SUPERLUMINAL EFFECTS AND BULK RELATIVISTIC MOTION

M.H. Cohen and S.C. Unwin
Owens Valley Radio Observatory
California Institute of Technology

ABSTRACT

The observational status of superluminal radio sources is reviewed, and the results for one well-studied source (3C 345) are discussed in detail. We discuss the relativistic-beam model of superluminal sources, and concentrate on one aspect, namely the geometric constraints provided by combined X-ray and proper-motion measurements.

1. OBSERVATIONAL SUMMARY

A superluminal source is one which shows internal motions with an apparent transverse velocity greater than the speed of light. There has been a marked improvement in our knowledge of these sources since the last VLBI symposium in Heidelberg, in 1978, and even since we wrote a review in 1981 (ref. 1). Whereas five years ago one could still question whether the motions were artifacts of analysis or of inadequate sampling, today we have accurate tracks of several components in each of the better-studied sources, and are beginning to get data on the evolution of the moving components.

The eight known superluminal sources are listed in Table 1, with the redshift z in column 3, proper motion relative to the core in column 5, and apparent transverse velocity in column 6. We assume that the sources are at cosmological distances, with $q_o = 0.05$ and $\underline{h} = H_o/100$, with H_o = Hubble constant in km/sec/Mpc. References in column 7 are only to recent articles; earlier references may be found in Ref. 1 and other reviews. Each of the sources (except NRAO 140) is discussed in separate articles in this volume.

Sequences of maps made from multi-station VLBI observations have been shown for 3C 120 (Ref. 2), BL Lac (5), 3C 273 (8,25), and 3C 345 (10,13,16,17,18). These clearly show the characteristic core-jet structure, with an optically-thick core and optically-thin jet components separating superluminally from the core. 3C 120 is highly variable and

R. Fanti et al. (eds.), VLBI and Compact Radio Sources, 95–103.
© 1984 by the IAU.

https://doi.org/10.1017/S0074180900077767 Published online by Cambridge University Press

TABLE 1

Superluminal Radio Sources

Name	IAU	z	Component	μ (mas/yr)	v/c	References
3C 120	0430+052	0.033	A	1.35	2.1 h^{-1}	1,2,3,4
			B	2.57	4.1	
			C	2.34	3.7	
			D	1.65	2.6	
BL Lac	2200+420	0.070		0.6	2	5,6,7
3C 273	1226+023	0.158	C3	0.79	5.5	1,8
			C4	0.99	6.9	
			C5	0.79	5.5	
3C 279	1253-055	0.538		0.17	3.5	1,8
3C 345	1641+399	0.595	C2	0.42	9.5	1,9 - 15
			C3	0.31	7.0	
			C4*	0.17	3.9	16,17,18
				0.27	6.1	
4C 39.25	0923+392	0.698		(-0.1)**	(-2.6)**	1,19
3C 179	0723+679	0.846		0.14	4.2	1,20,21,22
NRAO 140	0333+321	1.258		0.13	5.4	1,23,24

Notes: * This component shows an acceleration.
****Tentative result; negative sign means contraction.**

has the largest proper motions in Table 1 (consistent with the lowest redshift) and a consistent picture has only been obtained in the last two years, with frequent observations by Walker *et al.* (2). Four individual components have been tracked in 3C 120, since 1979. Their proper motions differ by a factor 2 (Table 1) but the errors on the slow components (A and D) are perhaps large enough that all four have nearly the same speed. 3C 120 shows no evidence for acceleration, non-radial motion, or ejection at different position angles; however, it is at $\delta = 5^\circ$ and the N-S resolution is very poor. 3C 345 ($\delta = 40^\circ$) shows more complicated behavior, as discussed below and in Ref. 16. In 3C 120, 3C 273, and 3C 345 the individual components decay with a time constant of one or two years.

BL Lac is also very active and must be observed several times per year to track the components. It is the only superluminal source for which there is evidence of a "counterjet" (5). The other sources (except 4C 39.25) are all one-sided on a small scale (to a level of ∿ 20:1 of the peak flux). 3C 273 is the only source which remains one-sided on a large scale, when looked at with very high dynamic range (26,27). 4C 39.25 is particularly interesting because in 1980 it began to contract, after a decade of serving as a "standard" stationary simple double source (19).

https://doi.org/10.1017/S0074180900077767 Published online by Cambridge University Press

NRAO 140 originally came to attention because of its low X-ray flux density (23), and the prediction of superluminal motion was confirmed by Marscher and Broderick (24). A similar prediction for 3C 147, however, has not been confirmed (28,29,44).

Bartel (ref. 9) has made the important measurement of the proper motion between 3C 345 and a nearby quasar, NRAO 512. They show that the core of 3C 345 is stationary with respect to NRAO 512, to a limit of 200 micro-arcsec in 9 years. This is an order of magnitude less than the internal proper motions in 3C 345 (Table 1).

Recent maps of 3C 279 (ref.8) show a new epoch of superluminal expansion at only one third of the rate found in 1971. The apparent velocity is now comparable with the other sources in Table 1. Other sources which are currently suspected of showing superluminal behavior include 0735+178, 2007+776, 2134+004 (ref. 30), 3C 454.3 (30), and 3C 446 (31).

2. BEAMING AND BULK RELATIVISTIC MOTION

Scheuer (32) discusses various models which can explain the superluminal effect, and we shall confine our remarks to the relativistic beam model. The beam lies at a small angle Θ to the line of sight, and the jet components are luminous "blobs" traveling with Lorentz factor γ along the beam. The core is stationary or moving very slowly (9); in one model it is the throat or region of the jet where the optical depth is unity (33,34). The Doppler factor δ and the apparent transverse velocity v/c are fixed by Θ and γ:

$$\delta = \gamma^{-1} (1 - \beta \cos \Theta)^{-1} \text{ and } v/c = \beta \sin\Theta (1 - \beta \cos \Theta)^{-1} \qquad [1]$$

where βc is the actual bulk velocity. Conversely, if δ and v/c can be measured, Θ and γ can be determined. Figure 1 shows a convenient graphical display of these quantities (13). VLBI gives v/c, and X-ray fluxes yield limits to δ; thus the kinematic parameters Θ and γ can be determined for the moving components. These parameters are derived below for 3C 345. If this procedure could be followed accurately for many sources, then in principle the Hubble constant could be determined (35).

Three independent types of observations suggest bulk relativistic motion in quasars and active galactic nuclei. Taken together, they provide strong evidence for bulk relativistic motion, and thus that the beam model or a variant thereof is most likely the correct explanation for the superluminal effect. A further virtue of these beams is that they lead fairly naturally into the jets seen on a kpc scale, which also are needed to power hot spots and the outer lobes of radio sources. However, the question of whether the extended jets are relativistic is by no means settled.

https://doi.org/10.1017/S0074180900077767 Published online by Cambridge University Press

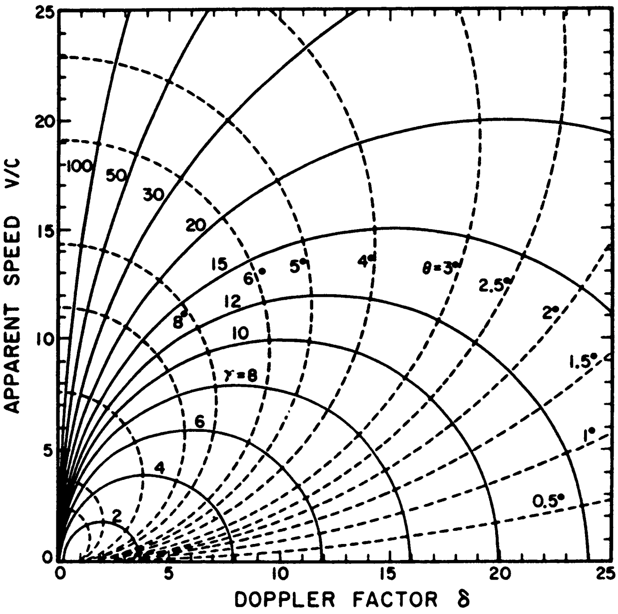

Figure 1

We now sketch these three lines of evidence, but omit discussion of beam collimation, the primary source of energy, and statistics.

a) Superluminal Motion

The measured quantities are proper motion μ and redshift z, which is converted to distance with a standard cosmological model and an assumed value of the Hubble constant. These give v/c, which in turn yields an upper limit to Θ, namely $\Theta_{max} = 2 \cot^{-1} (v/c)$, and a lower limit to γ, $\gamma_{min} = \sqrt{[1 + (v/c)^2]}$. The Doppler factor δ is not fixed by v/c alone, but if $\gamma = \gamma_{min}$, then $\sin \Theta = 1/\gamma$ and $\delta = \gamma$ (see Fig. 1). From Table 1, values of γ_{min} range from 2 to 20 for h between 0.5 and 1.

b) Inverse-Compton X-rays

Standard synchrotron theory predicts a definite ratio between the X-ray and radio fluxes from a cloud of high-energy particles, with the X-rays arising in the Inverse-Compton process. Gould (36) has made the calculation for a series of spherical models, and the application to determine the Doppler factor of radio sources was stressed by Burbidge, Jones, and O'Dell (37) and more recently by Marscher and Broderick (23). The principal result is that very weak X-rays imply bulk relativistic motion with $\delta > 1$.

https://doi.org/10.1017/S0074180900077767 Published online by Cambridge University Press

X-rays can also be produced by other processes: e.g. thermal bremsstrahlung, so that the measured X-ray flux density gives a lower limit to δ via the self-Compton process. The formula for δ_{min} may be written (13,38):

$$\delta_{min} = a(\alpha)(1+z)\, F_m \nu_m^{-p}\, \phi^{-q}\, S_x^{-r} \qquad [2]$$

where F_m is the peak radio flux density (Jy) at the turnover frequency ν_m (GHz), ϕ is the angular diameter (in milli-arcseconds, or mas) of the equivalent spherical radio source, and S_x is the X-ray flux density in units of $[10^{-11}(1+z)^{\alpha-1}]$ erg/cm^2/sec, in the band $(0.5 - 4.5)/(1+z)$ keV. The coefficient $a(\alpha)$ is of order unity, and the exponents p, q, and r are tabulated in ref. (13); for spectral index $\alpha = 0.75$, $a \simeq 0.65$, $p = 1.32$, $q = 1.64$, and $r = 0.18$.

The following points may be made about Eqn. [2]. (a) The calculation is based on the ratio of X-ray to radio brightness and is distance-independent, if the angular size is measured directly with VLBI. (b) r is small, so the calculation of δ is insensitive to S_x. (c) The calculation is most sensitive to ϕ, since typically $q \gtrsim 1.5$. (d) The spectral turnover (F_m, ν_m), must be known before δ_{min} can be calculated. If only an upper limit is known for ν_m, then a limit can still be calculated for δ but it is weak because $p > 1$. (e) The diameter ϕ is very difficult to determine, even with VLBI, and is usually the cause of most uncertainty in Eqn. [2].

If a source consists of several discrete homogeneous components then each has its own values of F_m, ν_m, ϕ, and δ_{min} (see the discussion below on 3C 345). If a component is inhomogeneous Eqn. [2] does not apply in a strict sense, but it should give a reasonable answer if $\phi = \phi_m$ is the effective diameter near the turnover frequency (38).

In summary, measurements of the radio synchrotron spectrum, angular diameter, and X-ray flux density give δ_{min}, a lower limit on the Doppler factor. This immediately gives an upper limit on Θ, $\sin \Theta'_{max} = 1/\delta_{min}$, and a lower limit on γ, $\gamma'_{min} = (\delta_{min} + 1/\delta_{min})/2$, which occurs at $\Theta = 0°$ (Fig. 1). If Θ takes its largest value (Θ'_{max}), then $\gamma = \delta_{min}$. Tighter limits can be set on both γ and Θ if v/c is also measured (Section 3 below).

c) Variability

Compact radio sources often show variability with a time scale $\tau = S\,|dS/dt|^{-1}$, where S is the flux density of the variable component. Velocity-of-light arguments suggest that the radius is less than $c\tau^*$, where $\tau^* = \tau\,\delta/(1+z)$ is the time scale in a co-moving frame. If the distance is known this gives ϕ_v, a limit to angular diameter which is often useful, although less so than a direct VLBI measurement. The apparent brightness temperature T_o, based on τ rather than τ^*, can be as high as 10^{15} K for the low-frequency variables (39), in apparent violation of the self-Compton limit $\simeq 10^{12}$ K. However, the limit applies

https://doi.org/10.1017/S0074180900077767 Published online by Cambridge University Press

only to the co-moving brightness $T_b^* \sim T_o\ \delta^{-3}$. Thus the lower limit to δ from low-frequency variability is about 10, in rough agreement with the largest values of δ_{min} deduced from the X-ray observations.

If there also are X-ray observations then ϕ_v can be used in Eqn. [2] to estimate δ_{min}. However, this must be done with caution as the variability diameter appropriate to the turnover frequency should be used. In particular, it is incorrect to use the X-ray variability time scale, since the rapidly variable X-rays presumably come from a region which is much smaller than the optically-thick radio components (38). Simon et al. (28) used radio variability data and X-ray flux data for 3C 147 to deduce $\delta_{min} \simeq 4$ (for h = 1).

The need to assume $T_b^* < 10^{12}$ K can be dropped if the diameter of a variable component can be measured with VLBI, or with interstellar scintillations (ISS). In this case one can set $\phi = \phi_v$ and directly solve for δ_{min}. Unwin et al. (13) showed that in 3C 345 the VLBI, X-ray, and variability data were all self-consistent with $\delta_{min} \simeq 10$. Dennison and Condon (40) have discussed the lack of ISS and showed that bulk relativistic motion is most likely responsible for the high brightness temperatures.

The superluminal motions, weak X-rays, and variability combine to provide powerful evidence for bulk relativistic motion with values of γ and δ up to 10. The strongest case comes from NRAO 140 and 3C 345, where VLBI measurements of angular size and spectrum, and X-ray flux measurements, give estimates of $\delta_{min} \simeq 10$, and $\gamma_{min} \simeq 5\ h^{-1}$ (see next Section.) The proper motion, variability measurements, and X-ray flux are all self-consistent if h $\simeq$ 1. Bulk relativistic motions cannot be dismissed by assuming non-cosmological distances, or gravitational lenses (41). The X-ray argument depends only on the (invariant) ratio of X-ray to radio brightness.

3. OBSERVATIONS OF 3C 345

We now describe in more detail the state of our understanding of one particular superluminal source. 3C 345 is probably the best-studied of the superluminals, and appears to be prototypical, in that it exhibits most of the common properties of the group. The following is a summary of the results reported in refs. 9-18.

Hybrid maps of 3C 345 made at intervals of about 6 months show a "core-jet" structure at every epoch, with a bright "core" at one end of the source, and a "lumpy" jet extending ∿ 5 mas in PA $\simeq -80°$. No "counter-jet" has been seen, although the limits are rather weak ($\lesssim 2\%$ of the core, or $\lesssim 10\%$ of the jet brightness). Superluminal motion at $v/c \simeq 8\ h^{-1}$ is seen in two "knots" in the jet at 5 and 10 GHz and in a third close-in component seen at 10 and 22 GHz (Table 1). The two outer components move with the same speed (to within the errors), and show no

https://doi.org/10.1017/S0074180900077767 Published online by Cambridge University Press

acceleration; they are very compact ($\phi \lesssim 0.5$ mas) and do not appear to expand. As they separate from the core, they decay with half-lives of about 2 years, and their spectra steepen to $\alpha \gtrsim 1$. This is rather steeper than the mean spectral index of the 2-arcsecond jet seen by MERLIN and the VLA (26,42). Presumably, particle reacceleration must occur in the large-scale jet.

The new jet component (C4 in Table 1) shows acceleration and does not move radially from the core. The data (ref. 16) are roughly consistent with constant acceleration at 3 c $\underline{h}^{-1}$ yr^{-1}. The track is consistent with straight-line motion which does not intersect the core. or with a curved trajectory starting at the core. In the latter case projection can greatly amplify the intrinsic curvature, which could be as small as 2° (ref. 16). The tracks of components C2 and C3 lie at different position angles, and the outer one (C2) has the same PA as reported for the "double" in 1971-74. This has given rise to the suggestion that the motion is rectilinear (i.e. ballistic), at least beyond a radius of 1 mas (ref. 12).

Observations at 2.3 GHz of 3C 345 and 3C 273 (43) show that the cores of both sources are strongly self-absorbed at this frequency and below. Combining fluxes from maps made in the frequency range 2.3 - 22 GHz enables the spectral turnovers (F_m, ν_m) to be made for the core and moving components. The X-rays from 3C 345 are very weak for a source with such a high radio brightness temperature. When the X-rays are combined with VLBI determinations of spectrum and diameter, Eqn. [2] yields $\delta_{min} >> 1$. Estimates from ref. 13 for v/c, δ_{min}, Θ_{max}, and γ_{min} are shown in Table 2. The core (D) is assumed to be stationary (ref. 9). An adequate spectrum could not be determined for the outer jet component (C2), so it has no limit for δ.

Component D in Table 2 has values of Θ_{max} and γ_{min} which are fixed geometrically by δ_{min} (see Fig. 1). For C2 they are fixed by v/c and thus involve $\underline{h}$. For C3 the limits are stronger because both v/c and δ_{min} are known. It seems likely that δ is near δ_{min} because this gives the largest allowed range of Θ and thus the most solid angle in which the jet direction must lie. If we take $\delta = \delta_{min}$ then the largest range of solid angle is obtained for $\delta = v/c$. Thus $\underline{h} \simeq 1$ is consistent both with the

TABLE 2

Geometric Constraints for 3C 345

	D	C_3	C_2
v/c	-	7 h^{-1}	9.5 h^{-1}
δ_{min}	18	8	-
Θ_{max} (deg)	3	7 h	12 h
γ_{min}	9	7 h^{-1}	9.5 h^{-1}

https://doi.org/10.1017/S0074180900077767 Published online by Cambridge University Press

solid angle argument, and with the observed values of proper motion, redshift, radio spectrum, diameter and X-ray flux density.

The X-ray limit applies to the core as well as to the moving components, and $\delta_{min} \simeq 18$ for component D. Thus the radiating material in the core is moving relativistically towards us, even though the core is assumed to be stationary. This is in accord with the beam model in which the core is a stationary region where the diverging relativistic beam has optical depth unity (33). We note again that this conclusion depends on brightness ratios and is independent of distance or lensing effects.

VLBI Research at the Owens Valley Radio Observatory is supported by NSF grant AST 82-10259.

REFERENCES

1. Cohen, M.H., and Unwin, S.C.: 1982, "Extragalactic Radio Sources", IAU Symp. No. 97, pp. 345-354.
2. Walker, R.C., Benson, J.M., Seielstad, G.A., and Unwin, S.C.: 1984, IAU Symp. No. 110, this volume.
3. Benson, J.M.: 1984, IAU Symp. 110, this volume.
4. Walker, R.C., Seielstad, G.A., Simon, R.S., Unwin, S.C., Cohen, M.H., Pearson, T.J., and Linfield, R.P.: 1982, Astrophys. J. 257, pp. 56-62.
5. Mutel, R.L.: 1984, IAU Symp. 110, this volume.
6. Aller, H.D.: 1984, IAU Symp. 110, this volume.
7. Mutel, R.L., and Phillips, R.B.: 1982, "Extragalactic Radio Sources", IAU Symp. No. 97, pp. 385-386.
8. Unwin, S.C., and Biretta, J.A.: 1984, IAU Symp. 110, this volume.
9. Bartel, N.: 1984, IAU Symp. 110, this volume.
10. Cohen, M.H., Unwin, S.C., Simon, R.S., Seielstad, G.A., Pearson, T.J., Linfield, R.P., and Walker, R.C.: 1981, Astrophys. J. 247, pp. 774-779.
11. Readhead, A.C.S., Hough, D.H., Ewing, M.S., Walker, R.C., and Romney, J.D.: 1983, Astrophys. J. 265, pp. 107-131.
12. Cohen, M.H., Unwin, S.C., Pearson, T.J., Seielstad, G.A., Simon, R.S., Linfield, R.P., and Walker, R.C.: 1983, Astrophys. J. Letters 269, pp. L1-L4.
13. Unwin, S.C., Cohen, M.H., Pearson, T.J., Seielstad, G.A., Simon, R.S., Linfield, R.P., and Walker, R.C.: 1983, Astrophys. J. 271,
14. Schraml, J., Pauliny-Toth, I.I.K., Witzel, A., Kellermann, K.I., Johnston, K.J., and Spencer, J.H.: 1981, Astrophys. J. Letters 251, pp. L57-L60.
15. Spencer, J.H., Johnston, K.J., Pauliny-Toth, I.I.K., and Witzel, A.: 1981, Astrophys. J. Letters 251, pp. L61-L63.
16. Moore, R.L., Biretta, J.A., Readhead, A.C.S., and Bååth, L.B.: 1984, IAU Symp. No. 110, this volume.
17. Biretta, J.A., Cohen, M.H., Unwin, S.C., and Pauliny-Toth, I.I.K.:

https://doi.org/10.1017/S0074180900077767 Published online by Cambridge University Press

1983, Nature (in press).
18. Moore, R.L., Readhead, A.C.S., and Bååth, L.B.: 1983, Nature (in press).
19. Shaffer, D.B.: 1984, IAU Symp. 110, this volume.
20. Porcas, R.W.: 1984, IAU Symp. 110, this volume.
21. Porcas, R.W.: 1981, Nature 294, pp. 47-49.
22. Porcas, R.W.: 1983, Proceedings Bangalore Winter School on Energetic Extragalactic Sources (in press).
23. Marscher, A.P., and Broderick, J.J.: 1981 Astrophys. J., 249, pp. 406-414.
24. Marscher, A.P., and Broderick, J.J.: 1982 Astrophys. J. Letters, 255, pp. L11-L15.
25. Pearson, T.J., et al.: 1981, Nature 290, pp. 365-368.
26. Browne, I.W.A., Clark, R.R., Moore, P.K., Muxlow, T.W.B., Wilkinson, P.N., Cohen, M.H., and Porcas, R.W.: 1982, Nature 299, pp. 788-793.
27. Schilizzi, R.T., and de Bruyn, A.G.: 1983, Nature 303, pp. 26-31.
28. Simon, R.S., Readhead, A.C.S., Moffet, A.T., Wilkinson, P.N., Allen, B., and Burke, B.F.: 1983, Nature 302, pp. 487-490.
29. Whyborn, N.: 1984, IAU Symp. No. 110, this volume.
30. Pauliny-Toth, I.I.K.: 1984, IAU Symp. 110, this volume.
31. Brown, R.L., Johnston, K.J., Briggs, F.H., Wolfe, A.M., Neff, S.G., and Walker, R.C.: 1981, Astrophys. Letters 21, pp. 105-110.
32. Scheuer, P.A.G.: 1984, IAU Symp. 110, this volume.
33. Blandford, R.D., and Königl, A.: 1979, Astrophys. J. 232, pp. 34-48.
34. Scheuer, P.A.G., and Readhead, A.C.S.: 1979, Nature 277, pp. 182-185.
35. Marscher, A.P., and Broderick, J.J.: 1982, "Extragalactic Radio Sources", IAU Symp. No. 97, pp. 359-360.
36. Gould, R.J.: 1979, Astron. Astrophys. 76, pp. 306-311.
37. Burbidge, G.R., Jones, T.W., and O'Dell, S.L.: 1974, Astrophys. J. 193, pp. 43-54.
38. Cohen, M.H.: 1983, Proceedings Bangalore Winter School on Energetic Extragalactic Sources (in press).
39. Fanti, R., Padrielli, L., and Salvati, M.: 1982, "Extragalactic Radio Sources", IAU Symp. No. 97, pp. 317-324.
40. Dennison, B., and Condon, J.J.: 1981, Astrophys. J. 246, pp. 91-99.
41. Subramanian, K.: 1984, IAU Symp. 110, this volume.
42. Perley, R.A., and Johnston, K.J.: 1979, Astron. J. 84, pp. 1247-1252.
43. Cohen, M.H., et al.: 1983, Astrophys. J. 272 (in press).
44. Simon, R.S.: 1984, IAU Symp. No. 110, this volume.

https://doi.org/10.1017/S0074180900077767 Published online by Cambridge University Press