SUPERLUMINAL RADIO SOURCES

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ABSTRACT

Several compact radio sources studied with VLBI show apparent transverse velocities much greater than the speed of light. This review is a summary of VLBI observations of these "superluminal" sources as of August 1981. The physical models proposed to explain this phenomenon are also discussed.

INTRODUCTION

The only direct observations of superluminal motion (1) are made using VLBI, and six examples are now known. These are shown in order of redshift z in Table I. All except 3C 279 also are the subject of individual contributions in this volume (2-6). We also carry along 4C 39.25 as an example of a non-superluminal source which nevertheless has many features in common with the others. The fourth column of Table I shows the transverse scale in light-years per milli-arcsec (mas) assuming the normal cosmological interpretation of redshift, and with H_o = 100 h km/sec/Mpc and q_o = 0.05. Column 5 gives a recent average value of flux density at centimeter wavelengths (all these sources are variable) and the last column is the corresponding luminosity at an emitted wavelength of 3 cm, assuming a flat spectrum.

Note that the distribution of sources with flux density (Table I) is inverted; i.e. there are many more strong sources than weak sources. There evidently are very many more such sources waiting to be found, with S_{cm} > 0.5 Jy. However, it is difficult to discover superluminal sources, mainly for lack of observing time needed to map candidates at several epochs. The best candidates seem to be BL Lac (7) and 3C 446 (8). Although the brightness distributions of these two change rapidly, a model with variable but stationary components is not excluded. It may be that the sampling interval has been too long to see systematic motions, if they exist.

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MORPHOLOGY AND KINEMATICS

The morphology and kinematics of the superluminal sources are summarized in Table II. Columns 2 and 3 indicate the projected size of large-scale radio emission; the size of the VLBI structure (column 4) is only approximate, since it is frequency- and time-dependent. △ PA (column 5)

TABLE I

Superluminal sources

Name	IAU	z	scale (ly/mas)	S_{cm} (Jy)	L_{cm} (10^{32} erg/s/Hz)
3C 120	0430+052	0.033	1.5 h^{-1}	4	0.5
3C 273	1226+023	0.158	6.0	35	95
3C 279	1253-055	0.538	13.5	10	315
3C 345	1641+399	0.595	14.1	12	465
3C 179	0723+679	0.846	16.3	0.5	40
NRAO 140	0333+321	1.258	18.3	2	370
4C 39.25	0923+392	0.698	15.2	8	430

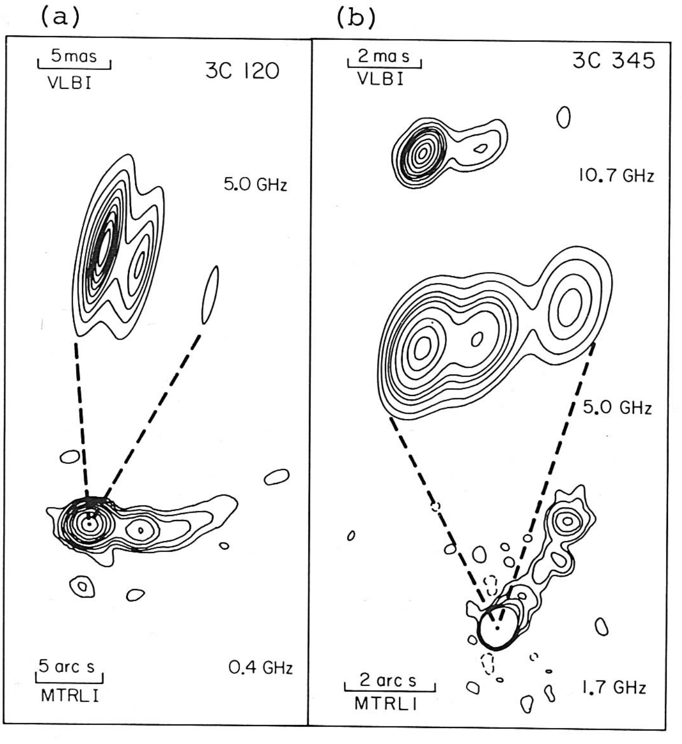

Figure 1. Large- and small-scale radio structure in (a) 3C 120 and (b) 3C 345. Dashed lines indicate the location of the VLBI structure within the compact core on each low-resolution map. The MTRLI maps are from Ref. 27; VLBI maps from Refs 16 and 26.

gives the total curvature at 2.8 cm, from the compact (VLBI) core to the outermost radio structure. Column 6 gives the measured proper motion μ in milli-arcsec (mas) per year. We emphasize that μ and z (Table I) are the only observed quantities. They show a strong inverse correlation, such as might be expected if z were a simple measure of distance and the intrinsic values of μ had only moderate dispersion. The other quantities are derived, and depend on h as indicated in Table II. Column 7 gives the apparent transverse velocity, calculated as $v/c = \mu\, s(1+z)$, where s is the scale in column 4 of Table I. References (column 10) are mainly since 1977; for earlier ones see the reviews by Cohen et al. (9), Kellermann and Shaffer (10), and Preuss (11).

Table II

Morphology and kinematics

Name	Outer structure jet (kpc)	Outer structure double (kpc)	Inner VLBI (pc)	Δ PA (deg)	μ (mas/y)	v/c	γ_{min}	$\theta(\gamma_{min})$ (deg)	References
3C 120	5 h^{-1}		3 h^{-1}	(45)[a]	1.35	2.1 h^{-1}	3 h^{-1}	20 h	2,16,23,27
3C 273	40		>15[b]	(35)[a]	0.76	5.3	5	11	3,13,20,23,27
3C 279	(10)	65 h^{-1}	(12)[c]	(15)[ac]	(0.5)	(10)	10	6	13,14,25,27
3C 345	15		20	107	0.36	8.2	8	7	4,26,27,29,30
3C 179	8	75	(6)[c]	(6)[c]	0.14	4.2	4	14	5,13,47
NRAO 140	(40)[d]		>10[b]	20	0.13	5.4	5	10	6,13,48
4C 39.25		20[e]	9	20	<0.02	<0.5			25,49-51

Notes: (a) VLBI accuracy limited by poor N-S resolution on low-declination sources. (b) Poorly-defined low-level extension also exists. (c) Double model. (d) See text. (e) Complex, but nearly linear.

Three of the superluminal sources (3C 120, 3C273 and 3C345) have several features in common: (i) each has a large-scale one-sided radio jet which is misaligned with the VLBI structure (12); (ii) a bright "core" at one end of the compact structure dominates these sources at most epochs; (iii) strong gradients in spectral index are found along both the compact and extended jet features; (iv) at every epoch for which good hybrid maps of these sources exist, there is no emission on the opposite side of the core from the jet, to a level of $\simeq$ 5% (2-4). Figure 1 shows the large- and small-scale structures in 3C 120 and 3C 345, and it illustrates the above points.

We believe that the other superluminal sources have a similar morphology, although the details have not been seen in all cases. VLA maps of 3C 279 are more complicated (13). In addition to a core-jet structure in PA -157^{o}, approximately aligned with the VLBI structure (14), there is an extended component at 50 h^{-1} kpc, in PA -34^{o}; it is unclear how these structures are related. The two newly-discovered sources 3C 179 and NRAO 140 as yet have no hybrid maps; the results are discussed in Refs (5) and (6) respectively. The outer structure of

NRAO 140 is ambiguous. A weak (1%) unresolved component which shows on the 20-cm VLA map may be a hot spot, but the jet, if it exists, is below the dynamic range of 500:1 (13).

3C 120 shows a misalignment of 45° between the VLBI structure and the MTRLI map (Fig. 1a), part of which is accounted for by a bend in the compact structure. Figure 2 shows most of the published history on the size of 3C 120. 3C 120 has such large internal proper motions, and the components evolve so rapidly, that it has not been possible to follow individual events except for two limited periods of time when the structure was dominated by two strong components. Between 1972.5 and 1974.4 the data were well-fitted by an expanding-double model, with proper motion μ = 1.51 ± 0.13 mas/yr in PA -115° (15). During 1979 the structure was again dominated by a close double, with μ = 1.35 ± 0.3 mas/yr in PA -115°, although the hybrid maps showed additional low-level structure (2,16); these two expansion phases were thus very similar. Between 1975 and 1978 there were insufficient observations to follow the structure changes properly. Some of the scatter in Figure 2 is probably due to fitting a double-model to structure which was actually more complicated.

3C 120 is classified as a Seyfert or N-galaxy (17). The emission-line axis, separating positive and negative velocities and thus possibly a rotation axis, is at $-108^{\circ} \pm 15^{\circ}$ (17), or very close to the inner VLBI axis. Optical images also show a "bent jet" (18,19) with curvature in the same general direction as the radio jet (Fig. 1a).

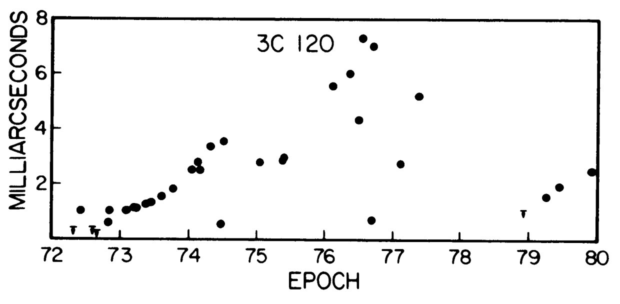

Figure 2. Angular size of the 3C 120 core against time. Points prior to 1978 are from Ref. 15, and represent the component separation of a double-model, found by least-squares fitting to amplitude data. Later points are measured from hybrid maps (16).

3C 273 has a core-jet VLBI structure with knots in the jet which move out from the dominant core; for the outermost knot, μ = 0.76 mas/yr (3,20). Earlier results based on fitting the visibility data from 1972 to 1977 with a double-model gave μ = 0.41 mas/yr (15,21-23). The difference probably arises from the complexity of the

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source, since recent hybrid maps show that it is usually at least triple. With limited amplitude data it is possible in this way to deduce expansion, but to underestimate the proper motion. There is no need to invoke acceleration (20).

3C 279 was the first suspected superluminal source (24) but it still has no modern hybrid maps. The most convincing data are in Ref. 14, visibility amplitudes from 1972-73 which, when modeled with a double, give $\mu \simeq 0.5$ mas/yr. 3C 279 varies rapidly and its visibility function has looked very different on different occasions (14,15,25). The very rapid motions reported in Ref. 25 are illusory if the separations do not represent the same pair of components at all epochs.

3C 345 The morphology and kinematics are best known for 3C 345 since good hybrid maps have been made for it since 1977 (23,26), and it is at high declination where the (u,v) coverage is good, and the restoring beam is nearly circular. Figure 1b shows 3C 345 on two angular scales. The large-scale jet has a projected length 15 h^{-1} kpc, and ends in a hot spot of intensity 2% of the peak (27). The VLBI maps of the core, taken near the same epoch (26), show an inner "core-jet" structure which is common on this angular scale (28) and repeats the outer morphology but on a scale 1000 times smaller. There are 3 inner components, with overall projected separation 20 h^{-1} pc. Comparison of 10.7 and 5.0 GHz maps shows that the eastern component ("core") has a spectral index $\alpha \simeq 1.0$, and variable flux density. This core appears to be the end of the system closest to the active center, because two prominent knots in the jet are separating from the core with the same proper motion (4). These components evolve rapidly, with half-lives $\simeq$ 3 years at 5.0 GHz, and spectra which steepen to $\alpha \simeq -1$ at the detection limit of the maps. As with 3C 273, there is no evidence for changes in the separation rate of a component. 3C 345 shows strong curvature in the jet close to the core; Figure 1b shows that the curvature continues along the outer jet. At 10.7 GHz the jet starts at PA -85°, and at 22 GHz the starting PA is $\simeq -130^{\circ}$ (29,30). The hot spot at the end of the jet is at PA -31° and the tangent there is at PA -23°; thus Δ PA $\simeq 107^{\circ}$.

In contrast with the early data (9,31,32) which interpreted the source as a double, the recent data provide two separations, since it as essentially a triple now. It is not clear how these can be reconciled, but as with 3C 120, it is likely that the source was poorly represented by a double for at least part of the time.

OTHER SOURCES

A few sources have been studied enough to say that they do not show rapid expansions in the manner of the superluminal sources. 4C 39.25 is shown in Tables I and II. Apart from the proper motion, it has most of the characteristics of the superluminals except for the lack of an outer jet. Even in this regard, however, it may not be unique, for the evidence for the outer jet in NRAO 140 is only circumstantial. 4C 39.25 has variations in total flux density, but they are slower and less pronounced than for the superluminals. 3C 84 (NGC 1275) is much more complex than the structures in Table II. It contains several components which vary in strength and which appear to separate slowly. Romney (33) reports evidence for expansion at v $\lesssim$ c. The high-redshift (z = 1.94) object 2134+004 has $\mu \lesssim 0.1$ mas/yr, which places a weak limit on the transverse velocity of v/c $\lesssim$ 5.8 (21). NRAO 150 is a double at 18-cm wavelength, and between 1974 and 1979 the strength of one component increased, but the spacing did not (34). At 3.8 cm NRAO 150 consists of a very close double, presumably located in the 18-cm variable component, which was stable from 1972 to 1975. This source has no redshift but is very interesting and deserves further study.

A number of rapid variables have been measured several times with VLBI (11,35). BL Lac, 3C 446, OJ 287, 3C 454.3, and others have variable brightness distribution and superluminal motions are suspected. However, in all these cases there are insufficient data to see if systematic expansions occur. The rapid variables present difficulties because they must be sampled frequently. The slower variables are being vigorously pursued, however, and it seems likely that the classes of confirmed superluminals and non-superluminals will increase rapidly.

PHYSICAL MODELS

The three well-studied sources 3C 120, 3C 273, and 3C 345 are very similar and any physical model must explain their essential characteristics: (i) core-jet structure, with several moving components, (ii) spectral gradient, (iii) evolution and decay of outer component, (iv) outer one-sided jet, (v) spatial curvature, mainly near core, (vi) superluminal motion, (vii) spacing and proper motion independent of wavelength (2-6 cm). The best data (4,20) show straight-line motion with no acceleration, but these data runs are only a few years long. The moving components can be at different position angles, corresponding to the general curvature of the source, but no component has yet been tracked around a bend. The polarization in the components of these sources is unknown; but high-resolution polarization measurements are starting, and in 3C 454.3 the magnetic field is along the jet, at 13-cm wavelength (36). Earlier studies (9) suggested that the extrapolated time of separation of a component from the origin was clse to the onset of a major outburst in total flux density. Recent work, however, has not borne this out. There even is a suggestion for 3C 345 that the outer component did not come from the origin, but from a region $\simeq$ 10 pc away (32).

Many suggestions for the origin of the superluminal effect have been made; these have been summarized by Blandford, McKee, and Rees (1), and by Marscher and Scott (37). Enhancement of proper motion and intensity by a gravitational lens (38) seems unlikely because 3C 120 is close and the chance of an undetected foreground object is small; also, the lens has to be arranged so that the primary image that we see is at least 20 times brighter than any secondary images. Schemes which depend on variations in opacity seem suspect because they most naturally lead to separations which vary with frequency, contrary to observations. The magnetic dipole model (39) has difficulty explaining the curvature; also, the separation velocity of 3C 120 is too low unless $\underline{h} \lesssim 0.5$, and the core-jet morphology does not match the expected double very well.

We feel that at present the relativistic jet model (40) is the best because (i) it is an economical unifying idea, with one jet responsible for the superluminal effects, the outer jet, and the outer hot spots, (ii) the one-sided core-jet morphology fits into it naturally, with the core being deep in the jet and moving components being generated by shock waves or instabilities, or perhaps being swept-up material (40,41), (iii) the common occurence of the superluminal effect (9) could be due to selection effects and the strong Doppler brightening of emitting material moving at a small angle to our line of sight (40,42,43). (iv) the strong curvature close to the core could be explained as a small intrinsic curvature amplified by the small angle to the line-of-sight (12,42), and (v) the near equality of the core and the jet components is reasonable if both are Doppler-enhanced but the core is the quasi-stationary region where the moving material becomes optically thin (40).

Table II contains values of the minimum Lorentz factor γ_{min} for the given value of v/c. (γ does not scale exactly with $\underline{h}$ so the values are approximate.) The angle θ to the line of sight corresponding to γ_{min} is also given. The solid angles are small, but this is not disturbing; in this model a radio-selected sample will have most of its objects with $\theta < 2\gamma^{-1}$, even though the objects have random orientations (42).

Over a long-term average the jet must be two-sided, to account for the outer double structure in 3C 179 and 3C 279, but there is no way at present to tell whether the retreating side is invisible because of the Doppler effect, or whether the jet is episodic and alternates sides. Unless the intrinsic curvature is rather large, the outer doubles are seen nearly end-on, and their true separation is up to 500 kpc. This is large, but not exceptionally so, for double sources.

An important statistical problem involving the large Doppler boost in flux density ($\sim\gamma^2$) does remain for the relativistic jet hypothesis. The most powerful way of stating it is for 3C 273: the optical continuum is unboosted (because the line/continuum ratio is normal) and so there should be 25 quasars as bright as 3C 273, in some z-range around 0.158. At radio wavelengths the many sources at large θ are much weaker, and indeed should be the radio-quiet quasars (42), but recent observations seem not to bear out the predictions (44). Also, 4C 39.25 becomes by far the most powerful source in Table I if it is at large θ and all the others are at small θ; even if its radiation is isotropic, 4C 39.25 is still much stronger than the others.

These problems are alleviated if the implications of the Doppler boost are changed. Rees (45) has proposed a "spray" model with a wide ejection cone. A strong gradient of intensity with cone-angle within the spray can alter the relation between the boost and the kinematic effects. The statistical objections to the relativistic jet model are ambiguous because the numbers are small and the samples are incomplete; if they persist, then the spray model and others will have to be carefully investigated.

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DISCUSSION

DAISHIDO: The spectral variations in quasars and Seyfert galaxies have been explained by the expanding models of Shklovsky, van der Laan, Kellermann, and others about 10 years ago. However, the observed "superluminal" clouds move rapidly, but do not seem to expand themselves. How then do you explain the spectral evolution?

COHEN: The moving components in 3C 345, for which we have the best N-S resolution, are unresolved and may have been expanding. The range of allowed sizes could give rise to substantial evolutionary effects.

TERRELL: Is there a critical number of superluminal cases beyond which the usual explanation (ejection toward the observer) will be in trouble?

COHEN: There is no critical number of sources, because the statistics depend on the distribution of radio luminosities and relativistic γ-factors. At present, the numbers of confirmed superluminals and non-superluminals is too small to exclude this explanation.

REES: Two comments: (i) The "Doppler enhancement" problem which occurs for $\gamma \gtrsim 10$ could be eased by assuming an intrinsic speed $\gtrsim \gamma^{-1}$ in the velocity vector of the ejecta. (ii) The internal pressure within individual superluminal "blobs" exceeds the likely gas pressure (estimated at a "deprojected" distance of ~50 pc). This supports the view that these blobs are generated by shock fronts in the jet; they expand and disperse as they move out, rather than having emerged directly from the core.

ABELL: What is the prognosis of getting absolute astrometry of these sources to 1 mas precision, so that we can pin down what is moving?

COHEN: Relative astrometry, e.g., 3C 345 vs NRAO 512 (Shapiro, *et al*. 1979, Astron. J., 84, pp. 1459-1469) already gives accuracy substantially better than 1 mas. In a few years it should be possible to make a series of maps of 3C 345 and tell whether or not the core is stationary with respect to NRAO 512. Absolute positions are much harder to measure to comparable accuracy.