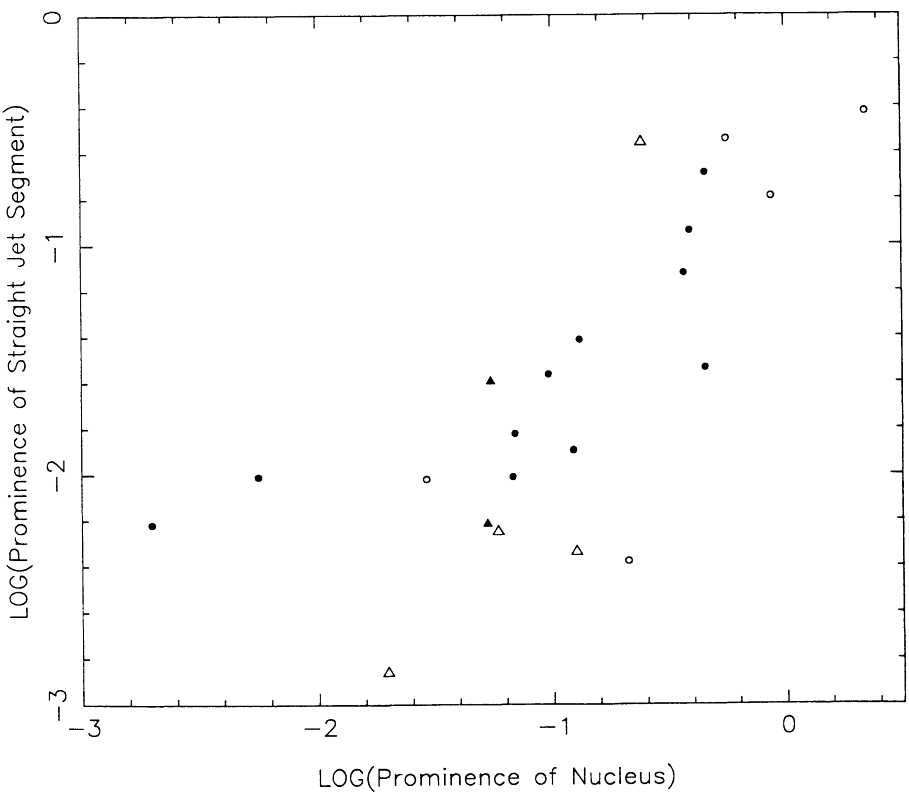

Figure 1: Prominence of the straight segments of the kiloparsec-scale jets vs. prominence of the nuclei, for 22 of the 25 objects in the 3CR complete sample of lobe-dominated quasars. The prominence is defined as the ratio of a feature's flux density to that of the extended emission on the jetted side of the source, at 5 GHz in the quasar rest frame. Filled symbols are from Bridle *et al.* (1994), open symbols are from data in the references to Table 1 of Hough and Readhead (1989). Objects at $z < 1.3$ are shown with circles, objects at $z > 1.3$ are shown with triangles.

as one option by Bridle *et al.* (1994). This was avoided because many of the additional sources have rather strong nuclei, and there is a greater danger of false correlation from the redistribution of the intermediate-scale emission to the fainter jets.

The slope of the relationship here (0.81 ± 0.16) does not appear quite as shallow as for the thirteen well-imaged sources (0.63 ± 0.12). There may be some dependence on redshift (see Figure 1), in which case the low redshift sample (those sixteen objects with $z < 1.3$, following Hough and Readhead 1989) slope of 0.65 ± 0.14 may be noteworthy. These slopes and their uncertainties were estimated using the method of York (1966) that takes into account uncertainties in both prominence measures, assuming the uncertainty for the jets is typically twice that for the nuclei. Bridle *et al.* (1994) give an expression for the slope predicted by a simple beaming model that allows different Lorentz factors in the nuclear and large-scale jets. They show that identical Lorentz factors on both size scales would lead to a slope of 1.30 for spectral indices 0.0 and 0.6, respectively ($S \; \alpha \; \nu^{-\alpha}$); deceleration in the large-scale jets would be reflected in a lower slope. In their work and this paper, $\gamma = 5$

is assumed for the nuclei and γ for the large-scale jets is inferred from the observed slope. On the assumption of jet axes oriented between 20° and 50° to the line of sight, the Bridle *et al.* (1994) slope for thirteen sources corresponds to $\gamma = 1.8 \pm 0.2$. On the slightly altered assumption of orientations between 10° and 50° here, the slope for 22 sources corresponds to $\gamma = 2.6 \pm 0.5$. Thus there appears to be significant evidence for deceleration in the straight segments of the kiloparsec-scale jets, with γ of perhaps $\sim 2 - 3$.

It must be pointed out, however, that this conclusion about deceleration rests heavily on two sources, 3C 68.1 and 3C 351, that Bridle *et al.* (1994) note as lowering their slope (and which also lower the slope presented here). These two sources are unusual in that they have highly asymmetric lobe and hot spot intensities, coupled with very weak nuclei and straight jet segments. Their omission leads to slopes of $\sim 1.2 \pm 0.2$ that imply a straight jet $\gamma \sim 4 \pm 1$. The evidence for deceleration is much weaker, but the prominence correlation nonetheless remains extremely strong for the remaining twenty sources. The fact that the sidedness of the small- and large-scale jets is the same led to the notion that "you must go the whole hog: either you are for fast jets, or you are for slow jets, all the way" (Scheuer 1984). The unequivocal presence of the prominence correlation provides strong evidence in favor of the first of these two possibilities.

Finally, the low redshift sample shows a significant anti-correlation between nuclear strength and projected linear size ($r = -0.56$, 98% confidence level) virtually identical to that found by Hough and Readhead (1989), despite the different measures of nuclear strength employed (possibly beamed jets and hot spots excised from the normalizing flux density here, but not by Hough and Readhead 1989). The straight jet prominence also anti-correlates with projected linear size ($r = -0.50$, 95% confidence level). Both of these trends are consistent with beaming in the nuclear and straight kiloparsec-scale jets over a wide range of source orientations. However, the far weaker trends relating source curvature to nuclear strength and projected linear size discussed by Hough and Readhead (1989) are absent here.

4 Conclusions

The results of the VLBI and VLA surveys to date lend strong support to a scenario in which relativistic beaming plays a critical role in the physics of powerful extragalactic radio sources on scales from parsecs to tens of kiloparsecs. Superluminal motions of $1 - 4c$, the correlation of jet sidedness on small and large scales, and the correlation of nuclear and straight kiloparsec-scale jet prominences in the 3CR lobe-dominated quasars all find straightforward explanations on a simple model of beaming into a narrow emission cone with a single value of the Lorentz factor.

However, there are tantalizing suggestions of departures from such a simple model. These include a range of γ and acceleration in the nuclear jets, and deceleration in the large-scale jets. Thus it is clearly crucial to complete multiple-epoch VLBI mapping of all 25 objects with the VLBA to determine the distribution of parsec-scale jet velocities for the entire sample. Similarly, high-resolution VLA/MERLIN images of all 25 objects are needed to dissect the intermediate- and large-scale structures adequately for tests of models of relativistic motion on these scales. Extensions of these programs to samples of low- and high-luminosity radio galaxies should be made where observationally feasible. Ultimately, the results of these surveys for the complete sample of 25 3CR lobe-dominated quasars should prove valuable in testing broad schemes for the unification of quasars and active galactic nuclei that incorporate some form of relativistic outflow.

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References

Barthel, P. D. 1989, *Astrophys. J.*, **336**, 606.

Blandford, R. D., and Königl, A. 1979, *Astrophys. J.*, **232**, 34.

Bridle, A. H., Hough, D. H., Lonsdale, C. J., Burns, J. O., and Laing, R. A. 1993, *Bull. Am. Astron. Soc.*, **25**, 1418.

Bridle, A. H., Hough, D. H., Lonsdale, C. J., Burns, J. O., and Laing, R. A. 1994, *Astron. J.*, submitted.

Hough, D. H. 1986, Ph. D. thesis, California Institute of Technology.

Hough, D. H., and Readhead, A. C. S. 1987, *Astrophys. J. (Letters)*, **321**, L11.

Hough, D. H., and Readhead, A. C. S. 1989, *Astron. J.*, **98**, 1208.

Hough, D. H., Readhead, A. C. S., Wood, Jr., D. A., and Feldmeier, J. J. 1992, *Astrophys. J.*, **393**, 81.

Hough, D. H., Vermeulen, R. C., and Readhead, A. C. S. 1993, in *Sub-arcsecond Radio Astronomy*, ed. R. J. Davis and R. S. Booth (Cambridge: Cambridge University Press), p. 193.

Hough, D. H., Wood, Jr., D. A., Vermeulen, R. C., Readhead, A. C. S., and Standifird, J. 1994, in preparation.

Hough, D. H., Zensus, J. A., and Porcas, R. W. 1994, in preparation.

Hough, D. H., Zensus, J. A., Vermeulen, R. C., Readhead, A. C. S., Porcas, R. W., and Rius, A. 1993, in *Sub-arcsecond Radio Astronomy*, ed. R. J. Davis and R. S. Booth (Cambridge: Cambridge University Press), p. 195.

Impey, C. 1987, in *Superluminal Radio Sources*, ed. J. A. Zensus and T. J. Pearson (Cambridge: Cambridge University Press), p. 233.

Orr, M. J. L., and Browne, I. W. A. 1982, *Monthly Notices Roy. Astron. Soc.*, **200**, 1067.

Rogers, A. E. E., *et al.* 1983, *Science*, **219**, 51.

Scheuer, P. A. G. 1984, in *IAU Symposium 110, VLBI and Compact Radio Sources*, ed. R. Fanti, K. Kellermann, and G. Setti (Dordrecht: Reidel), p. 197.

Scheuer, P. A. G., and Readhead, A. C. S. 1979, *Nature*, **277**, 182.

Vermeulen, R. C., Bernstein, R. A., Hough, D. H., and Readhead, A. C. S. 1993, *Astrophys. J.*, **417**, 541.

York, D. 1966, *Can. J. Phys.*, **44**, 1079.

Zensus, J. A., Hough, D. H., and Porcas, R. W. 1987, *Nature*, **325**, 36.

Zensus, J. A., and Porcas, R. W. 1987, in *Superluminal Radio Sources*, ed. J. A. Zensus and T. J. Pearson (Cambridge: Cambridge University Press), p. 126.