RADIO SOURCES WITH STRONG JETS AND WEAK CORES

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Received 10 March 1987; revised 10 August 1987

ABSTRACT

High-resolution radio maps of radio quasars with strong jets and weak cores are presented. The implications of these low core-to-jet flux-density ratios are discussed, with particular regard to the possibility of relativistic flow speeds and Doppler boosting of the emission from the core and/or jet. It is demonstrated that the observed spread in core/jet flux ratios for radio sources, in general, is sufficiently large that no meaningful constraints can be placed on the relative flow velocities in the core and jet, contrary to earlier claims. The large spread also implies that there is probably a substantial scatter in intrinsic core/jet ratios, independent of beaming effects.

I. INTRODUCTION

A major issue in the field of extragalactic radio astronomy is the question of the flow speeds in extragalactic radio-source jets (e.g., Bridle and Eilek 1984). It is important to answer this question, since not only does the flow speed of the energy-supply beam affect the overall energetics and dynamics of a source, but it also places constraints on the mechanisms of beam production and propagation, and can markedly affect the manner in which observational data are interpreted in terms of the physical conditions inside jets.

There are presently two schools of thought on this question. Proponents of the various schemes that seek to unify the properties of radio sources by orientation and relativistic beaming effects (e.g., Scheuer and Readhead 1979; Blandford and Konigl 1979; Orr and Browne 1982) generally invoke highly relativistic parsec and kiloparsec scale flows, whose observed properties are therefore markedly affected by aspect. Model-based arguments have been advanced that support (Orr and Browne 1982; Browne 1983) or are consistent with (Rusk and Rusk 1985) a typical flow speed corresponding to a Lorentz factor of ~ 5, at least in powerful radio sources. Observational support for the view that flow speeds are relativistic comes from studies of the compact, flat-spectrum cores of many sources. The superluminal motion frequently observed in such sources is most likely due to bulk relativistic motion of emitting material within a few parsecs of the core. Also, the parsec-scale structure is almost always one-sided with respect to the core itself, which invites interpretation in terms of Doppler favoritism from one side to the other. In all sources where the parsec- and kiloparsec-scale jet sidedness has been ascertained, the asymmetry is in the same sense on both scales. For this reason, and for reasons of flow energy and momentum conservation (e.g., Scheuer 1982), it is argued that the kiloparsec flows are also relativistic. Additional arguments have been made for large-scale jet velocities $v_j \sim c$, and are summarized by Bridle and Perley (1984).

The alternative viewpoint is that large-scale flow speeds are nonrelativistic, or, at most, only mildly relativistic (e.g., DeYoung 1985). Support for this view comes primarily from direct observations of kiloparsec-scale jets themselves. In the lower-luminosity radio sources, several head–tail sources and other morphologically complex sources have been modeled successfully in terms of the motions of the parent galaxy with respect to the surrounding medium or nearby galaxies. One of the parameters in this modeling is often the jet flow speed (e.g., Jones and Owen 1979), which is typically required to be, at most, 20% of the speed of light (O'Dea 1985). In high-luminosity sources, several jets are known that are sharply curved (e.g., Potash and Wardle 1980; this paper). The similarity of the jet brightness before and after the bend is cited as evidence that the Doppler boosting factor is similar in both locations. Since it is likely that the orientation to the line of sight is markedly different before and after the bend, the flow speed is unlikely to be highly relativistic. Again, additional arguments for $v_j \ll c$ can be found in Bridle and Perley (1984) and references therein.

This paper will not address the above arguments specifically, but will concentrate on one additional argument for $v_j \sim c$ that has been repeatedly quoted in the literature, but not yet critically examined. The argument centers around the fact that there are no published maps of jets whose associated core components are undetected (e.g., Saikia 1984). If large-scale jets were moving slowly, they would appear equally bright, independent of orientation. By contrast, the core components are generally accepted as being composed of relativistically moving material, and their flux density will therefore change dramatically with aspect. Consequently, there ought to be a population of sources whose cores are pointed away from us, which have strong jets but undetectable cores. The quoted absence of such sources is then cited as compelling evidence against greatly differing Lorentz factors in cores and large-scale jets (Scheuer 1984), or that at least a portion of the core flux originates in slow-moving material (Bridle and Perley 1984; Bridle 1985a,b). This argument can be turned around so that one predicts a correlation between jet and core prominence in a radio-source sample if jets are relativistic. This aspect has been investigated by Burns *et al.* (1984) and Lonsdale (1985) with inconclusive results.

Following an earlier report (Barthel and Lonsdale 1983), we here present maps of several sources with very weak cores relative to their jets, and demonstrate that when stated with precision, the coreless-jet argument is invalidated by current data, and that the different core-jet ratios must result at least partially from differing intrinsic source properties. In Sec. II we present our observations, and demonstrate the low ratios of core to jet flux density. Section III deals with the coreless-

 0004-6256/87/061487-06$00.90

jet argument in some detail, and our conclusions are given in Sec. IV.

II. OBSERVATIONS AND RESULTS

In this section, we present maps of five extragalactic radio sources produced from data taken at the VLA at 6 cm observing wavelength. The observational parameters are summarized in Table I. All five of these sources belong to a large sample of steep-spectrum high-redshift quasars which is being systematically mapped with the VLA by the authors for the purposes of a statistical study of radio-source properties and cosmological evolution. We present a small subset of the maps produced so far, in order to demonstrate the existence of sources with strong jets and weak cores. For further information on the main project, the reader is referred to Barthel (1984).

Radio maps of the five sources are presented in Fig. 1. In each case, the maps were produced from the calibrated VLA data by means of the CLEAN and self-calibration algorithms as implemented in the NRAO AIPS software package. The core position is marked by the cross, whose size indicates the approximate 1σ error in the optical position. The identification of the core was made on the criteria of proximity to the optical quasar position, lack of strong polarized flux, lack of resolution, and a flat spectrum (where known from maps at other frequencies) relative to the rest of the source. The distinction between a jet and a hotspot is made using the polarization characteristics. As pointed out by Bridle (1982), and Bridle and Perley (1984), the magnetic field in the jets of powerful radio sources is invariably longitudinal, a trend that is confirmed in our data. Often, however, the terminus of the jet displays a circumferential or transverse field configuration, and such features are interpreted here as hotspots, not part of the jet.

Notes on individual sources:

0017+154 (=3C 9). An early VLA map of this source exists (Swarup *et al.* (1982), which does not show a clear core component. Our 6 cm map has a dynamic range of 1200:1 (peak/rms), and the core component is clearly detected at about 3.5 mJy. We also have a 2 cm map that indicates that this component has a spectral index of 0.4 between these two wavelengths, so it is likely that part of its flux density originates in a small-scale jet, and that the true core component is weaker still. The jet in this source is very strong, and the polarization **E** vectors indicate that it does not terminate in a hotspot. Consequently, we have used the integrated flux density of the entire feature in Table II.

0238+100. This source was included in the paper in order to illustrate the fact that there is a large spread in core/jet flux ratios within our steep-spectrum source sample. Although this is not the most extreme example we have of a strong core and a weak jet in the sample, it serves to emphasize the effects of instrumental sensitivity limits. The jet (which does *not* include the terminating hotspot) would be undetected if it were only a few times weaker, and thus there may be many sources in the sample that have very high core/jet flux ratios that we cannot measure.

0730+257. This 6 cm map gives an example of a source with a moderately low core/jet flux ratio. As in all our sources, the jet is entirely one-sided. Once again, there is no terminating hotspot, and we have used the total integrated flux on the western side of the core. We have a 2 cm map that indicates that the core component has a steep spectrum.

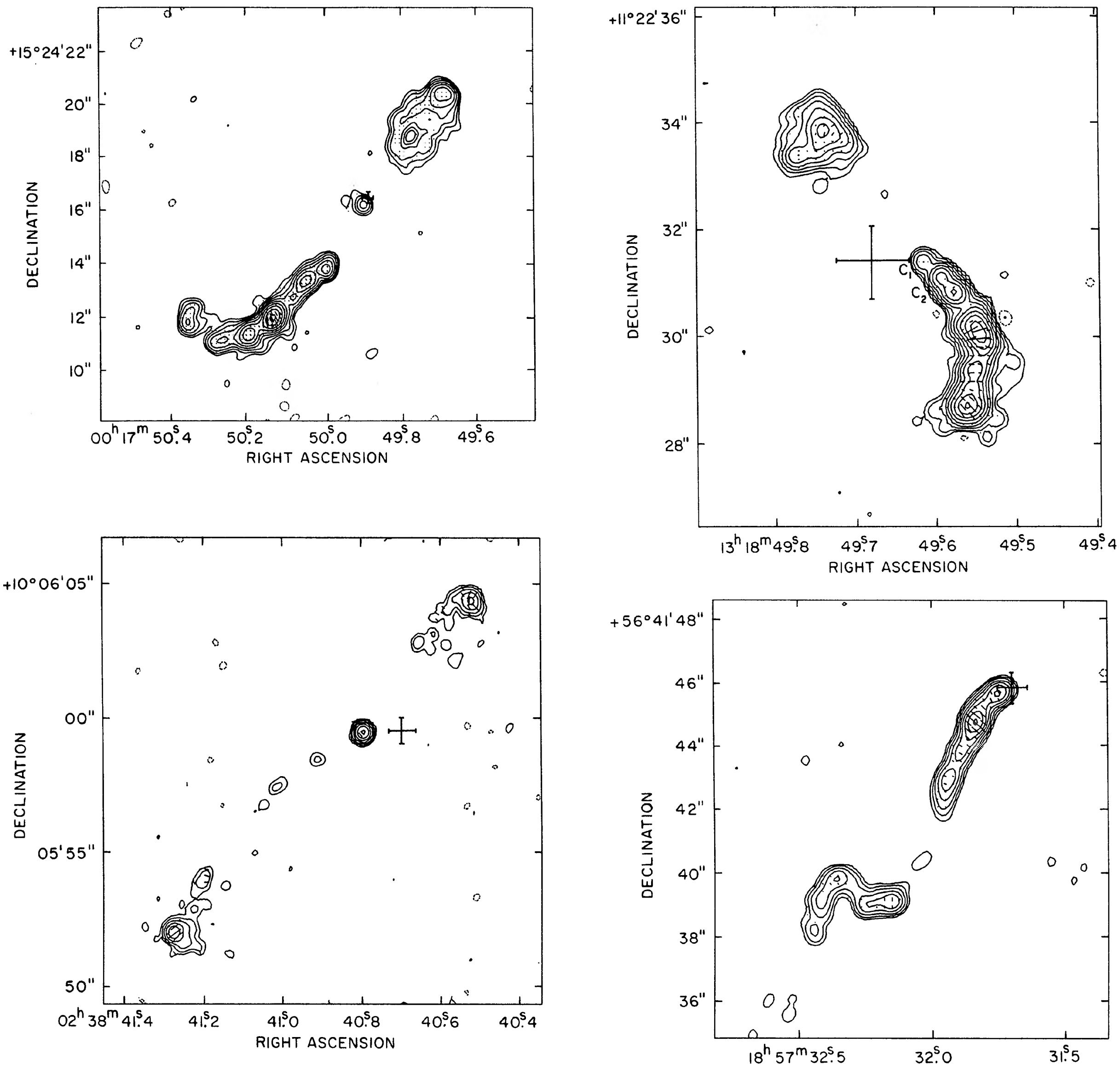
1318+113. This source was slightly superresolved by the use of a 0.25 arcsec restoring CLEAN beam (compared to a FWHM of the peak of the dirty beam of 0.37 arcsec). This was done in order to show the assumed core component C1 clearly. The accuracy of the superresolved structure was verified by making a 2 cm map at 0.12 arcsec resolution. Both C1 and C2 are unresolved on both maps, are negligibly polarized, and have steep spectra. However, considering that the spectrum of C1 is somewhat less steep than that of C2, that no other known radio quasar has any sign of a counterjet, and that C1 is significantly closer to the measured position of the optical object, we will assume that C1 is the true core. Also by reference to other sources, the core component is usually separated from the main body of the jet by a small gap, further supporting the identification of C1 as the core. At 2 cm, the core flux density is only 2.5 mJy. The data are consistent with the complete absence of a flat-spectrum core, but we have assumed a core flux density of 3 mJy in Table II.

1857+566. This source has been previously mapped by Owen and Puschell (1984), and our map shows structure similar to theirs. This is an example of the core flux density having an upper limit due to instrumental effects (in this case resolution). Although Owen and Puschell claimed to have measured a core flux density of 12.6 mJy, it is clear from our map that the component they identified as the core (on the basis of positional coincidence with the optical quasar) is both resolved and 15%–20% polarized, and thus indistinguishable from the rest of the jet. We have an unpublished 2 cm map that clearly shows this component to be composed of two components of approximately equal brightness. Using these two pieces of information, we take the core flux to be 6 mJy, a value that can probably be regarded as an upper limit.

In Table II, we list the flux densities of the core and jet of each source, corrected to 10 GHz in the rest frame of the quasar. We have assumed spectral indices for the core and jet of 0.0 and 0.6, respectively, in this calculation. In some cases, we know that the core component has a steep radio spectrum, and is therefore dominated by components that are not very compact. In these cases, the flux density of any true flat-spectrum core is significantly less than the value in Table II, and the ratio R of core to jet flux density can be regarded as an upper limit. In Table II we have also included values for a few core-dominated sources, taken from Pearson *et al.* (1985) and Perley (1986, private communication), in order to illustrate the large range of known core/jet flux ratios.

TABLE I. Observation parameters. For all the observations, the VLA was in the A array, and a bandwidth of 50 MHz was used. The observing frequency was 5 GHz.

Source	Observe Date	Integration Time
0017+154	April 1986	7 min
0238+100	April 1986	8 min
0730+257	August 1985	8 min
1318+113	August 1985	7 min
1857+566	April 1986	5 min



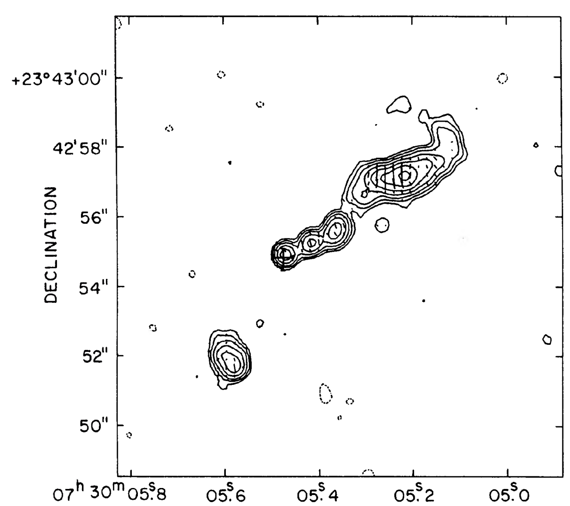


FIG. 1. Contour plots of five radio quasars. On all the maps, the contour levels are −0.3, 0.3, 0.6, 1.2, 2.5, 5, 10, 20, 40, 80, 160 mJy/beam, and the polarization lines represent the **E** vector of the polarized emission. The cross marks the position of the optical quasar, and its size indicates the approximate 1σ error. (a) 0017 + 154 (= 3C 9). The restoring CLEAN beam has a FWHM of 0.39×0.35 arcsec in P. A. 5°. The optical position is from Argue and Kenworthy (1972). (b) 0238 + 100. The CLEAN beam is 0.40×0.36 arcsec in P. A. 13°. The optical position was measured by Barthel (1984). (c) 0730 + 257. The CLEAN beam is 0.49×0.36 arcsec in P. A. 20°. The optical position is from Wills (1978). (d) 1318 + 113. The CLEAN beam is circular, with a FWHM of 0.25 arcsec (see the text). The optical position is from Jenkins *et al.* (1977). (e) 1857 + 566. The CLEAN beam is circular, with a FWHM of 0.40 arcsec. There is substantial diffuse emission both to the NW and SE of the displayed map, which is irrelevant to the present discussion. The optical position is from Cohen *et al.* (1977).

TABLE II. Core and jet fluxes for various sources. Column 2 is the redshift of the associated optical object. Columns 3 and 4 are the observed 5 GHz flux densities, and columns 5 and 6 are flux densities reduced to 10 GHz in the parent-galaxy rest frame. Column 7 is the logarithm of the parameter R discussed in the text. †—Pearson *et al.* (1985). ‡—Perley (1986) (private communication).

Source	z	S_c	S_j	S_c(10GHz)	S_j(10GHz)	$\log_{10} R$
0017+154	2.012	3.8	347	3.8	445	-2.07
0238+100	1.816	26	7.3	26	9	0.46
0730+257	2.686	17	126	17	182	-1.03
1318+113	2.171	3	400	3	525	-2.24
1857+566	1.595	6	200	6	235	-1.59
3C345†	0.595	8610	~ 80	8610	~ 70	~ 2.1
3C454.3†	0.859	12200	~ 110	12200	~ 105	~ 2.1
3C286†	0.849	6100	~ 36	6100	~ 34	~ 2.25
3C84‡	0.0172	53000	~ 25	53000	~ 17	~ 3.5

III. DISCUSSION

The argument concerning core/jet detectability and its implications for kiloparsec scale jet velocities referred to in the Introduction has been stated in various ways. Scheuer (1984) refers to it in his item (d) as the "disappearance of the middle ground." Citing the constant presence of a VLBI core accompanying a large-scale jet, he implies that a fast VLBI jet (the core) pointed away from us would be invisible, and that slow large-scale jets (which would be visible in any orientation) are thus in conflict with observation. Bridle and Perley (1984), when considering a "broader unified model," simply claim that $\gamma_j \ll \gamma_c$ cannot be a common circumstance, otherwise we would see many "coreless" jets, after earlier pointing out that all known jets have associated cores. Bridle (1985a) is more guarded, stating that "a significant fraction of the core luminosity in most sources is no more strongly beamed than is the large-scale jet luminosity." This allows for slow jets, but only if a significant fraction of the core flux originates in slow-moving material. If this is not the case, Bridle's statement again implies $\gamma_j \sim \gamma_c$.

All of the above statements are unquantified, and rely on the concept of jet and core detectability. However, the relative detectability of cores and jets is a function of resolution, observing frequency, redshift, and source morphology. A core is always unresolved, a jet never is (by definition, almost). A far more reliable measure of the relative strength of cores and jets is the ratio of integrated core and jet flux densities, corrected to a given frequency (10 GHz is convenient) in the parent-galaxy rest frame. This parameter, which we denote by R, will be the same for any given radio source independent of resolution, redshift, or observing frequency, except that instrumental limits will cause upper or lower limits on R which vary from source to source.

The argument can now be more rigorously restated as follows: *Assuming that slow-moving material in the core contributes negligibly to the core luminosity, the condition $\gamma_j \ll \gamma_c$ would result in a scatter in R much greater than that which is observed.* For this hypothesis to be valid, differences in core and jet boosting must be capable of producing the observed spread in R *without* the assistance of an intrinsic (source rest frame) scatter in core/jet flux ratios. Such an intrinsic scatter would constitute a free parameter in the model that would permit consistency with any observational data, and thus should not be invoked at this stage.

This assertion can now be assessed objectively, by predicting the scatter in R on theoretical grounds, and comparing that prediction to observation.

We now investigate qualitatively and quantitatively the anticipated effects of relativistic beaming on observed core/jet flux ratios. In view of the frequent detection of milliarcsecond-scale jets emerging from flat- or inverted-spectrum cores on VLBI maps (Preuss 1981), the most popular model is that the core component is simply the optically thick base of a continuous beam (Blandford and Konigl 1979). As they point out, the variation of flux density with viewing angle is a function not only of the Doppler factor, but also of the geometry of the emitting region. For a conical beam, they show that the core component will appear to have a flat spectrum, and the flux density will vary as $D^{2.2}$ (their Eq. (29)). They indicate that additional weak dependencies on the angle to the line of sight exist, but we will ignore them here. Thus, we will adopt the value of 2.2 for the exponent of the Doppler factor in the flux-boosting expression. There is also the possibility that some of the flux density of the core originates in a stationary component whose strength is therefore independent of orientation.

The kiloparsec-scale jet may also be relativistically boosted, and will have its own Doppler factor D_j. Since it is generally agreed that the jet is moving much faster than the outer lobes, the formation of a pipeline (i.e., the jet itself) between the core and the lobe may be regarded as instantaneous when compared to the lifetime of the source, and we are thus unlikely to find many sources with partially formed jets. Thus, a jet will have the same apparent length whether it is approaching or receding (its length is determined by the location of the lobe), but the surface brightness will be diluted due to time compression by a factor of D_j. As a result of this, the jet flux-boosting factor is $D_j^{2+\alpha}$, instead of $D^{3+\alpha}$ for a single component. Since the mean spectral index of jets is 0.6 (Bridle and Perley 1984), the exponent in the flux-boosting expression for jets is 2.6.

Note that Eq. (29) of Blandford and Konigl indicates a dependence of the observed flux density of a factor of $(1+z)$ in addition to the dependence on the square of the luminosity distance. This additional redshift dependence will tend to increase the core dominance of a source as it is moved to higher redshift, thus slightly increasing the scatter in core/jet flux ratios in a sample with a variety of redshifts. We have ignored this effect, since it is model dependent and its magnitude is generally much smaller than the flux boosting associated with the motions of the core and jet relative to the parent galaxy. In addition, the sources presented in this paper all have high redshifts, whereas the sources with the highest known values of R are at significantly lower redshifts, so the abovementioned effect is working to reduce the observed spread in R in this instance.

We thus consider a three-component model for the core–jet system—a stationary core component, a core component moving with Lorentz factor 5 (following Orr and Browne 1982), and a jet moving with a Lorentz factor γ_j not exceeding 5. This model is both straightforward to assess and is consistent with the assumptions inherent in the hypothesis we are examining. It should be noted that more complex models (e.g., Lind and Blandford 1985) predict significantly different beaming behavior from that given below. However, until observations can discriminate between such models, only the simplest model is appropriate for studies of this type. We can now define some relevant quantities:

S_{sc} = Flux density of stationary part of the core;

S_{ic} = Flux density the moving part of the core would have if it were stationary;

S_{ij} = Flux density the jet would have if it were stationary;

θ = angle between the line of sight and the motion of both core and jet.

Note that the subscript i stands for "intrinsic." All flux densities are at 10 GHz in the parent-galaxy rest frame.

Now,

$$D_j = \frac{1}{\gamma_j(1-\beta_j \cos\theta)},$$

and since the Lorentz factor of the core is defined to be 5, we have

$$D_c = \frac{0.2}{1-(0.9798\cos\theta)},$$

where D_c is the Doppler factor of the core, and D_j is the Doppler factor of the jet.

The source-intrinsic (i.e., unbeamed) ratio of core to jet flux R_i is given by

$$R_i = \frac{S_{ic}+S_{sc}}{S_{ij}},$$

while the observed ratio of core to jet flux density R is

$$R = \frac{S_{ic}D_c^{2.2}+S_{sc}}{S_{ij}D_j^{2.6}}.$$

The dispersion in R for a sample will be a function of the distribution of θ, as well as the scatter in R_i. If $S_{sc}=0$ (i.e., there is no stationary component in the core), R is simply given by

$$R = \frac{R_i D_c^{2.2}}{D_j^{2.6}} = R_i r,$$

where $r(\gamma_j,\theta)$ is the ratio of the flux-boosting factors for the core and jet.

Adopting a conservative approach, the maximum scatter in R, ΔR ($=R_{max}/R_{min}$) for a large sample (in which all values of R_i are represented for all orientations in the sample) is given by $\Delta R_i \times \Delta(D_c^{2.2}/D_j^{2.6})$. This expression is valid when $S_{sc} < \sim 0.001 S_{ic}$, since the minimum value of $D_c^{2.2}$ is 0.0065. Larger values for S_{sc} will tend to reduce ΔR, as implied by Bridle (1985a) when qualifying the $\gamma_j \sim \gamma_c$ argument. Assuming S_{sc} does not dominate S_{ic}, ΔR is maximized when $\gamma_j = 1$.

In Fig. 2 we have plotted $\log(D_c^{2.2}/D_j^{2.6})$ for various inclinations to the line of sight and various values of γ_j up to and including the assumed γ_c of 5. If all sources have the same intrinsic (unbeamed) ratio R_i of core to jet strength (i.e., $\Delta R_i = 1$), this diagram illustrates the expected spread in the observed core/jet flux ratio R. Note that the flux-boosting ratios change most sharply with θ when θ is small. The probability that a randomly oriented source will have a θ value smaller than ϕ is $\frac{1}{2}(1-\cos\phi)$ for a one-sided source and $(1-\cos\phi)$ for a two-sided source, so that a small sample of sources with random orientation is unlikely to contain sources with small values of θ, and will therefore show a limited spread Δr in flux-boosting ratios. Samples selected on the basis of the lobe flux density should be randomly oriented, and estimates of ΔR should take the above effect into account for such samples. The effect is enhanced if strong cores are specifically selected against, as in the case of our steep-spectrum quasar sample. We will arbitrarily assume for now that among the ~ 80 sources in our sample, the steep-spectrum selection has eliminated all sources closer than 30° to the line of sight. This corresponds to eliminating less than 7% of a randomly oriented sample, or about five sources, out of ~ 80 in our sample.

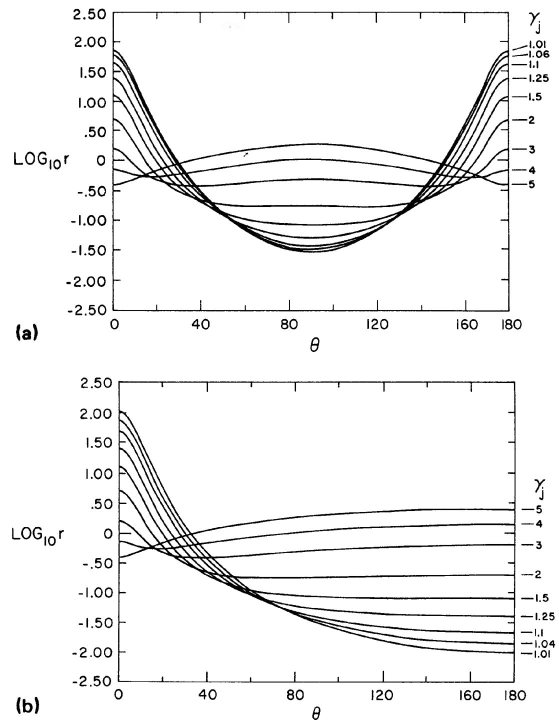


FIG. 2. Plots of core/jet flux-boosting ratio log r for various values of angle θ to the line of sight. The upper plot (a) corresponds to a source population with symmetric two-sided jets and cores, while the lower plot (b) corresponds to one-sided sources. The different curves are produced by different values of γ_j, the Lorentz factor of the large-scale jet, assuming $\gamma_c = 5$. The scatter in r, Δr, can be found by taking the extrema of the θ distribution and finding the corresponding extrema in r from the appropriate curve.

A second effect that serves to reduce ΔR is the likelihood that the large-scale jets are moving with mildly relativistic speeds. On energetic grounds alone it is difficult to envision flow speeds of less than $\sim 0.1c$, and if v_j reaches $0.5c$ ($\gamma_j \sim 1.15$) the dispersion Δr, by reference to Fig. 2, is markedly reduced.

Thus we expect small, randomly oriented samples and steep-spectrum samples to display a relatively small Δr of 10^2–10^3. For our steep-spectrum sample, assuming $\Delta R_i = 1$, $\theta > 30°$ and $\gamma_j = 1$, ΔR should be no more than ~ 150. For a randomly oriented sample with 150 members, the smallest value of θ is likely to be around 10°, corresponding to a $\Delta R \sim 4000$. Samples that contain a full range of θ, such as those selected at high frequency, where Doppler-boosted emission from the core frequently dominates, should approach the maximum ΔR of $\sim 10^4$. This value of 10^4 also corresponds to all sources regardless of sample membership. The original argument now asserts that the observed values of ΔR are significantly smaller than these values, thus constraining γ_j.

How do the observations compare with the above predictions? The observed ΔR for all sources, which is quite possibly limited only by the resolution and dynamic range on the maps, is more than 5×10^5. If we eliminate from the 3CR sample those sources whose large-scale emission alone is not strong enough to result in inclusion in the sample, we obtain a randomly oriented sample of ~ 150 members, the case cited above. 3C 345 would remain in such a sample (Pearson *et al.* 1985), and with 3C 9 this results in a measured ΔR of nearly 15 000. For our steep-spectrum sample, just the sources in this paper show $\Delta R > 500$, and 0238 + 100 is not the most extreme example of a large R value. The observed values of ΔR already significantly exceed the predicted values, even for $\gamma_j = 1$. Thus, based on the above analysis, it is not possible to constrain γ_j with these data, even assuming $S_{sc} = 0$. This may change with a higher assumed value for γ_c, but there is considerable room even in the present data for higher flux-boosting ratios.

A much more complex question to answer is what the expected distribution of core/jet ratios in a given sample should look like under our assumptions. The problem is that in order to calculate such a distribution, we need to know not only the intrinsic (i.e., unbeamed) distribution, but also the orientation distribution, which will not be uniform in general. The orientation distribution of a flux-limited sample depends on the fraction of a typical source flux that is beamed, and what the typical Lorentz factor of that fraction is. One can obtain self-consistent solutions to this problem by making simplifying assumptions and using additional information such as source counts (e.g., Orr and Browne 1982), but for the general case we are considering here, with the possibility of Doppler boosting of both steep- and flat-spectrum emission by different amounts, such analyses are complex. In addition, we would need to take into account poorly understood observational biases. One obvious observational effect is that many sources have been mapped with dynamic ranges of a few hundred, but hardly any approaching 200 000 as with 3C 84. This will lead to a deficit of sources with very high values of R. In summary, presently available data on the relative strengths of cores and jets in the general radio-source population appear to contain no information relevant to the velocity dilemma.

As a result of these findings, it appears necessary to invoke one or more additional mechanisms to increase the spread in core/jet flux ratios. These may include a spread in core and jet speeds, differences in the flow directions of the core and jet, and intrinsic variations in the core/jet ratio between sources and as a function of time in a single source.

IV. CONCLUSIONS

We have demonstrated that under the simplest of assumptions regarding source geometry, dynamics, and homogeneity, present data on the relative strengths of cores and jets do not contain useful information concerning the flow speed in large-scale jets. It is clear that there are many possible causes of the large observed spread in core/jet flux ratios reported here. The main point is that it is no longer possible to claim that the spread in core/jet ratios constrains models of relativistic beaming in a meaningful way.

We wish to thank Dr. R. Perley for showing us a map of 3C 84 prior to publication, and Prof. M. Cohen for constructive remarks. This work was supported in part by NSF grants AST 83-51447 and AST 85-09822. The National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc., under contract with the National Science Foundation.

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