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Relativistic Beaming in the Central Components of Double Radio Quasars

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Abstract. Using a large sample of 78 well-observed double quasars, we have investigated several consequences of the relativistic beaming model. In this model the ratio of the strengths of the central component and outer lobes of a double source depends on whether the jet axis lies close to or away from the line of sight. If this is the actual situation, the fraction of emission from the core, f_c, may be used as a statistical measure of the orientation of the source and should be correlated with other source parameters which also depend on the inclination of the jet axis to the line of sight.

We find f_c to be anticorrelated with the overall projected linear size of the extended emission but to exhibit a positive correlation with both the observed degree of misalignment from a collinear double structure, and the ratio of separations of the outer hotspots from the central component. As might be expected from these relationships, we also find sources of smaller projected linear sizes to appear more misaligned and the degree of misalignment to be correlated with the ratio of separations of the outer hotspots. All these correlations are consistent with the predictions of the relativistic beaming model.

Key words: quasars—relativistic beaming—active galactic nuclei—extragalactic radio sources

1. Introduction

In the relativistic twin-jet models of Scheuer and Readhead (1979) and of Blandford and Königl (1979), both compact and extended double radio sources are believed to be intrinsically similar, only appearing to be different due to the different inclinations of their jet axes to the line of sight. When viewed from a direction close to the jet axis the radio emission from the core is strongly enhanced due to relativistic beaming and tends to mask the emission from the extended lobes which radiate quasi-isotropically. In contrast, the jet axis of a normal double source lies well away from the line of sight and the core appears weak in comparison with the outer lobes.

It has recently been shown (Browne and Orr 1982; Orr and Browne 1982) that some observed statistical properties of quasars, such as the proportion of those with flat radio spectrum in flux-limited samples selected at different frequencies and the flux density counts of flat spectrum quasars, are quite consistent with the predictions of beaming models. In the present paper, we have attempted to verify some other statistical predictions of these models. If beaming is indeed strong in the cores of radio quasars, the fraction of the total emission coming from the core should be a statistical measure of the orientation of the source axis. This parameter should therefore be related to other observable source properties which also depend on the inclination of the jet axis to the line of sight. Three such parameters that are fairly readily measurable are (i) the projected maximum linear separation between the outer lobes, (ii) the apparent misalignment of the hotspots from collinearity with the core and (iii) the ratio of the angular displacements of the hotspots from the radio core. We have investigated these relationships using a large sample of well-observed double quasars and find the results to be consistent with the relativistic beaming hypothesis.

2. The sample of double quasars

Although compact central components (hereafter referred to as CCs) are found in radio galaxies and quasars, we consider here only quasars as in these the occurrence of CCs is known to be much more common (*e.g.* Riley and Jenkins 1977) and also because several samples of quasars have been mapped with good angular resolution in the past few years. Ideally, a complete sample observed to well-defined resolution and sensitivity limits should be used. However, the number of quasars in any such available sample is too small to make statistically significant tests and as a first step we have collected together structural information on all classical double QSOs with known redshift that have been reported in the literature (mainly from Jenkins, Pooley and Riley 1977 and references therein; Miley and Hartsuijker 1978; Potash and Wardle 1979; Owen, Porcas and Neff 1978; Wills 1979; Fanti *et al.* 1977, 1979). Nearly all these quasars have been mapped by aperture synthesis techniques at frequencies between 2·7 and 8 GHz, but with a considerable range in instrumental sensitivity and angular resolution. Therefore in order to keep the final sample fairly homogeneous and free from serious selection effects, we have imposed the following additional restrictions.

(a) We exclude quasars for which the angular separation of the outer lobes (LAS) is $<$ 8 arcsec and those that have been mapped with less than 3 resolution elements along their main axes, where one resolution element is equal to the half-power beamwidth. The requirement of at least 3 resolution elements is necessary if a reasonably reliable estimate of the flux-density in the CC is to be made. Although few sources with LAS $<$ 8 arcsec would satisfy the resolution criterion, several larger sources (particularly at low declinations) had also to be excluded on this criterion. This is unlikely to have introduced any serious bias into the data.

(b) We require that the total flux density of a quasar at 178 MHz be $S_{178} \geqslant 2$ Jy, the limit of the 4C catalogue. This condition excludes a few weak quasars that have been mapped with poor sensitivity at high frequencies. A few quasars with $\delta < -7°$, for which flux densities at 178 MHz have not been directly measured have, however, been included because they appear in the Parkes radio catalogue and are all known to have flux densities of greater than ~ 8 Jy at 160 MHz (Slee 1977).

(c) We have disregarded the observations of Wills (1979) as these appear to have been intended only for estimating the overall angular sizes and not for determining reliable flux densities of the CCs. Although the observations were made using the same instrument and frequencies as those reported by Potash and Wardle (1979) for samples selected at comparable flux densities at 178 MHz, there is a marked difference in the reported detection of CCs in the two sets of observations. Wills detected CCs in only 4 of the 26 quasars found to be double, while Potash and Wardle report detections in 27 of the 35 such quasars.

(d) We do not include quasars with one-sided asymmetric radio structure, often referred to in the literature as D2 type (*cf.* Miley 1971; Kapahi 1981). We shall comment on such sources in Section 3.

Our final sample consists of 78 quasars, 66 of which have detected CCs. As the positions of the outer radio components and of the optical quasars are generally known with an accuracy of ~1 arcsec there is little difficulty in identifying the CCs. The sources in our sample are listed in Table 1 which is arranged as follows.

Columns 1 and 2 give the coordinate designation and an alternative catalogue number of the quasar. The redshift is given in column 3 and the estimated total radio luminosity at 5 GHz in column 4. The LAS and the corresponding linear size are entered in columns 5 and 6 respectively. The next three columns give an estimate of the fractional flux density in the core (f_c), the misalignment angle (Δ), and the ratio of separations of the hotspots from the core (Q), respectively. The estimation of these parameters is explained in the subsequent sections of the paper. The last column gives coded references (explained at the end of the Table) to the best available maps of the quasars from which the observed parameters have been estimated.

3. The f_c–l relation

In the relativistic beaming model, sources inclined at small angles to the line of sight should appear smaller due to projection and have more prominent cores. The fraction of radio emission from the core should therefore be anticorrelated with observed linear size. For each quasar in our sample we have calculated,

(a) the projected linear size, l, of the quasar from its measured LAS, in an Einstein–de Sitter world model ($q_0 = 0{\cdot}5$) with $H_0 = 50$ km s^{-1} Mpc^{-1}, and

(b) the ratio, f_c, of the observed flux density of the CC (or an upper limit to it) to the total flux density of the source at a fixed frequency of 8 GHz in the rest frame of the quasar. The rest frame was used because the central and outer components generally have quite different spectral indices. The transformation was made using the observed spectral indices of the central (α_c) and extended (α_e) components, when available, otherwise assuming $\alpha_c = 0{\cdot}2$ and $\alpha_e = 0{\cdot}9$ (α defined as $S \propto \nu^{-\alpha}$), the median values for quasars in the sample that have good spectral information. For quasars in which no CCs have been detected, we estimate that such components are unlikely to account for more than 10 per cent of the total flux density.

Table 1. The sample of double radio quasars.

Source (1)	Alternative name (2)	Red-shift (3)	log P 5GHz (4)	LAS arcsec (5)	Linear size kpc (6)	f_c (7)	Δ deg (8)	Q (9)	Reference (10)
0003 + 15	4C 15·01	0·450	25·48	31·5	214	0·37			MH
0007 + 33	4C 33·01	0·750	25·48	77	625	0·05	3	1·16	PW
0017 + 25	4C 25·01	0·280	25·13	46·2	244	0·78	46	1·07	PW
0110 + 29	4C 29·02	0·363	25·11	76·6	469	0·24	12	1·11	PW
0118 + 03	4C 03·02	0·765	25·90	43	351	0·07	24	1·10	MH
0130 + 24	4C 24·02	0·453	25·36	53·4	364	0·32	9	1·23	PW
0133 + 20	3C 47	0·425	25·89	69	457	0·08	6	1·23	PH
0214 + 10	4C 10·06	0·408	25·49	119	773	0·21	10	1·18	MH
0229 + 34	3C 68·1	1·238	26·76	46	396	<	5	1·18	JPR, L81
0232 − 04	4C -04·06	1·436	26·74	13	111	0·40	13	3·26	S82
0313 + 34	4C 34·13	1·156	26·01	26·5	228	0·03	2	1·39	PW
0349 − 14	PKS	0·614	25·96	114	875	0·03	3	1·06	MH
0350 − 07	PKS	0·962	26·34	41·5	352	<0·03	0	1·52	MH
0610 + 26	3C 154	0·580	26·44	50	376	0·26	9	1·96	RP1
0704 + 38	4C 38·20	0·579	25·56	21·8	164	0·20			PW
0710 + 11	3C 175	0·768	26·21	48	392	0·06	6	1·32	JPR
0723 + 67	4C 67·14	0·846	26·49	13·6	113	0·42			OPN
0742 + 31	4C 31·30	0·462	25·92	115	792	0·78	3	1·13	F77
0814 + 22	4C 22·20	0·980	26·29	25	213	0·08			PW
0833 + 65	3C 204	1·112	26·33	31·1	267	0·12	0	1·07	PH, OPN
0835 + 58	3C 205	1·534	26·90	15·9	136	0·03	0	1·17	PH, OPN, L81
0837 − 12	PKS	0·200	25·09	169	714	0·23	6	2·13	MH
0838 + 13	3C 207	0·684	26·38	8·4	67	0·40			PH
0839 + 61	4C 61·19	0·862	25·85	25·8	215	0·09	13	1·69	OPN
0846 + 10	4C 09·31	0·366	24·99	54	332	<0·23			MH
0850 + 14	3C 208	1·110	26·47	11	94	0·08	8	1·29	JPR, L81
0855 + 14	3C 212	1·048	26·68	9	77	0·30	1	1·13	JPR, L81
0903 + 16	3C 215	0·411	25·33	28·5	186	0·07			PH
0937 + 39	4C 39·27	0·618	25·53	51·8	398	0·12	3	1·28	PW
0952 + 35	4C 35·21	1·241	26·04	18·9	163	<			PW
1001 + 22	4C 22·26	0·974	25·93	66	561	0·11	5	1·24	PW
1004 + 13	4C 13·41	0·240	25·10	115	550	0·02	8	1·56	MH
1007 + 41	4C 41·21	0·613	25·93	31·2	239	0·29	7	1·76	OPN, S82
1011 + 28	4C 28·25	0·899	25·90	14·8	124	0·46			PW
1012 + 48	4C 48·28	0·385	24·96	109	688	<0·02	6	1·01	MH
1047 + 09	4C 09·37	0·786	25·61	70	574	0·10			MH, S82
1048 − 09	PKS	0·344	25·36	83	494	0·07	6	1·30	MH
1048 + 24	4C 24·23	1·270	26·03	15·6	134	0·10			PW
1058 + 11	4C 10·30	0·420	25·23	31	204	0·41			MH
1100 + 77	3C 249·1	0·311	25·40	23	129	0·18	9	2·07	PH
1111 + 40	3C 254	0·734	26·25	13·2	107	<	15	6·3	PH, SKN
1137 + 66	3C 263	0·652	26·26	45	352	0·11	0	1·81	PH, OPN
1150 + 49	4C 49·22	0·334	25·66	13	76	0·75			OPN
1206 + 43	3C 268·4	1·400	26·82	10·2	88	0·05	14	1·13	PH, SKN
1218 + 33	3C 270·1	1·519	27·11	9	77	0·20	37	1·24	RP2, PW

Table 1. Continued.

Source	Alternative name	Red-shift	log *P* 5GHz	LAS arcsec	Linear size kpc	f_c	Δ deg	*Q*	Reference
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1221 + 18	4C 18·34	1·401	26·07	23	198	0·10			MH
1223 + 25	4C 25·40	0·265	24·49	67	342	0·06	1	1·01	MH
1232 − 24	PKS	0·355	25·47	86	520	0·02	4	1·04	MH
1241 + 16	3C 275·1	0·557	26·07	14	104	0·29	24	1·53	JPR, RP2
1244 + 32	4C 32·41	0·949	25·85	23·1	196	0·41	14	1·31	PW
1248 + 30	4C 30·25	1·061	25·76	28·9	248	<	2	1·18	PW
1253 − 05	3C 279	0·538	27·02	17	125	0·75			J81
1258 + 40	3C 280·1	1·659	26·67	23·1	195	0·05	20	1·06	JPR, SSS
1317 + 52	4C 52·27	1·060	26·49	28·2	242	0·59	30	1·87	OPN
1327 − 21	PKS	0·528	25·96	36	262	0·31			MH
1332 + 55	4C 55·27	1·210	25·86	76	655	0·04	4	1·13	MH
1354 + 19	4C 19·44	0·720	26·41	43	345	0·82	7	1·76	S82
1356 + 58	4C 58·29	0·321	24·67	43·8	251	<	3	1·17	OPN
1400 + 16	4C 16·39	0·244	24·97	25	121	0·46	52	1·23	B77, HO
1423 + 24	4C 24·31	0·649	25·92	20·2	158	0·20	32	1·33	PW
1451 + 09	4C 09·52	0·627	25·53	23	178	0·26			MH
1512 + 37	4C 37·43	0·371	25·28	50·9	315	0·11	1	1·28	PW
1545 + 21	3C 323·1	0·264	25·23	68·2	347	0·09	0	1·39	PH
1548 + 11	4C 11·50	0·436	25·51	50	335	0·57			A74
1606 + 28	4C 28·40	1·989	26·53	30·6	251	<			PW
1618 + 17	3C 334	0·555	25·93	48	356	0·25	20	1·35	JPR
1622 + 23	3C 336	0·927	26·45	21·7	183	0·03	0	2·75	PH
1628 + 36	4C 36·28	1·254	26·10	16·1	139	0·25			PW
1634 + 26	4C 26·49	0·561	25·74	39·3	292	<	2	1·26	PW
1704 + 60	3C 351	0·371	25·66	85·2	528	<	4	1·31	OPN, L81
1721 + 34	4C 34·47	0·206	25·02	220	949	0·59	1	1·03	CBV, J82
1732 + 65	4C 65·21	0·856	25·90	17·4	145	0·21			OPN
1857 + 56	4C 56·28	1·595	26·59	27·5	234	0·65	5	1·73	OPN
2120 + 16	3C 432	1·805	26·37	13	109	<			JPR
2135 − 14	PKS	0·200	25·23	150	634	0·10	4	1·25	MH
2308 + 09	4C 09·72	0·432	25·36	101	674	0·21	16	1·67	MH
2325 + 29	4C 29·68	1·015	26·31	50·4	430	0·07	1	1·19	PW
2349 + 32	4C 32·69	0·670	25·67	66	520	0·09	15	1·35	PW, PW80

References to radio structure:

A74 Argue *et al.* (1974)
B77 Baldwin *et al.* (1977)
CBV Conway, Burn and Vallee (1977)
F77 Fanti *et al.* (1977)
HO Hintzen and Owen (1981)
J81 Joshi (1981)
J82 Jägers *et al.* (1982)
JPR Jenkins, Pooley and Riley (1977)
L81 Laing (1981)
MH Miley and Hartsuijker (1978)
OPN Owen, Porcas and Neff (1978)
PH Pooley and Henbest (1974)
PW Potash and Wardle (1979)
PW80 Potash and Wardle (1980)
RP1 Riley and Pooley (1976)
RP2 Riley and Pooley (1978)
S82 Salter *et al.* (1982)
SKN Schilizzi, Kapahi and Neff (1982)
SSS Swarup, Sinha and Saikia (1982)

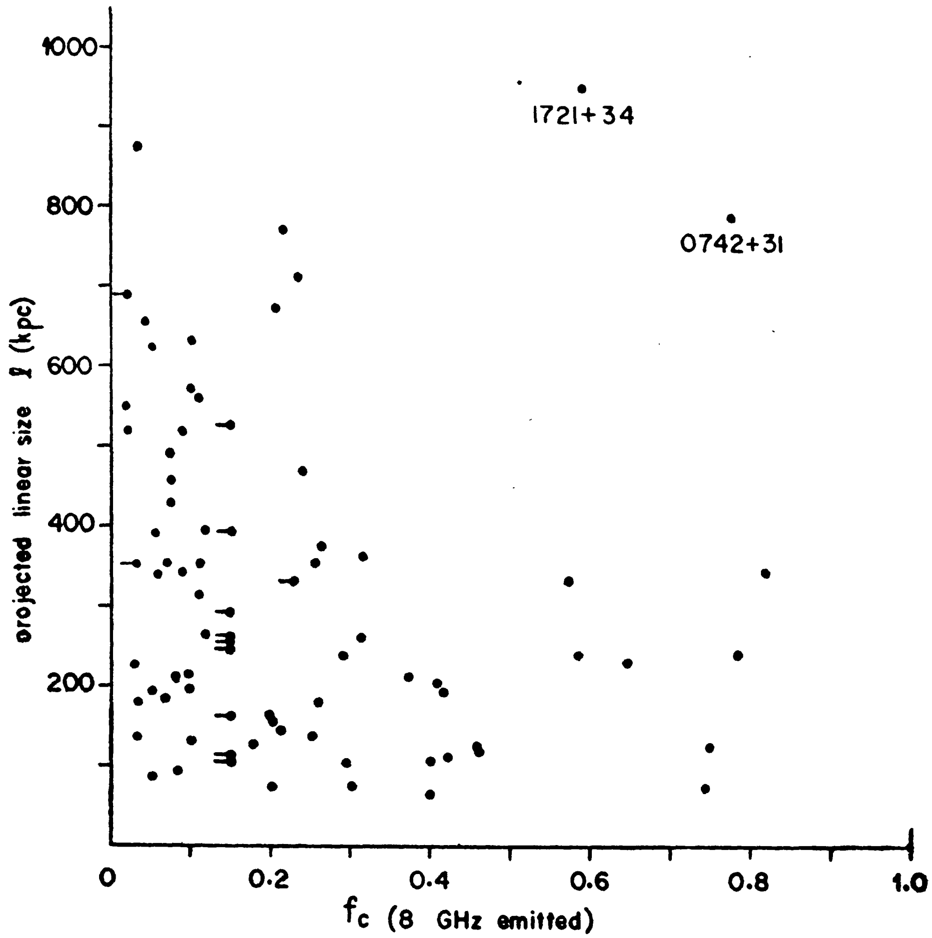

Figure 1. Plot of the projected linear size *vs.* the core fraction. Horizontal bars indicate upper limits to f_c.

A plot of the values of f_c and l for the 78 quasars is shown in Fig. 1. Except for the two large quasars with strong central components (that are separately identified in the figure and discussed in Section 7) there appears to be a tendency for quasars with larger values of f_c to have smaller projected linear sizes. The apparent deficiency of points in the region $f_c > 0{\cdot}25$ and $l > 400$ kpc is unlikely to arise from observational difficulties. The components of a source with $l = 500$ kpc in this region of the diagram would have a separation of 55 to 90 arcsec for $z > 0{\cdot}3$ and should be readily detectable by existing aperture synthesis telescopes, particularly as the individual components of QSOs are generally found to be much smaller in extent than their separations (Kapahi 1978).

The significance of the apparent anticorrelation between f_c and l may be tested by applying the Kolmogorov-Smirnov two-sample test. If the data are divided into two roughly equal groups at a linear size of $l = 250$ kpc the possibility that the two samples are drawn from the same population can be rejected at the 95 per cent confidence level if the two apparently discrepant quasars are excluded and at the 90 per cent level if they are included. Although the level of significance may not be sufficient to establish an anticorrelation beyond doubt, the data must be considered to be consistent with such an anticorrelation. It is also worth noting that possible selection effects present in the data could only have led to a weakening of any true anticorrelation. The limited angular resolution and dynamic range of the observations can discriminate against sources of small size that have strong CCs because when the size of the source is not much larger than the angular resolution, it is easier to recognize the double structure in a source with low f_c than in one with large f_c. Furthermore, limiting the sample to sources larger than a certain angular size implies that at any redshift only quasars above a certain minimum projected size can come into the sample.

Since quasars in the present sample have been selected largely from radio surveys at low frequencies (< 1 GHz) there are relatively few with strong CCs. The sample may be enlarged by including quasars selected at high frequencies and by mapping the quasars that are presently unresolved in low-frequency surveys, with high angular resolution. Recent investigations on both these lines appear to provide some additional support for an anticorrelation between f_c and l. Maps of high dynamic range, made with the VLA at λ 6 cm , of many, flat-spectrum quasars selected from 5 GHz surveys indicate (Perley, Fomalont and Johnston 1980, 1982) that several of them have a double or asymmetric extended structure accounting typically for $\lesssim$ 10 per cent of the total flux density and having projected angular sizes $\lesssim$ 10 arcsec. These sources would thus fall in the bottom right-hand portion of Fig. 1. Gopal-Krishna, Preuss and Schilizzi (1980) have carried out VLBI observations of unresolved sources (angular size $\lesssim$ 4 arcsec and mostly associated with empty fields) taken from an Ooty occultation survey at 327 MHz. They find at least half the sources to have compact cores accounting for $\gtrsim$ 25 per cent of the total flux density at 5 GHz. As these sources have normal spectra ($\alpha > 0{\cdot}5$) between 327 MHz and 5 GHz, they are quite likely to have extended structure of size $\lesssim$ 4 arcsec.

In view of the possible selection effects in the data at small values of l we have not attempted to extract an average or median value as a function of f_c in order to check with the prediction of the beaming model. We restrict ourselves to a prediction of the expected upper envelope to the f_c–l relation by considering a standard quasar of intrinsic linear size $L = 1$ Mpc, typical of the largest known quasars, and estimating the values of f_c and l as the quasar is viewed from different angles.

We assume that the core emission comes from a quasi-continuous stream of material travelling at speed $\beta = v/c$ (Lorentz factor γ) in oppositely directed jets and the outer lobes to be at rest and radiating isotropically. If θ is the angle between the jet axis and the line of sight, the observed values of f_c and l are given by,

$$f_c(\theta) = \left[1 + \frac{2}{B(\theta)}\left\{\frac{1}{F_c} - 1\right\}\right]^{-1}$$

and

$$l(\theta) = L \sin\theta,$$

where

$$B(\theta) = (1 - \beta\cos\theta)^{-(2+\alpha)} + (1 + \beta\cos\theta)^{-(2+\alpha)},$$

and $F_c = f_c$ (90°), the fractional flux density in the core that would have been observed if the jet axis were transverse to the line of sight.

The relation between f_c and l thus depends on the values of F_c and the Lorentz factor γ. From the observed distribution of the parameter R [defined as the ratio of the flux density of the CC to the flux density of the outer lobes, $f_c = R/(1 + R)$], for quasars in the 3CR catalogue, Orr and Browne (1982) suggest a typical value of $R(90°) = 0{\cdot}024$ at an emitted frequency of 5 GHz, which corresponds in our case to F_c (8 GHz) $= 0{\cdot}033$. Further, from the observed spread in the R-distribution of extended 3CR quasars, Scheuer and Readhead (1979) concluded that typically $\gamma \lesssim 2$. Orr and Browne (1982) have however argued that this result is likely to be incorrect because the core-dominated sources were excluded from the distribution. Inclusion of such sources implies typical values of $\gamma \sim 5$. Using $F_c = 0{\cdot}033$ the predicted upper envelopes to the f_c–l points for values of $\gamma = 2$ and 5 are shown in Fig. 2. While a value of $\gamma = 2$ appears to provide a satisfactory upper envelope to most of the data points, an extension of the γ distribution to larger values is required to explain the small number of sources with very strong cores ($f_c > 0{\cdot}5$).

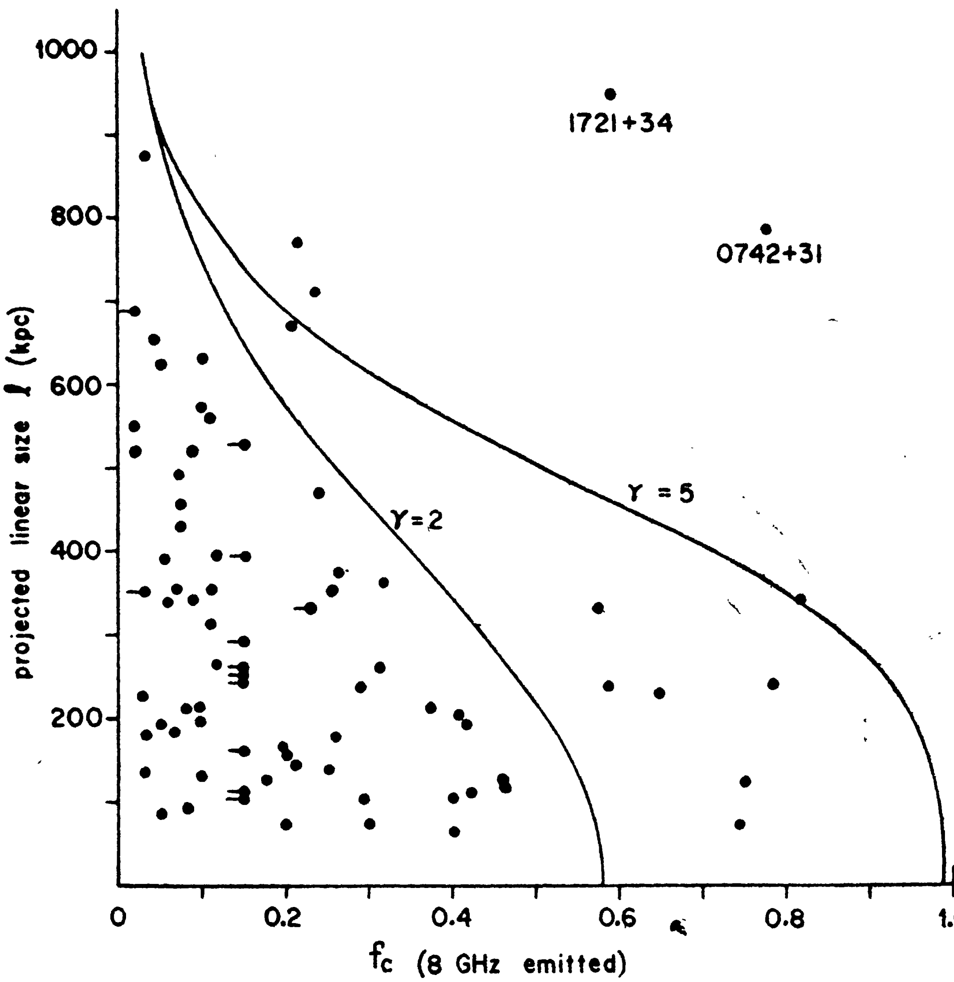

Figure 2. Upper envelopes to the $f_c - l$ relation for values of $\gamma = 2$ and 5, estimated as explained in the text.

It is of interest to note here that the observed properties of the asymmetric D2 type quasars also seem to be consistent with the anticorrelation between f_c and l of Fig. 1. VLBI observations of a few such quasars suggest that their jet axes may indeed be oriented close to our line of sight (*e.g.* Readhead *et al.* 1978). Recently it has been pointed out by Kapahi (1981) that D2 quasars have significantly more prominent cores than the normal double quasars. Apart from 3C 186 (in which the outer lobe appears to be separated by ~ 900 kpc from the core although the reality of the physical association of the lobe with the quasar is uncertain) nearly all the other D2 quasars with known redshift and LAS > 5 arcsec have $l < 100$ kpc and $f_c > 0{\cdot}5$. They therefore fit in well with the f_c–l relation (even if their observed linear sizes are doubled to take account of the hypothetical missing weaker lobes) but suggest values of γ considerably larger than 2.

Although the observed ıelation between f_c and l finds a natural explanation in the relativistic beaming hypothesis, it is important to examine other possible explanations. If the CCs were on average stronger at earlier epochs or in sources of higher total luminosity, an anticorrelation between f_c and l could result from the possible decrease in linear sizes of quasars with increasing redshift or luminosity inferred from the angular-size–redshift tests (*e.g.* Wardle and Miley 1974; Masson 1980). Plots of f_c against redshift and against total radio luminosity are shown in Figs 3

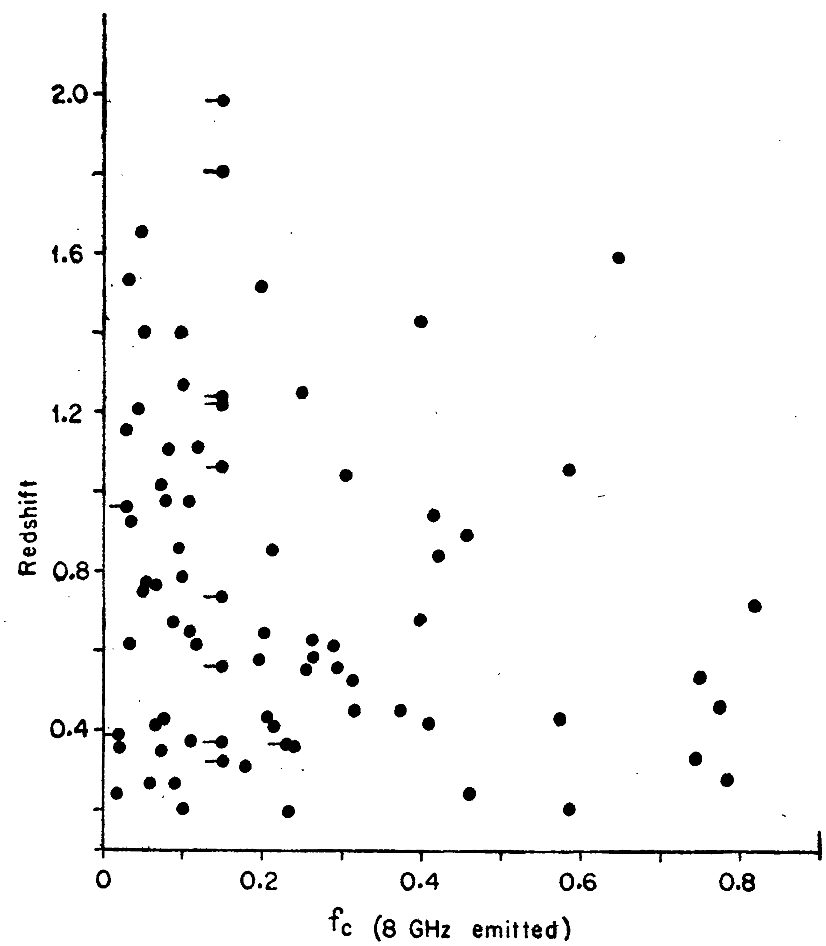

Figure 3. Plot of redshift *vs.* core fraction.

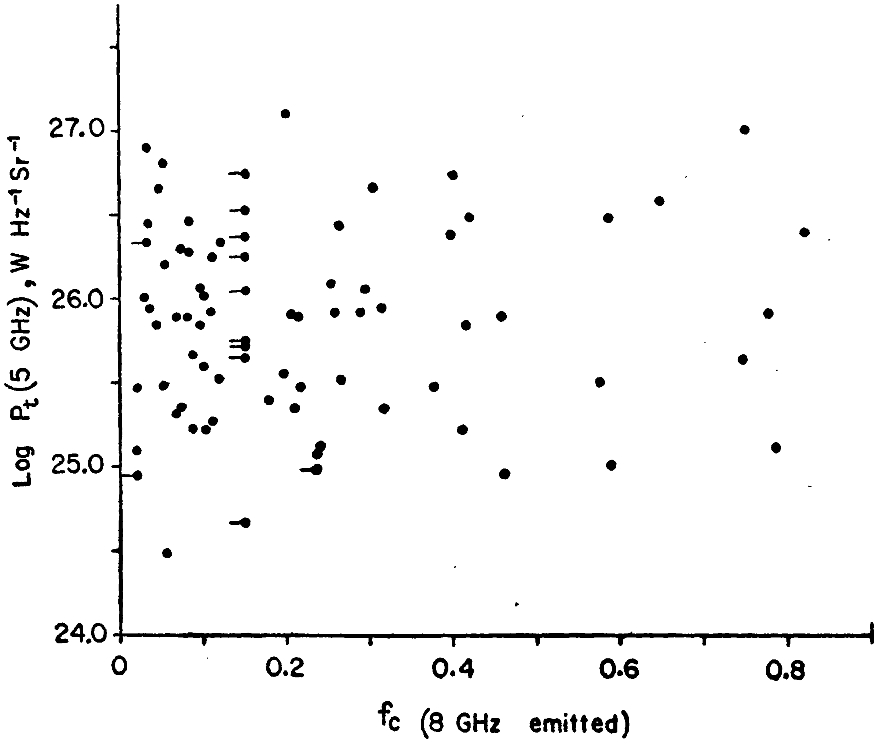

Figure 4. Plot of total radio luminosity at 5 GHz *vs.* the core fraction.

and 4 respectively. Visually, there is a possible suggestion in Fig. 3 of an inverse correlation, but opposite in sense to that required to explain the f_c–l relationship. Statistical tests do not however show any significant correlations in Figs 3 and 4.

Another possibility is that quasars with strong CCs are seen at younger ages and are therefore smaller in overall size. This does not however explain the presence of a large number of sources, many of which are possibly young that have small linear sizes and weak CCs, unless most young quasars have CCs of low intrinsic luminosity. There does not also appear to be any significant difference in the spectral indices of the outer lobes of quasars with and without strong CCs that could be attributed to age differences.

4. The $f_c - \Delta$ relation

For a source in which the two outer lobes are not perfectly collinear with the CC, the intrinsic misalignment may appear amplified or diminished depending on the orientation of the source with respect to the observer. However, for sources inclined at small angles to the line of sight, the misalignment angle appears amplified for most directions of view. On the beaming interpretation, one may therefore expect a statistical relationship between f_c and the observed misalignment angle, Δ (defined to be the complement of the apparent angle formed at the CC or the optical quasar by the two outer hotspots), such that sources with larger values of f_c should, on average, appear more misaligned.

Ideally, the misalignment angles Δ should be estimated from the positions of the hotspots as these are believed to be the ends of the beams supplying energy to the radio lobes. But since many of the quasars in the present sample have not been mapped with sufficient angular resolution to locate the hotspots, we had often to use the positions of the peaks of emission or of centroids of the outer lobes. In order to minimise such errors we have used a subsample of quasars comprising of only those sources that have been observed with at least six resolution elements along their major axes. Of the 58 quasars that satisfy this criterion, two (namely 1047 + 09 and and 1111 + 40) were excluded as Δ is very poorly determined for them. It is clear from the $f_c - \Delta$ diagram for the remaining 56 quasars, shown in Fig. 5, that there is indeed a tendency for sources with stronger CCs to appear more misaligned than those with weaker CCs. In Fig. 6 we show the distributions of Δ for sources with $f_c \leqslant 15$ per cent and $f_c > 15$ per cent. A Kolmogorov-Smirnov test shows the two distributions to be different at a significance level of 99 per cent. Fig. 5 also suggests, that intrinsicially the misalignment is likely to be $< 10°$ in most cases.

Hintzen and Owen (1981) have suggested that the apparent distortion from a collinear structure seen in 1400 + 162, which is known to be in a group of galaxies

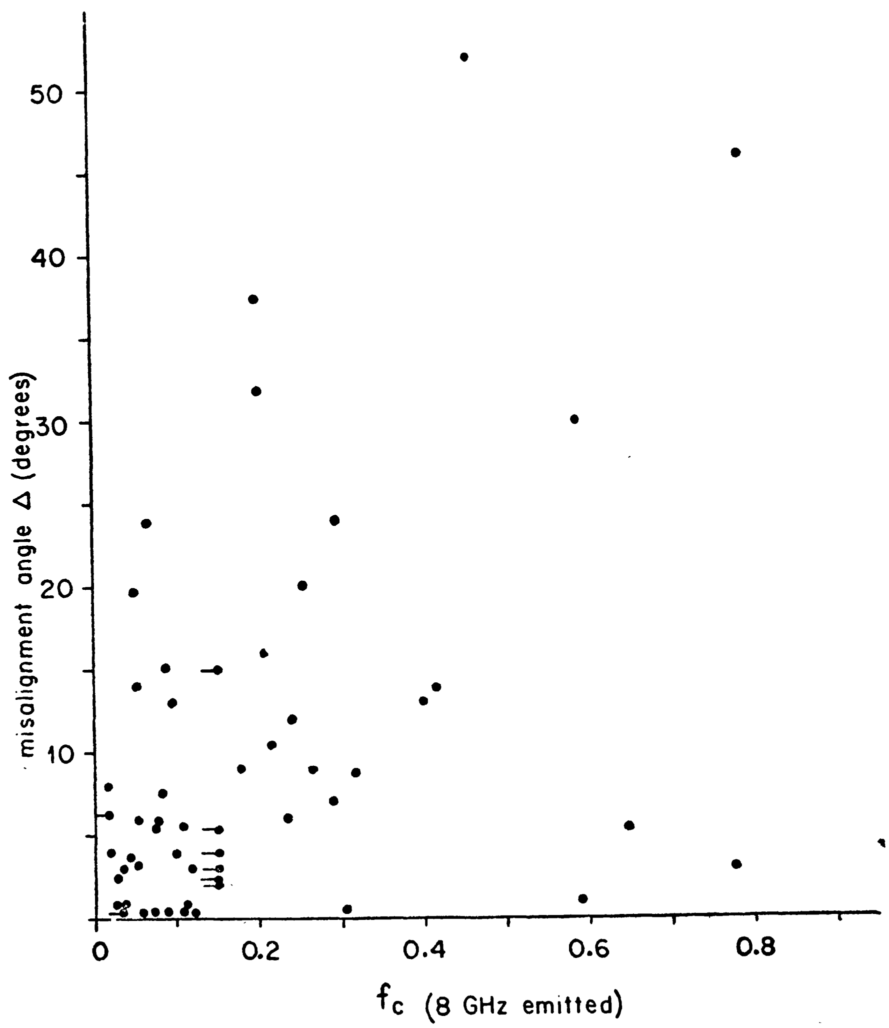

Figure 5. Plot of misalignment angle *vs*. the core fraction.

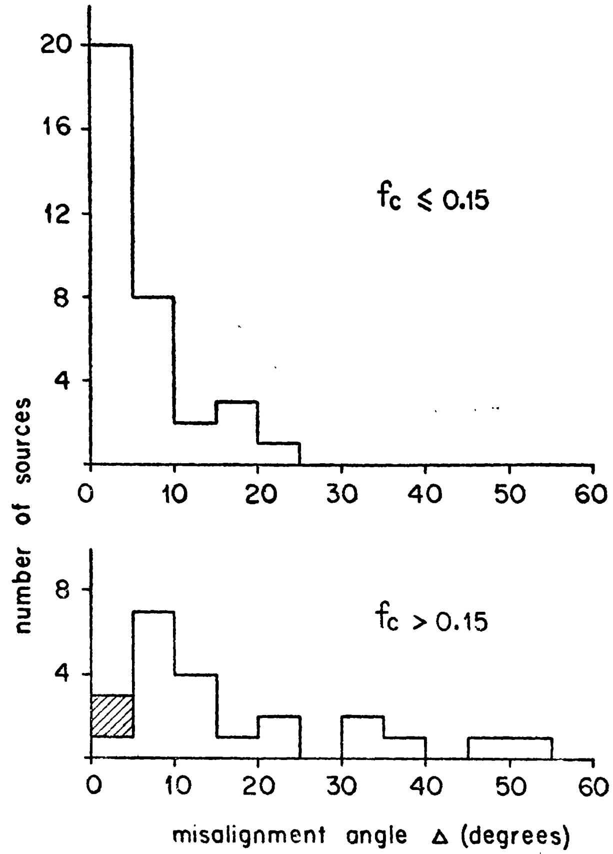

Figure 6. Distributions of the misalignment angle for sources with $f_c \leqslant 0{\cdot}15$ and $f_c > 0{\cdot}15$. In this and subsequent histograms the shaded portion refers to the two discrepant quasars identified in Fig. 1.

(Baldwin *et al.* 1977), is due to the interaction of the radiating material in the lobes with the intracluster medium. Further, Riley and Pooley (1978) have speculated that the 'bent' structures seen in 3C 270·1 and 3C 275·1 are possibly due to the motion of the parent quasar through the intergalactic medium. Although such effects can certainly give rise to structures lacking collinearity, it must be stressed that any small intrinsic misalignment will appear amplified when the source is inclined at a small angle to the line of sight. The fact that the three above-mentioned quasars all have prominent cores suggests that the intrinsic misalignment in these sources may be lower than that observed. Deep optical and X-ray studies of the fields of at least the relatively nearby quasars would be useful in studying the environments of these sources and may help in deciding between the two possibilities.

Since sources with prominent CCs have smaller linear sizes and also appear more misaligned, it is to be expected that l and Δ may also be correlated in the sense that the smallest sources appear most misaligned. We have plotted in Fig. 7 the l–Δ relationship for the subsample of 56 quasars and find good evidence for such a correlation. A somewhat similar correlation was noted earlier by Macklin (1981) who examined the symmetry parameters of a sample of 76 well-observed 3CR double sources, including both radio galaxies and quasars.

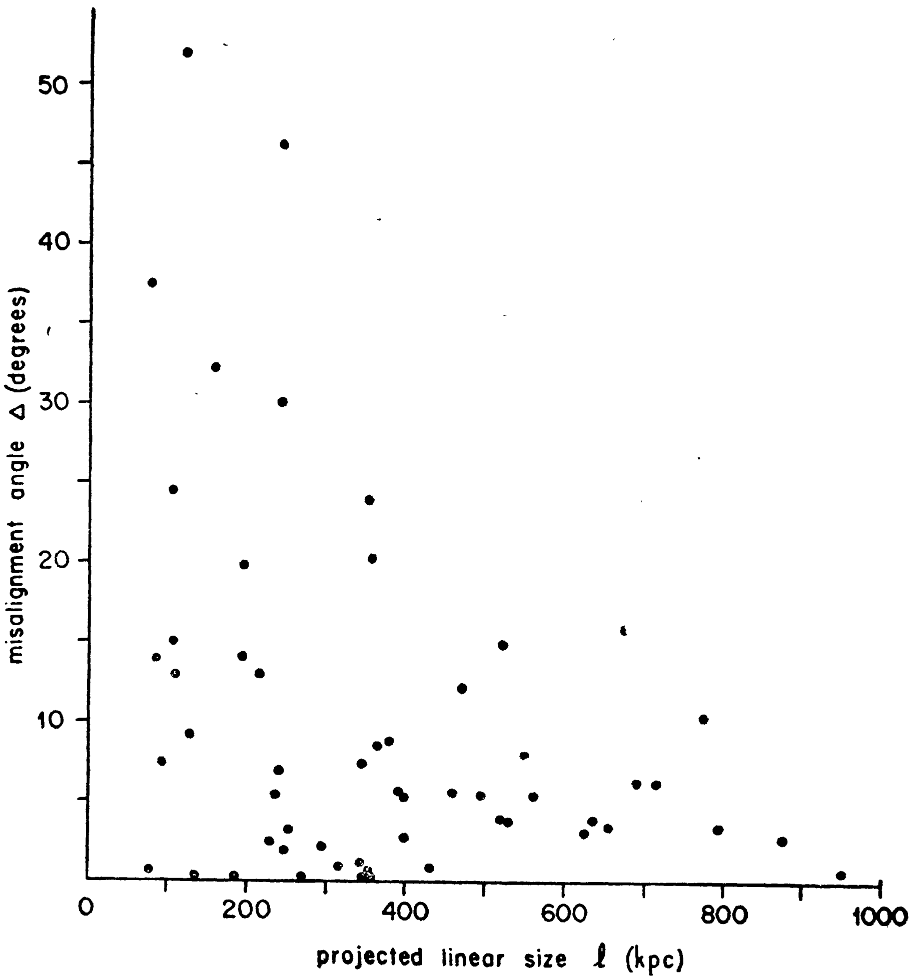

Figure 7. Plot of misalignment angle *vs.* the projected linear size.

5. The f_c – Q relation and the velocity of advancement of the hotspots

If the initial ejection and the kinematic evolution of the two outer lobes are assumed to be intrinsically symmetric, then the ratio, Q of the angular separations of the outer hotspots from the CC can be expressed as

$$Q = (1 + \beta_0 \cos \theta) / (1 - \beta_0 \cos \theta)$$

where $v_0 = \beta_0 c$ is the velocity of advancement of the hotspots. Several authors have attempted to estimate v_0 from the observed distribution of Q, assuming the sources to be intrinsically symmetric and to be oriented randomly in the sky. It is clear from the above equation that the measured value of Q should tend to be closer to unity for sources inclined at larger angles to the line of sight. In the relativistic beaming model, these sources would also have less prominent CCs and thus there should be a positive correlation between f_c and Q. In estimating the values of Q, it is important that the separations be measured with respect to the hotspots or fairly large errors can result, particularly for sources with small overall sizes. Therefore, here too we have confined ourselves to the same subsample of 56 quasars which have been observed with at least six resolution elements along their major axes.

The relationship between f_c and Q for this sample is shown in Fig. 8. Although there is a large spread in Q at all f_c there does appear to be a significant tendency for values of Q close to unity (symmetrically placed lobes) to occur more frequently among quasars with weak CCs. This can also be seen in the histograms of Q shown separately in Fig. 9 for quasars with $f_c \leqslant 0{\cdot}15$ and $f_c > 0{\cdot}15$. The distribution for quasars with weak CCs is quite similar to that for the sample of well-observed 3CR double sources (both quasars and radio galaxies) considered by Longair and Riley (1979) who estimated the velocities of hotspots to be in general $\lesssim 0{\cdot}2c$. The Q distribution for quasars with strong CCs is subject to larger statistical uncertainty due to the smaller number of sources. However, it is worth noting that the distribution is relatively flat with a more pronounced tail in the region $Q > 1{\cdot}4$, suggesting that the distribution of v_0 may extend upto $\sim 0{\cdot}3c$ in a significant number of quasars. This is broadly in agreement with the conclusions based on an analysis of Q for sources in general (Banhatti 1980; Katgert-Merkelijn, Lari and Padrielli 1980; Swarup and Banhatti 1981; Macklin 1981). If the distributions shown in the figure are confirmed by observations of higher resolution for a larger sample of quasars with strong CCs, it would provide possibly the best available evidence for component velocities upto $\sim 0{\cdot}3c$.

Rudnick (1982) has pointed out recently that the distribution of Q in a sample of 47 double quasars shows a significant dip at values of Q close to unity. This has led him to suggest that the ejection from the nuclear engine occurs in only one direc-

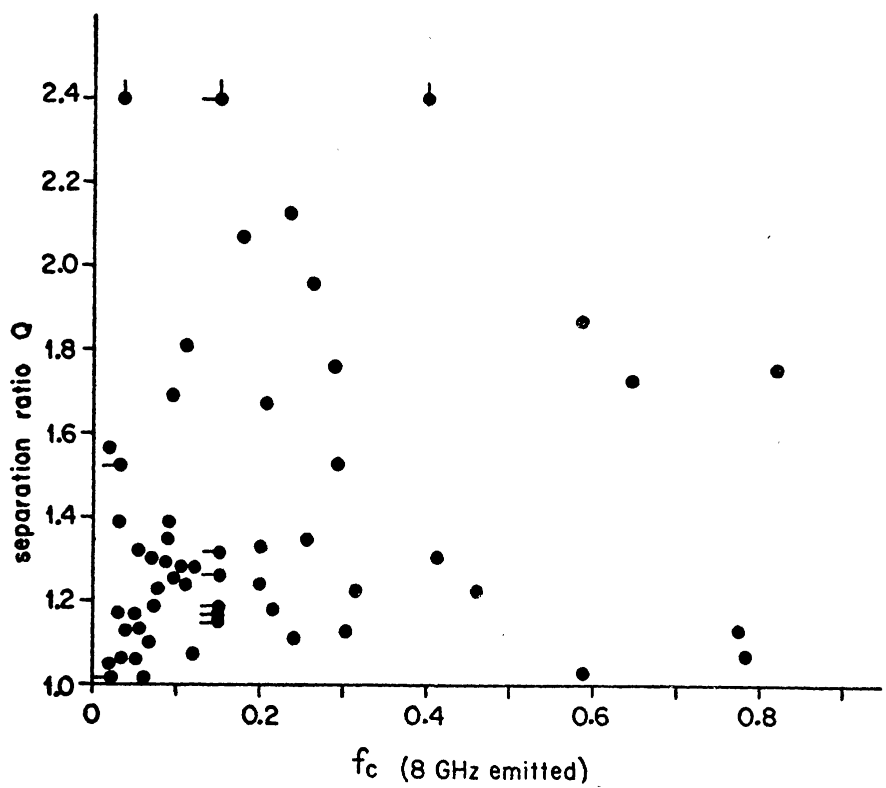

Figure 8. Plot of separation ratio *vs*. the core fraction.

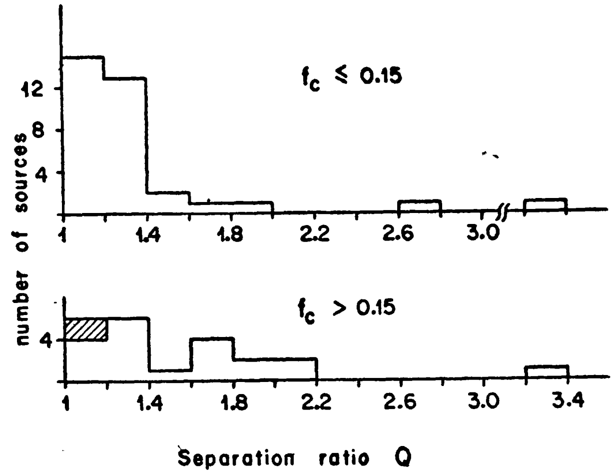

Figure 9. Distributions of the separation ratio for sources with $f_c \leqslant 0{\cdot}15$ and $f_c > 0{\cdot}15$.

tion at a time but there is a switching of the direction back and forth. For comparison with Rudnick's data, we show in Fig. 10 the Q distribution for all the 56 quasars taken together. The dip in the distribution near $Q = 1$ is seen to be much less pronounced than in Rudnick's data and is not statistically significant. It should be noted that Rudnick included only those quasars in his sample that are known to have CCs. This can introduce a bias against values of Q near 1 since sources seen transverse to the line of sight are more likely to appear symmetric and on the beaming hypothesis such sources would have the weakest CCs. Measurement errors can also contribute to an apparent dip near $Q = 1$ because such errors can only move sources in the first bin to larger values of Q whereas those at larger Q values can move either way.

6. The Δ–Q relation

Since both Δ and Q are expected to be larger for sources inclined at small angles to the line of sight, one might expect a statistical relationship between these two parameters. Despite the large scatter, Fig. 11, which shows the Δ–Q diagram for the sample of 56 quasars, provides evidence supporting such a relationship. This can be seen more clearly in the distributions of Q for sources with $\Delta \leqslant 5°$ and with $\Delta > 5°$ shown in Fig. 12. The most noticeable features are a possible shift in

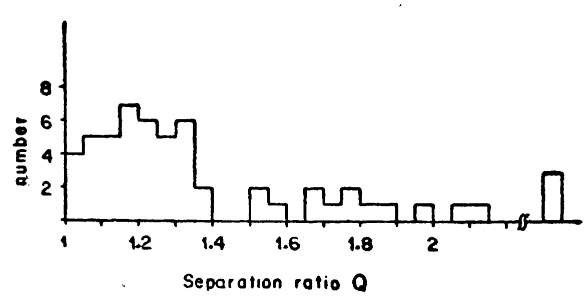

Figure 10. Distribution of the separation ratio for the sample of 56 quasars.

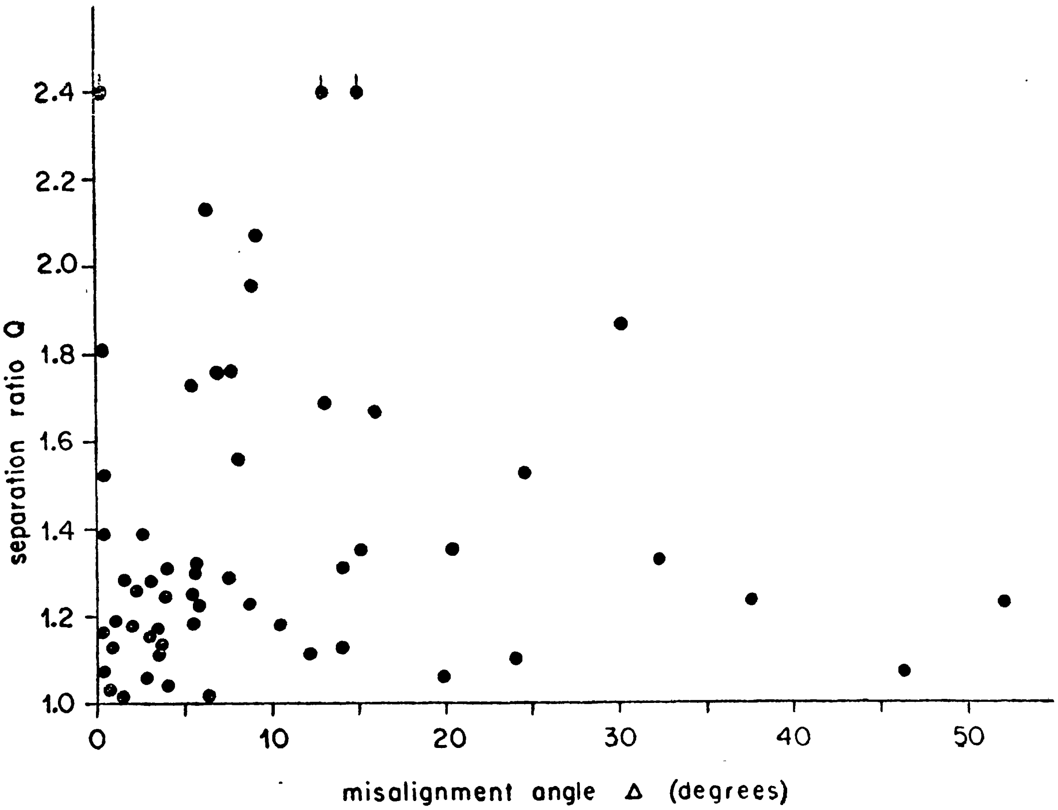

Figure 11. Plot of the separation ratio *vs.* misalignment angle.

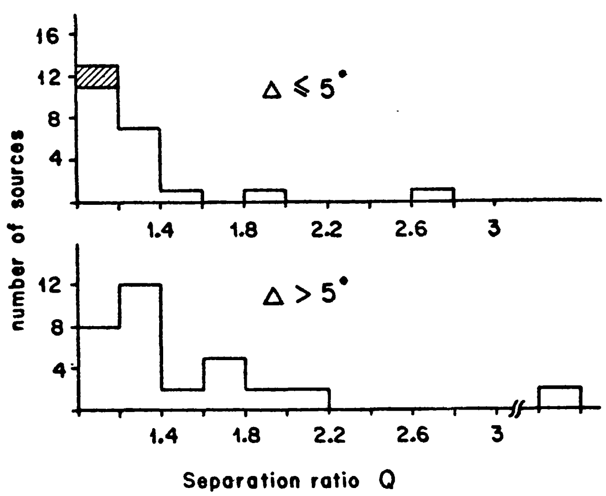

Figure 12. Distributions of the separation ratio for different values of the misalignment angle.

the peak and a more pronounced tail in the distribution of Q for sources with $\Delta > 5°$. The Kolmogorov-Smirnov test shows the two distributions to be different at a significance level of about 95 per cent.

Recently it has been reported by Macklin (1981) that in his sample of 76 3CR double sources, which includes both radio galaxies and quasars, those with the largest values of Q appear most misaligned. Macklin suggested that his correlation is best explained if the major contribution to the Q distribution is independent of orientation and is correlated with the intrinsic misalignment. However, it can be seen from his calculations that the correlation coefficient obtained by assuming a random orientation of sources in the sky and adopting values for the intrinsic misalignment parameter and the velocity of the hotspots which best fit the observed data, is also consistent with the observed coefficient. Our present analysis suggests that the observed Δ–Q correlation arises largely from the effects of orientation.

7. Discussion and conclusions

We have examined several simple statistical consequences of the relativistic beaming model using a large sample of double quasars and find the results to be consistent with this model. Using the fractional emission from the core, f_c, as a statistical measure of the orientation of the source, we find that f_c is anticorrelated with the observed linear size l, but shows a positive correlation with both Δ, the complement of the apparent angle formed at the CC or the optical object by the hotspots in the outer lobes, and Q, the ratio of separations of the hotspots from the CC or the quasar. All these correlations are in the sense predicted by the relativistic beaming model. Furthermore, in conformity with the above correlations, we also find quasars with smaller projected linear sizes to appear more misaligned and Δ to be correlated with Q.

Although the present data in the $f_c - l$ diagram do not permit an accurate determination of the Lorentz factor γ, of the radiating material in the nuclear jets, a typical value of $\gamma = 5$, as suggested by Orr and Browne (1982), appears to be consistent with the data.

The correlation between f_c and Q suggests that the distribution of the velocity of advancement of hotspots in the outer lobes may extend up to $\sim 0{\cdot}3c$ in a significant number of sources. Even larger velocities are in fact required if the asymmetry in the extended emission of D2 quasars arises from the Doppler boosting of the emission from the approaching component. One should then expect to see a correlation between f_c and the ratio of flux densities of the two outer lobes. No significant correlation can however be found in the present sample of quasars which show a fairly large spread in the flux density ratio independent of f_c. The reason is at present unclear. Possible complicating factors that may be important are (i) in general only a fraction of the emission that arises from the hotspots within the lobes is subject to Doppler boosting due to relativistic velocities; (ii) the evolution of luminosity with age must be considered since the two lobes are seen at different ages (Ryle and Longair 1967; Swarup and Banhatti 1981); (iii) it is difficult to detect weak radio lobes in the presence of strong nuclear components; (iv) the extended components of D2 sources may be counterparts of relativistic jets linking the lobes to the nuclei rather than being the lobes themselves (*e.g.* Moore *et al.* 1981; Browne *et al.* 1982). Observations with high angular resolution and large dynamic range that are now becoming available may help in understanding the importance of these factors.

In the $f_c - l$ diagram, the two discrepant quasars (*viz.* 0742 + 31 and 1721 + 34) with dominant CCs and large linear sizes do not appear to fit in with the beaming model. The reason for this is unknown. While no spectral information is available for the different components of 0742 + 31 (Fanti *et al.* 1977), the outer lobes of 1721 + 34 appear to have normal spectral indices of about 0·75. VLBI observations of its core (Jägers *et al.* 1982) indicate that the CC is elongated in the same direction as the axis defined by the outer lobes. It is, however, of interest to note that both these quasars appear to be well aligned ($\Delta = 3°$ and $1°$ respectively) and symmetric ($Q = 1{\cdot}13$ and $1{\cdot}03$ respectively), suggesting that they might indeed be inclined at large angles to the line of sight but have intrinsically strong radio cores, perhaps due to a recent burst of nuclear activity.

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