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On the nature of compact steep spectrum radio sources

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Abstract. In this paper we discuss the properties of Compact Steep-spectrum radio Sources (CSS's), based on VLA, MERLIN and VLBI data.

A classification based on radio morphology is presented. It is found that there is a clear distinction between the radio structure of galaxies and quasars. Galaxies generally have a simple double radio structure, sometimes with weak radio jets and weak radio cores. Quasars, on the other hand, show either a triple structure, with a strong central component, or jet-like or complex morphology. Their cores and jets are considerably stronger than in radio galaxies.

On the basis of various arguments, we show that most ($\gtrsim 70\%$) of the CSS sources are likely to be intrinsically small (not foreshortened by projection effects) and that there is no major radio luminosity amplification by Doppler effects.

On the assumption that CSS sources are an early stage of radio source evolution, we estimate, from their rate of occurrence, that this stage lasts $\lesssim 5\ 10^6$ years. This is consistent with dynamical time scales calculated on the assumption of ambient gas densities of $0.1-1\ \mathrm{cm}^{-3}$ in the inner few kpc of the parent optical objects.

Key words: radio sources - radio galaxies - quasars - jets

1. Introduction

Compact Steep-spectrum Sources (CSS's) are those sources which are unresolved or barely resolved by conventional interferometry (angular size $\lesssim$ 1"–2") and have a steep high frequency spectrum ($\alpha \gtrsim 0.5$; $S \propto \nu^{-\alpha}$) (Kapahi, 1981; Peackock and Wall, 1982). Their occurrence is pretty high in catalogues of radio sources (from $\approx 15\%$ to $\approx 30\%$, depending on the selection frequency). For many years they were not studied intensively because of their uninteresting structure at arcsec resolution. In recent years, however, the advent of high resolution interferometers (VLA, MERLIN and VLBI) has allowed the systematic study of small samples ($\lesssim 40$) of them, mainly from the 3 CR and PW catalogues (van Breugel et al., 1984; Pearson et al., 1985; Fanti et al., 1985; Spencer et al., 1989), but also from other source lists (e.g. Cotton, 1983; Hodge et al., 1984).

Different authors use different definitions of these sources, which however make little difference in practice: some are based on angular size, some others on linear size; some include objects of widely different radio powers, others only the high power objects. Our definition is based on linear size and the selection criteria are described in Sect. 2. Also the nomenclature can be different: "Steep Spectrum Cores" (SSC) in van Breugel et al. (1984); "Steep Spectrum Compact" (SSC) in Pearson and Readhead(1985). Since the term SSC is also used for "steep spectrum cores" in extended sources (see e.g. Saikia et al., 1986), we prefer the name CSS, which is meant to indicate sources whose *overall size* is subgalactic. The specific group of sources known as "Compact Doubles" (CD) of Phillips and Mutel (1982) is a subclass of the CSS's.

The above studies revealed a rather complex morphological situation for this class of objects. At resolutions of hundredths to tenths of arcsec, CSS's show the same variety of structure as the more extended radio sources, i.e. double, triple, and core-jet. In addition, very complex structures reminiscent of sharply bent jets are also observed (see, e.g., Saikia, 1989, for a review of properties).

CSS's are, in our definition, objects which *appear* to have sub-galactic dimensions (van Breugel, 1984). If this is actually the case, their structure might result from interactions of the jet with the local dense medium (cold clouds, a rotating disk, etc.). Indeed objects such as 3C 119, 3C 309.1, 3C 380 display a strongly distorted radio structure and are difficult to explain without invoking the existence of an inhomogeneous, dense and possibly turbulent medium which the jet strikes and by which it is then abruptly deflected: "... *the cosmological equivalent of a brick wall* ..." (Wilkinson et al., 1985). On this scheme they can be seen either as the initial stage of radio source formation, when

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beams emanating from the central source of energy have not yet drilled through the inner dense interstellar medium, or as a peculiar class of objects where unusual conditions of the interstellar medium (higher density and/or turbulence) inhibit the radio source from growing to large dimensions.

Alternatively, CSS's could be those sources whose small apparent size is the result of projection effects, associated with Doppler boosting of some part of their radio emission. Projection would, of course, amplify any intrinsic distortion in the structure.

With the aid of the available data we examine which of the two views (intrinsically small or small by projection) is the best description of the situation and show, in Sect. 4.1, that only $\lesssim 25\%$ are likely to be larger sources shortened by projection.

We also discuss some implications of a scenario in which intrinsically small CSS's are an early stage in the evolution of the large powerful radio sources.

2. The CSS sample

For some years we have been studying two samples of CSS's at several wavelengths and resolutions using the European VLBI Network, the MERLIN interferometer and the Very Large Array. The observations are not homogeneous, not every source having been observed with every array at any particular frequency. However there are now enough data to carry out a statistical analysis of the properties of this class of source. CSS's in our sample come from the 166 3CR catalogue (Jenkins et al., 1977) and from the Peacock and Wall (PW) sample (1982).

The two samples were selected at different frequencies and therefore have different properties. Spencer et al. (1989) show that the PW sample contains a number of sources whose radio spectra turn over at frequencies higher than those of the 3CR and whose angular sizes are smaller.

We have constructed a sample of CSS's without spectral bias by integrating the 3CR sample with those sources from PW which would be stronger than 10 Jy at 178 MHz (the limiting flux density of the 3CR catalogue) if corrected for low-frequency absorption by extrapolation of the straight high-frequency part of the spectrum. Table 1 lists the resulting representative sample of CSS's, with projected Linear Sizes (LS) less than 15 kpc[1], (corrected) flux density at 178 MHz $\geq$ 10 Jy, in a well defined area of sky ($|b| > 10°$, $\delta > 10°$) and with $\log P_{178} > 26.5$. This sample is marginally different from the one treated by Spencer et al. (1989). A number of CSS's in the table do not satisfy all the selection criteria and are marked with an asterisk. They are included in the discussion of properties when completeness is not required. Note that two sources in Table 1 (3C 216, 3C 380) are more extended than 15 kpc. These sources were thought earlier to be of smaller size, but subsequent high sensitivity observations have revealed weak surface brightness components, previously undetected.

[1] We use $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 1$.

Table 1. Compact steep-spectrum sources from the 3 CR and PW catalogues

Name	z	Id[a]	$S_{2.7}$ (Jy)	Size (arcsec)	α	ν_{max} (MHz)	$\log P_{2.7}$ (W/Hz)	LS (kpc)	Mor.	Ref.
3C 43 0127 + 23	1.46	Q	1.7	2.6	0.71	<20	27.48	9.4	T	2,3,4b
3C 48 0134 + 32	0.37	Q	9.1	1.3	0.82	80	27.06	2.1	C	3,7,4b
3C 49 0138 + 13	0.62	G	1.5	1.0	0.89	120	26.75	3.6	D 1	1,3,6
3C 67 0221 + 27	0.31	G	1.7	2.5	0.93	50	26.20	6.8	D	1,3,4
0223 + 34*		Q	1.8	1.1	0.53	250	27.2	3.8	T	3
0316 + 16		G?	9.5	0.1	0.82	900	27.90	<0.4		3
0319 + 12*	2.67	Q	1.6	<0.1	0.59	400	27.86	<0.3		3
3C 93.1*	0.24	G	1.3	0.3	0.84	60	25.91	0.7		3
0404 + 76	1.4?	G	4.0	<0.1	0.58	600	27.80	<0.4		3,4b
0428 + 20	0.22	G	3.2	0.1	0.50	1000	26.12	0.2		3
3C 119*	0.41	Q	5.4	0.2	0.65	150	26.92	0.9	J	1,9
3C 138 0518 + 16	0.76	Q	6.0	0.8	0.65	100	27.49	2.9	J	3,4,6
3C 147 0538 + 49	0.55	Q	13.0	0.7	0.83	150	27.56	2.4	T	3,4b,7
3C 186	1.06	Q	0.6	2.2	1.08	40	26.94	8.2	T	2
3C 190	1.2	Q	1.4	4.0	0.89	≈40	27.36	14.1	T	2,4b,5

(*continued*)

Table 1 (continued)

Name	z	Id[a]	$S_{2.7}$ (Jy)	Size (arcsec)	α	ν_{max} (MHz)	$\log P_{2.7}$ (W/Hz)	LS (kpc)	Mor.	Ref.
3C 216*	0.67	Q	2.4	8.0	0.78	≈40	26.95	28.8	T	4b,11
3C 237*	0.88	G	3.7	1.2	0.91	50	27.48	4.5	D 1	1,3,5
3C 241	1.62	G	0.7	1.2	1.28	40	27.48	2.8	D 1	1,3,5
1153 + 31	1.56	Q	1.7	0.9	0.92	100	27.69	3.2	D 1	3,4
3C 268.3	0.37	G	2.0	1.3	0.97	80	26.55	3.9	D	1,3,4
1225 + 36		Q	1.6	<0.1	1.17	950	27.3	<0.4		3
3C 277.1* 1250 + 56	0.32	Q	1.5	1.6	0.72	<100	26.22	4.4	D 1	3,4
1323 + 32	0.37	G	3.3	<0.1	0.58	400	26.62	<0.3		3
3C 286 1328 + 30	0.85	Q	10.3	3.8	0.55	≈80	27.79	14.2	T	2,3,4
3C 287 1328 + 27	1.06	Q	4.6	0.1	0.63	≈50	27.65	0.4	J	1,6
1358 + 62	0.43	G	2.7	<0.1	0.78	600	26.70	<0.3		3
1413 + 34*			1.7	<0.1	0.6	900	27.2	<0.4		3
3C 298*	1.44	Q	2.7	2.5	1.1	80	27.86	9.1	T	3,4b,5
3C 299 1419 + 41	0.37	G	1.6	0.5	0.88	80	26.32	1.5	C	2,3,4b
1442 + 10	3.53	Q	1.7	<0.1	0.68	950	28.33	<0.3		3
3C 303.1	0.27	G	0.6	2.0	1.07	100	25.77	5.0	D	1,3,5
3C 305.1	1.13	G	0.8	2.8	0.96	90	27.02	9.0	D	3,5
3C 309.1	0.9	Q	5.3	2.2	0.60	<40	27.58	7.8	T	3,4,7
3C 318 1517 + 20	0.75	G	1.3	0.8	0.92	<40	26.91	7.8	T	2,4b,5
1600 + 33			2.2	<0.1	0.63	950	27.3	<0.4		3
1607 + 26	0.47	G	2.9	<0.1	0.89	950	26.8	<0.3		3
3C 343 1634 + 62	0.99	Q	2.7	0.25	0.84	250	27.47	0.7	C	1
3C 343.1 1637 + 62	0.75	G	2.2	0.38	0.99	250	27.15	1.3	D	1,4b
3C 346	0.16	G	2.3	8.0	0.65	<40	25.8	14.0	D 1	2,4b
1819 + 39	0.4	G	1.8	1.0	1.02	100	26.5	3.1	D	3
3C 380*	0.69	Q	9.9	7.0	0.57	<40	27.59	25.0	C	5,8
1829 + 29	2.51	Q	1.9	3.0	0.85	100	28.10	9.3	T	3
2230 + 11	1.04	Q	4.9	2.6	0.52	900	27.64	9.7	T	3
3C 454	1.76	Q	1.2	0.6	0.76	<40	27.61	2.1	T	2,5
3C 454.1*	1.84	G	0.6	1.6	1.24	<40	27.44	5.5	D	3,5
3C 455*	0.54	Q	1.5	4.0	1.06	<40	26.62	13.7	D	3,4b
2342 + 82	0.74	G	2.3	<0.1	0.92	400	27.11	<0.4		3

[a] Objects with no red-shift were assigned $z = 1$.
Optical identifications and red-shifts are taken mainly from Spinrad et al. (1985) and Peackock and Wall (1982). A few extra red-shifts, mostly from private communication, are taken from Spencer et al. (1989). 3C 119, given alternatively as radio galaxy or quasar in the literature (see Fanti et al., 1986), is now believed to be a quasars (W.v.B.).

References: 1) Fanti et al., 1985; 2) in preparation; 3) Spencer et al., 1989; 4) van Breugel et al., 1984; 4b) in preparation; 5) Pearson et al., 1985; 6) Fanti et al., 1989; 7) Wilkinson et al., 1984a; 8) Wilkinson et al., 1984b; 9) Fanti et al., 1986; 10) in preparation; 11) Barthel et al., 1988.

The 3CR sample of CSS's has been observed almost completely with the EVN and MERLIN at 1.6 GHz and partly with the VLA at 1.4, 5, 15 and 22 GHz. The PW sample has been observed with MERLIN at 1.6 GHz and with the VLA at 5 and 15 GHz. Sparse observations at other frequencies exist for some sources in either sample. Table 2 gives an overview of the observations conducted.

As a reminder of some characteristic properties of CSS's in our sample, we show in Figs. 1–3 the distribution of the turnover frequencies in the radio spectra, of the redshift and of the monochromatic radio luminosity at 2.7 GHz, separately for radio galaxies and quasars. The two histograms in Fig. 2 are slightly different, indicating higher redshifts for the quasar subsample. The radio power of quasars is about half an order of magnitude greater than that of radio galaxies. Note that the identification level of sources of Table 1 is $\approx 95\%$ and that for $>90\%$ of these, redshifts are known. A full discussion of the properties of the sample is given in Spencer et al. (1989).

3. The radio morphology

3.1. *Morphological classification*

The appearance of CSS's is dependent on the resolving power, frequency and sensitivity of the measurement, making a morphological classification of individual sources difficult. Observations at low frequency may miss a weak flat spectrum core; observations with a lower sensitivity or dynamic range may miss low brightness extended emission associated with high brightness compact components. A physically meaningful classification requires a range of resolutions and frequencies in order to describe properly the whole structure and not just a few details of the source. In addition, optical positions with accuracy comparable to those measured with the VLA are required to locate correctly the radio components with respect to the parent object, so as to distinguish D 1 from D 2 doubles or correctly identify the true radio core.

The classifications reported here are based on radio data available to us from VLBI, MERLIN and VLA measurements. Despite the data being inhomogeneous, owing to non-uniformity in resolution, frequency and sensitivity, we are confident that the high dynamic range VLA and MERLIN observations at 1.4 and 1.6 GHz respectively allow us to map the whole source structure correctly so that no radio components have remained undetected down to a brightness level of $\lesssim 1:1000$ (corresponding to 4 times the rms noise) of the main component.

We adopt a classification which favours the description of the whole source structure, rather than substructures in it. To accomplish this, we have used observational data typically having a source to beam size ratio $\gtrsim 5:1$. This might lead to some differences with earlier classifications. A number of sources unresolved by both MERLIN and VLA, and for which VLBI data do not exist, cannot be classified. In practice, a classification is possible for sources $\gtrsim 0.4$ kpc. References for the maps we used for classification are given in Table 1.

We divide the objects in the following classes:

- Doubles: two well separated components, occasionally with a (generally weak) flat-spectrum unresolved component (*core*) in between, seen at high frequencies.
- Triples: three well separated components, not necessarily aligned, of which the central one may contain the true core. The central component is generally resolved and with steep radio spectrum and has a luminosity $\gtrsim 15\%$ of that of the outer components (but in most cases is much larger).
- Jet-like: straight or bent, sometimes with a visible core.
- Complex: sources having structures which are more complicated than can be accommodated in the previous classes.

(a) Doubles

Fourteen sources are classified as Double:

3C 49	3C 67	3C 237	3C 241
1153 + 31	3C 268.3	3C 277.1	3C 303.1
3C 305.1	3C 343.1	3C 346	1819 + 39
3C 454.1	3C 455		

We emphasize that our classifications in the Double class is generally unable to distinguish between D 1 (where the two components lie on either side of the nucleus) and D 2 (where one of the components is located on the nucleus). Distinction between the two types requires either an accurate enough optical position (this is never the case) or the detection of a *flat spectrum unresolved core*, which is the best indicator of the location of energy production. Only in six Doubles (3C 49, 3C 237, 3C 241, 1153 + 31, 3C 277.1, 3C 346) is a *core* detected between the outer components by the VLA at high frequency, showing that these are

Table 2. Observational status of the CSS sample

Array	ν (GHz)	Resolution (arcsec)	Noise (mJy beam^{-1})	Dynamic range[a]	Ref.
EVN	1.6	0.03	1–2	200:1	1,2
MERLIN	1.6	0.3	1–2	1000:1	3
VLA	1.4	1.2/4.0	0.5–2	5000:1	10
VLA	4.9	0.4	0.5–1	1000:1	3,4,5
VLA	14.8	0.12	0.5–1	1000:1	3,4,4b

[a] Peak flux to rms noise ratio.

References: See references to Table 1

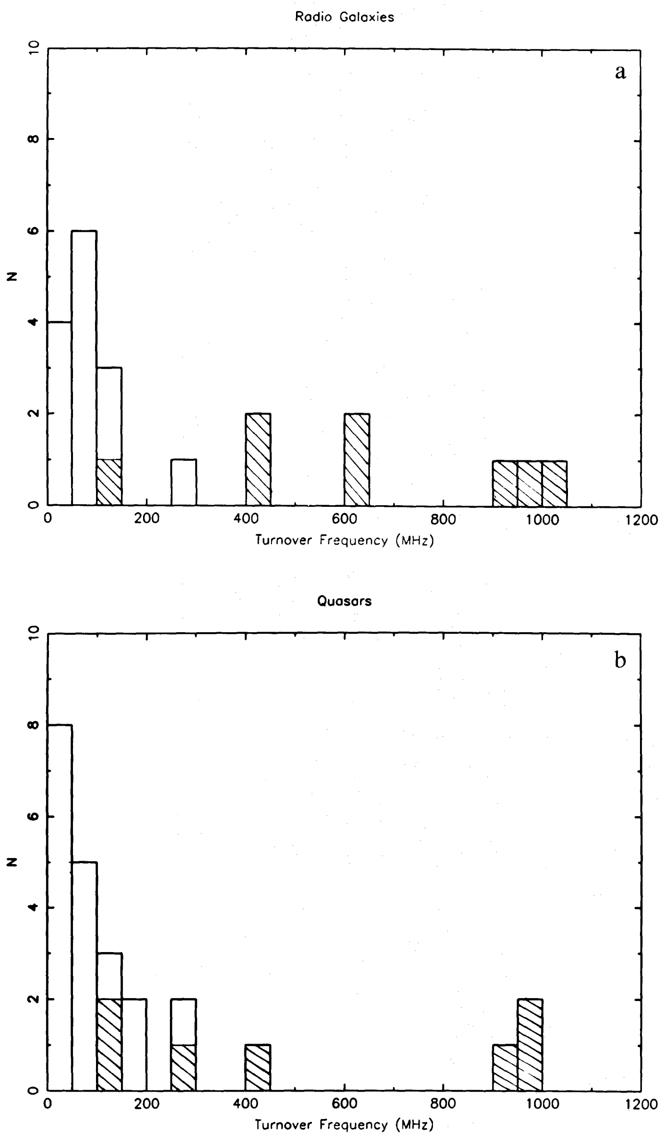

Fig. 1a and b. Histograms of low frequency turnover for CSS radio galaxies and quasars. PW sources are shown hatched

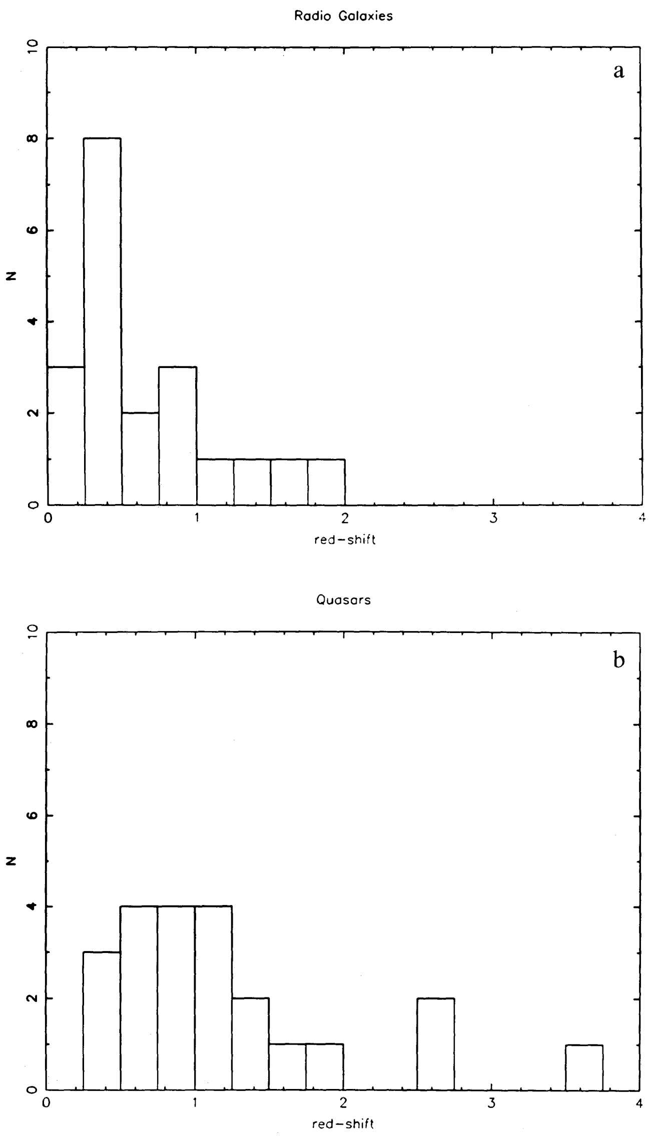

Fig. 2a and b. Histograms of redshift for CSS radio galaxies and quasars

genuine D 1 type (for 1153 + 31 and 3C 277.1 the radio spectrum is not known). In the following we shall assume that the other doubles are also of the D 1 type, but this assumption awaits confirmation.

(b) Triples

Thirteen sources are classified as Triple. They are:

3C 43	0223 + 34	3C 147	3C 186
3C 190	3C 216	3C 286	3C 298
3C 309.1	3C 318	1829 + 29	2230 + 11
3C 454			

Five of these, 3C 43, 3C 147, 3C 286, 3C 309.1 and 3C 454, have a pronounced non-linear structure with bends larger than 30°.

The distinction between Triple and Double may be somewhat arbitrary, depending on resolution, sensitivity and observing frequency (e.g. 1819 + 39 has been classified as Double, although we suspect it be Triple. Our resolution is not enough to confirm this.) Further we point out that Triple sources are not necessarily Doubles with a strong core, since the central component in a Triple often has a steep radio spectrum (see Fig. 4b) and appears extended, while our recognition of the core is based on a *flat* radio spectrum *unresolved* component. In a number of cases, when observations exist at high enough resolution, the central component appears resolved into the true core plus a jet (see Sect. 3.3); we suspect that this situation is rather general. This is why we also include in this class 3C 186 and 3C 190 which, at all our resolutions, are both clearly resolved into a two lobed structure plus a bright one-sided jet and a weak core.

(c) Jet-like sources

The Jet-like class contains three clear examples:

3C 119   3C 138   3C 287

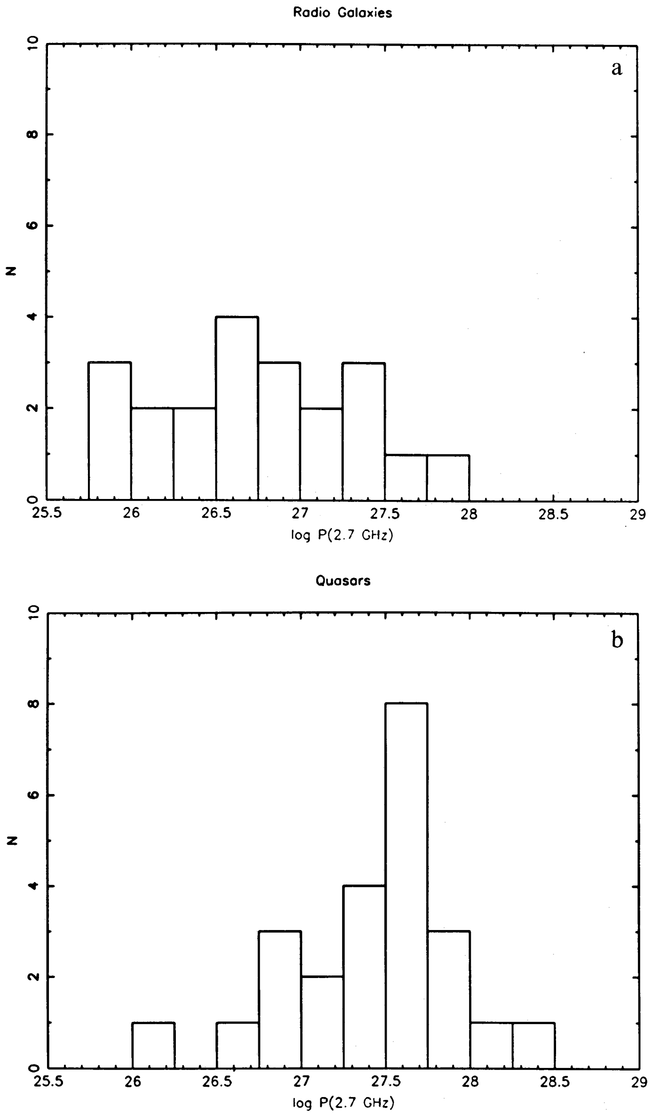

Fig. 3a and b. Histograms of the logarithm of the monochromatic luminosity (W/Hz) for radio galaxies and quasars

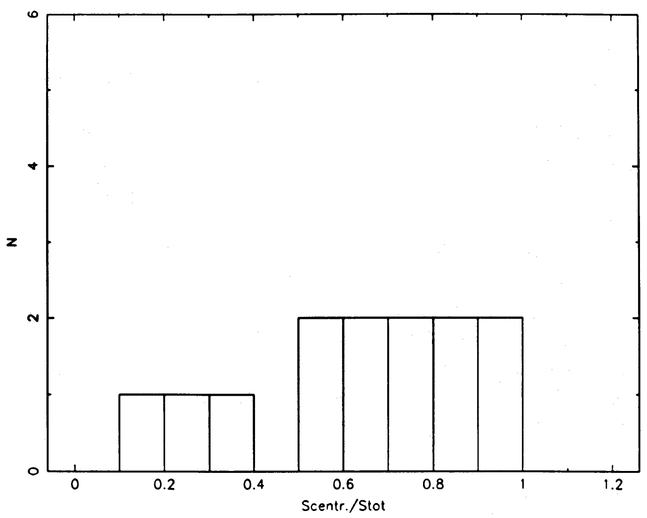

Fig. 4a. Histogram of the ratio of *Central Component* luminosity to total luminosity, for Triples

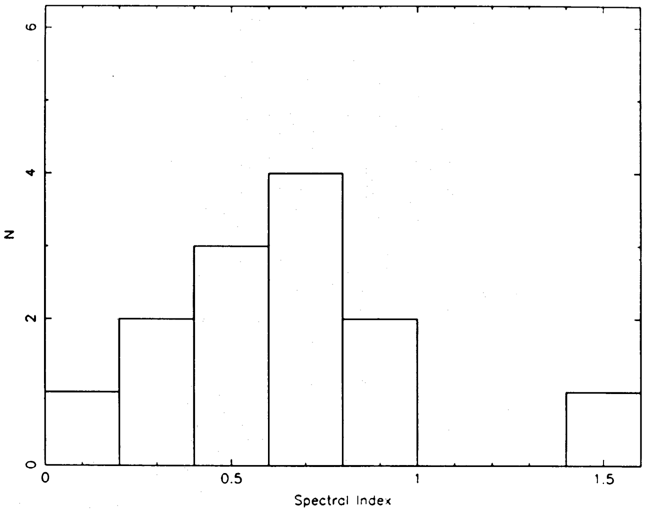

Fig. 4b. Histogram of the spectral indices of *Central Components* in Triples

3C 138 is an example of an almost straight jet, while the two other sources show a large amount of bending (>90°). All these are similar to jets found in flat spectrum sources (e.g. 3C 273). Jets or jet-like features are also found in Doubles or Triples (Sect. 3.3), but the sources we put in the present class are the ones where the jet dominates the whole source structure.

(d) Complex

Complex sources are those which do not fit any of the other categories. Included here are:

3C 48 3C 299 3C 343 3C 380

These sources could be related to the other classes, with radio structure more distorted either by projection effects or by a higher degree of intrinsic complexity.

The nature of 3C 299 is still unclear. It is dubious whether a second source at ≈ 12 is related to the main one. In case the association were real, the source would be an asymmetric double of $\approx 30-40$ kpc. In the following we will not consider this possibility, which, any way, is not going to change the general conclusions.

3.2. Radio cores

It is not yet known whether all CSS galaxies and quasars contain compact flat spectrum radio cores. A search for cores in objects of high brightness like the CSS's would require high resolution (<10 mas) at high frequencies (>5 GHz). Such data are not available for the whole sample yet. Most of the information comes from the 1.6 GHz VLBI observations where, however, the cores might be self-absorbed, from a few sparse VLBI observations at 5 GHz or from the VLA at 15 or 23 GHz, where, however, the resolution is often not sufficiently high. For sources resolved in our observations (LS $\gtrsim$ 0.4 kpc) we give in Table 3 estimates of core flux densities at 5 GHz, or upper limits, and the relevant references. When a 5 GHz flux density measure does not exist, the core flux density is estimated from other frequencies, assuming a flat spectrum. For a number of sources,

Table 3. Cores of CSS sources

Name	S_c (mJy)	ν (GHz)	S_c/S_e[a] (%)	Ref.
3C 43	30	1.6	5.	2
3C 48	300	23	5.	4b
3C 49	10	5,15	0.7	3,6
3C 67	<20	15	<1.6	3,4
3C 119	60	1.6,5	1.3	9
3C 138	250	5	4.6	6
3C 147	170	5	6.9	7,13
3C 186	15	15	1.8	11
3C 190	40	5,15	2.7	2,5
3C 216	500	5	32.4	12
3C 237	2	15	0.06	4b
3C 241	3	15	0.23	4b
1153 + 31	10	15	0.5	3
3C 268.3	<20	15	<1.2	3,4
3C 277.1	50	15	5.5	3
3C 286	900?	5	9.1?	2
3C 287	240?	5	4.7?	6
3C 298	220	15	5.8	4b
3C 299	<20	1.6,15	<2.0	2,4b
3C 303.1	<5	15	<1.0	4b
3C 305.1	<6	15	<0.6	3,4
3C 309.1	700	5	16.0	7,12
3C 318	<90	23	<7.0	4b
3C 343	<130	1.6	<5.0	2
3C 343.1	<60	1.6,23	<2.0	1,4b
3C 346	220	1.6,23	14.7	2,4b
3C 380	1000	5	38.0	12
3C 454	<200	1.6,23	<11.0	2,4b
3C 454.1	<15	1.6	<1.4	3
3C 455	<10	1.6,15	<0.6	3,4b
0223 + 34	No information			
3C 93.1	No information			
1819 + 39	No information			
1829 + 29	No information			
2230 + 11	No information			

[a] At 5 GHz, corrected for the k term. S_e is the flux density of extended emission.

References: 1–9 See references to Table 1; 11 Cawthorne et al., 1986; 12 Pearson and Readhead, 1988; 13 Alef et al., 1988

particularly for a few Triples whose central, slightly extended, component has not been studied at a good resolution, the scarce data we have do not even allow to set any reliable upper limit to core flux densities.

Nevertheless, the present limited data on cores demonstrate that a difference exists between galaxies and quasars: the ratio of core to total radio luminosity is substantially less in galaxies than in quasars.

In Fig. 5 we compare the cumulative distribution of the ratio of core to extended flux density for our CSS quasars with the corresponding distribution for larger size quasars of similar radio luminosity (from the 3 CR). This ratio is corrected for the k-term, assuming a spectral index ≈ 0 for cores, and ≈ 0.8 for the extended emission. The two distributions are computed at 5 GHz using a method which also takes into account the upper limits (see Giovannini et al., 1988). The median ratio for CSS quasars is 0.05 (± 0.03; errors are 2σ), quite consistent with that of large scale quasars of comparable radio luminosity (median value 0.03 ± 0.02, errors are 2σ; see Orr and Browne, 1982; and Kapahi and Saikia, 1982).

A similar comparison is more uncertain for radio galaxies, due to the small number of detected cores in the CSS sample. However the distributions of $Sc/Sext$ for large radio galaxies and its median value (0.003 ± 0.001; Giovannini et al., 1988) are consistent with the upper limits and the few detections of CSS galaxies.

3.3. *Radio jets*

In addition to the Jet-like sources (3C 119, 3C 138, 3C 287), where the jet emission dominates the whole radio structure, small scale radio jets are also found in many other sources.

Amongst the Doubles, 3C 346 has a prominent jet embedded in one of the lobes, and 3C 241 shows an elongated feature in VLBI and VLA maps, which can also be interpreted as a jet.

Jets are more common amongst Triple sources (3C 43, 3C 147, 3C 186, 3C 190, 3C 216, 3C 286, 3C 309.1, 3C 318, 3C 454), where they account for most of the flux density in the central component. Some of these are strongly bent or misaligned with respect to the main radio axis (3C 43, 3C 216, 3C 309.1, 3C 454). They are generally one-sided, with the possible exceptions of 3C 286 and 3C 318.

3.4. *Radio lobes*

The components of Double sources and the outer components of Triples bear a great similarity to each other. We shall refer to them as the *radio lobes.*

The distribution of the flux density ratio of the lobes in Triples is similar to that for the Doubles (the distribution is

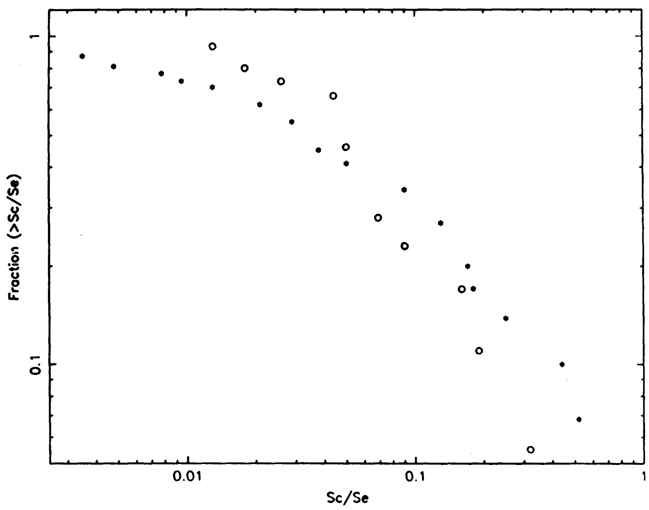

Fig. 5. Cumulative distribution of core flux to extended emission flux ratio for CSS quasars (∘) and large size quasars (*)

shown in Fig. 6). The same is true for the *arm ratio* (the ratio of lobe distances to the core, or centroid of central component for Triples with barely resolved central components), whose distribution is shown in Fig. 7. It is interesting to compare these distributions with the corresponding ones for large scale (tens of kpc) Doubles (e.g. Longair and Riley, 1979; Katgert – Merkelijn et al., 1980). While the distributions of flux density ratio are quite similar, the distribution of the arm ratio for CSS's is broader than the one for large doubles. In Fig. 8 we plot the arm ratio versus the flux density ratio.

The ratio of component transverse size (i.e. perpendicular to the main axis) to component separation is about 0.1 (Fig. 9) for both Triples and Doubles, also similar to that found in large scale high luminosity doubles observed with similar source/beam-size ratios (MacKay, 1971; see also Leahy and Williams, 1984).

The spectral indices of the lobes in Triples are similar to those of Doubles ($\alpha \approx 1.15 \pm 0.10$ in the range 1.6–15 GHz).

Finally we note that the lobes of Triples in our sample have absolute luminosities similar to those of Doubles.

3.5. Radio structure and optical identification

There is a clear segregation in radio morphology between quasars and galaxies. Well resolved galaxies are mostly Double (12/14). Quasars are generally either Triple (12/20), Jet-like (3/20) or Complex (3/20).

The radio structure of quasars seems to evolve towards a triple morphology as the overall size progressively increases. Quasars smaller than $\approx$3 kpc are mostly jet-like or complex, with little or no evidence of radio lobes. The radio lobes tend to appear at larger sizes. This trend in morphology is at the moment marginally significant ($\approx$90%) and has to be improved, e.g. by higher resolution studies of the still unresolved sources of our sample.

Distortion, either in the overall structure or in the components, seems more frequent in quasars. If we introduce the distortion angle ψ, measured as the angle between the orientation of the two arms with respect to the core (in such a way that a

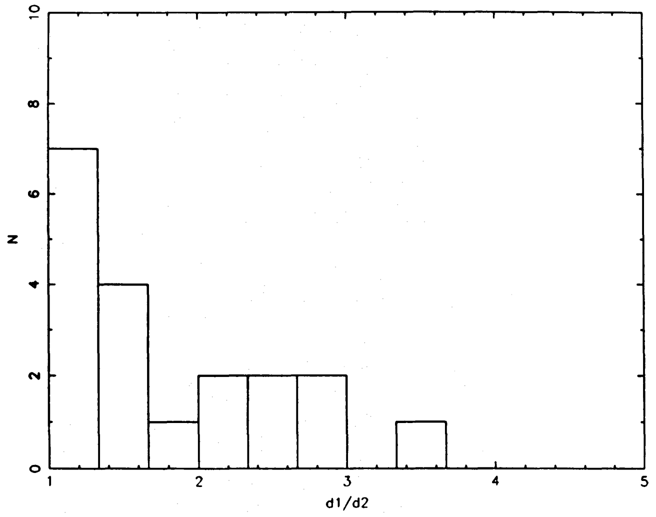

Fig. 7. Histogram of the radio lobes arm ratios for Doubles and Triples

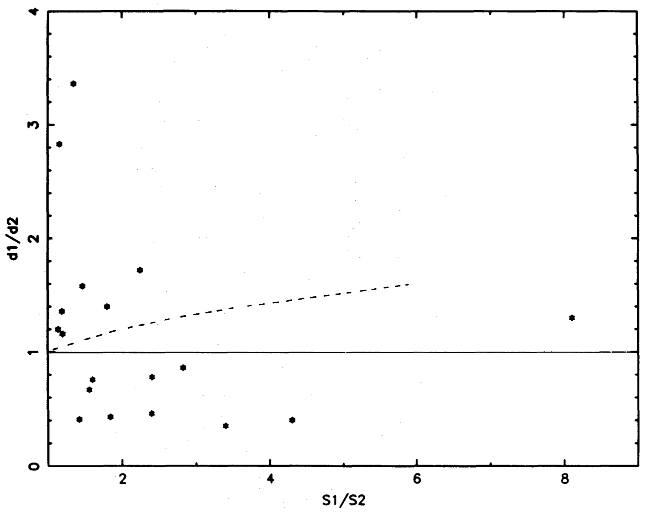

Fig. 8. Plot of flux densities ratio versus arm ratio for lobes of Doubles and Triples. The broken line is the locus expected for sources with Doppler boosted lobes (Sect. 4.1).

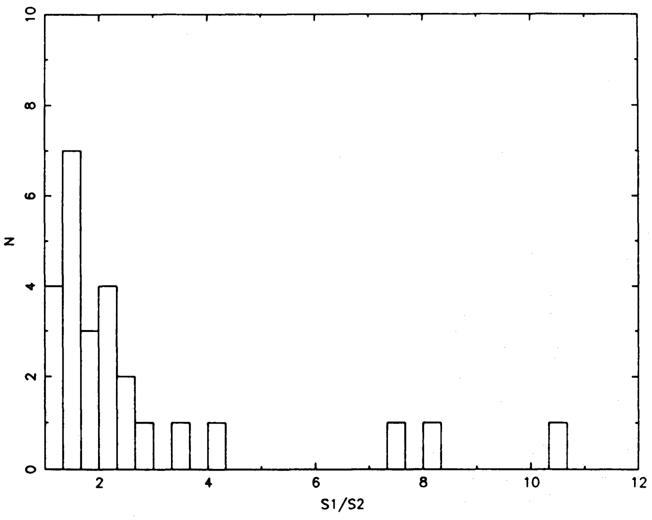

Fig. 6. Histogram of the ratios of radio lobes flux densities in Doubles and Triples

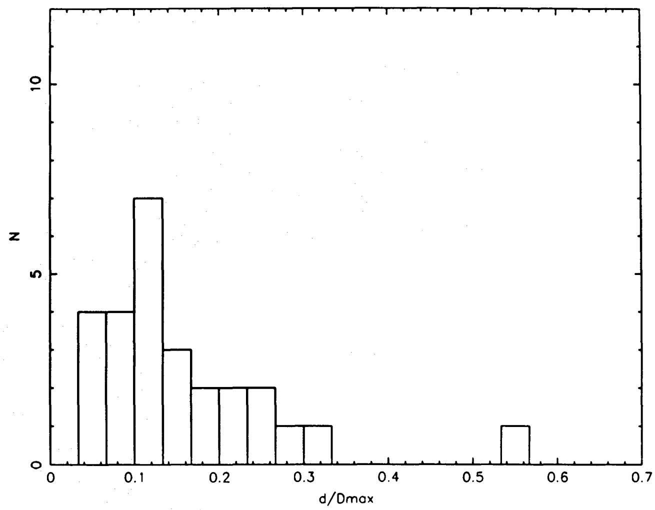

Fig. 9. Histogram of the ratios of component transverse size to total size, for Doubles and Triples

linear source has $\psi = 0°$), we find that $\approx 40\%$ of the CSS quasars have $\psi > 35°$. For radio galaxies we cannot measure ψ in those cases where the core is not detected. This limits severely our statistics. Out of 6 radio galaxies with measured ψ, one displays a marked distortion (3C 299, $\psi \approx 170°$), while the others have $\psi \lesssim 10°$.

Jets are weak ($\lesssim 10\%$ of total luminosity) and rare amongst galaxies, but are much more common in quasars, where they account for a significant fraction ($\approx 60\%$) of the total luminosity.

Finally, as for large size sources, radio cores in quasars are a factor ≈ 10 stronger than in galaxies (Sect. 3.2).

Such a morphological segregation, which was first pointed out by Wilkinson et al. (1984a), is not due to luminosity or redshift effects, as shown by Spencer et al. (1989).

The relative brightness of the various radio components in CSS galaxies and quasars is summarized as follows, in arbitrary units, *at 5 GHz*:

	Lobes	Jets	Core
Quasars	0.35	$\approx .60$	0.05
Radio galaxies	0.9	$\lesssim 0.1$	≈ 0.005

We remark finally that the so far unresolved sources ($< 0''.1$) are found to be associated with both galaxies and quasars.

3.6. Correlations

Several correlations exist between observed parameters. We only mention the following.

The turnover frequency is broadly correlated with the average observed brightness and inversely correlated with the average size of source components. The former correlation is shown in Fig. 10. The statistical significance is greater than 99%. A correlation like this is expected if the low frequency turnover is due to synchrotron self-absorption. We point out that the component sizes we used were obtained at 1.6 GHz, which is generally very different from the turnover frequency. The well known existence of several components dominating the spectrum at different frequencies can increase the dispersion of a correlation considerably if the turnover frequency is very different from the frequency at which the sizes are obtained. A more accurate choice of the parameters would probably produce a better correlation.

An anticorrelation is found between the turnover frequency and the total Linear Size (Fig. 11; statistical significance greater than 99%). When the LS increases the turnover frequency decreases.

Of course these correlations are not independent, since sources with larger linear sizes also have larger component sizes and therefore, on average, lower surface brightness.

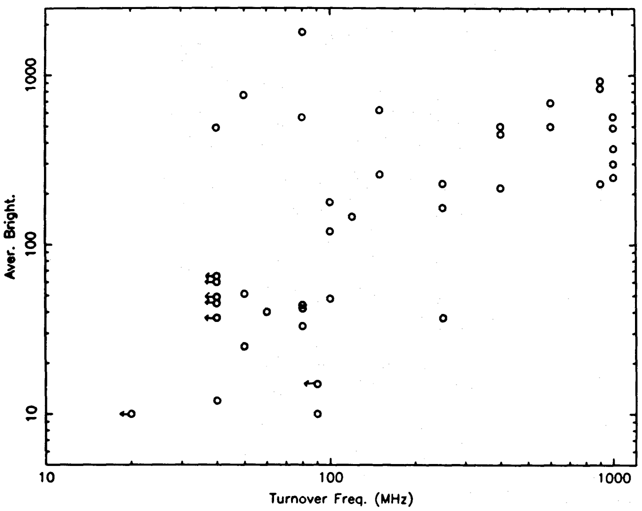

Fig. 10. Plot of turnover frequency (MHz) versus average source brightness (mJy arcsec^{-2})

3.7. Distribution of radio source sizes and the CSS sources

It is important for the following discussion to examine how the size distribution of the CSS's compares with that of radio galaxies and quasars in general. Figure 12 shows the distributions of (projected) LS of all quasars and galaxies with $\log P_{178} > 26.5$ in the combined 3 CR + PW sample (the CSS's shown are only those from the complete sample described in Sec. 2). One should note that:

(i) there is continuity between CSS's and large sources, both galaxies and quasars;

(ii) the CSS's are clearly a conspicuous fraction of the two populations ($\approx 17\%$ for Galaxies and $\approx 30\%$ for quasars at LS $\approx$ 10 kpc);

(iii) they have high radio luminosity and high redshift ($z > 0.2$).

In contrast the LS distribution for the most powerful nearby ($z < 0.2$) radio galaxies ($10^{25} < P_{1.4}$ W Hz^{-1} $< 10^{26.5}$) is, in fact, quite flat, without any marked increase towards small sizes. In nearby radio galaxies a peak at small LS appears at low radio power only ($P_{1.4} < 10^{24.0}$ W Hz^{-1}; see de Ruiter et al., 1989).

4. Discussion

4.1. CSS sources: intrinsically small or shortened by projection?

The first question to address about the nature of CSS's is whether they are intrinsically small or whether they are larger sources shortened by projection effects. In what follows we attempt an answer to this question.

A starting point is the LS distribution of both quasars and galaxies shown in Fig. 12. We first assume that these objects are randomly oriented, namely that the probability of having a source at an angle θ to the line of sight is proportional to $\sin\theta$. We then model an intrinsic diameter distribution and project the sources at random on the plane of the sky. The model is modified until the predicted distributions of projected diameters reproduce the observed ones (see Fig. 12). The comparison between the true and the projected diameter distributions shows that no more than a quarter of the sources with observed diameters < 10 kpc derive from larger objects seen at small angles ($\lesssim 20°$–$30°$) from the line of sight. The other small sources must belong to the model distribution in order to reproduce the observed peak at sizes $\lesssim 10$ kpc.

We conclude, from this simulation, that, if CSS sources are randomly oriented in space, *only a minority of them are larger sources of the same intrinsic radio luminosity shortened by projection effects.*

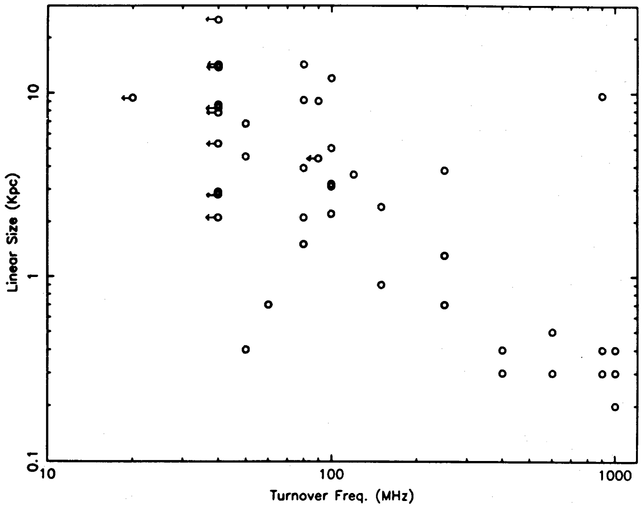

Fig. 11. Plot of source Linear Size (LS) versus turnover frequency

Another possibility, however, is that CSS's are the result of projection from some other source population more numerous than the one displayed in the distributions of Fig. 12. An easy way of envisaging this is to think of radio sources of lower luminosity, and therefore more numerous, which become brighter by Doppler boosting when oriented at small angles to the line of sight. In a flux limited sample like ours, Doppler boosting would introduce a bias in the source orientation which could increase the fraction of sources at small θ, compared to the random expectation. The number of foreshortened sources would therefore be larger than in a randomly oriented sample and would account for most of the observed peak.

In order to evaluate the orientation bias due to Doppler boosting, we follow a similar analysis to that of Browne and Perley (1986). Assume that Doppler boosting increases the luminosity of a source sub-component of spectral index α having bulk velocity $v = \beta c$ at an angle θ to the line of sight, by the factor $(1 - \beta \cos \theta)^{-(n+\alpha)}$ with respect to the luminosity at 90° orientation (n is taken equal 2 for a jet and 3 for a radio lobe). If at 90° a moving radio component accounts for a fraction R of the total flux density S of the source, then at an angle θ the observed source flux density will be:

$$S'(\theta) = S((1 - R) + R(1 - \beta \cos \theta)^{-(n+\alpha)})$$

Sources in the sample at any angle θ will actually be sources boosted according to the above expression and therefore picked from a lower flux density interval and thus more numerous according to the $\log N - \log S$ relation. The smaller θ is, the more numerous are the sources which, due to boosting, will exceed the sample flux limit. If δ (assumed = 1.7) is the slope of the $\log N - \log S$ relation, S'_1 the sample limit and $S_1(\theta)$ the unboosted flux density, then the probability of finding a source at an angle θ will be given by:

$$P'(\theta) \propto \sin \theta \, (S'_1/S_1)^{\delta}$$

instead of $P(\theta) \alpha \sin \theta$.

We will now examine which radio components could be boosted enough to raise the total flux density of the source above the limit of our sample and whether it is possible to justify the large number of CSS's merely by this mechanism, i.e. projection and boosting of some part of the flux of larger size ($\gtrsim 20$ kpc) sources. We start with a diameter distribution which has no intrinsic excess at small diameters. With a careful choice of β for the various source components (core, lobes, jets) and using the above expression for $P'(\theta)$, it could be possible, in principle, to reproduce the observed diameter distribution peaked at $\lesssim 10$ kpc.

Roughly speaking, in order to achieve this result, one should increase the number of sources oriented at $\approx 20°$–$30°$ by a factor 4 to 5, and this, according to the above relation, requires that the flux density of the whole source is increased by a factor ≈ 3.

The question is whether the values of β required to reproduce the observed number of CSS's in this way is also satisfactory in other respects; e.g. the derived core/total luminosity, core/jet

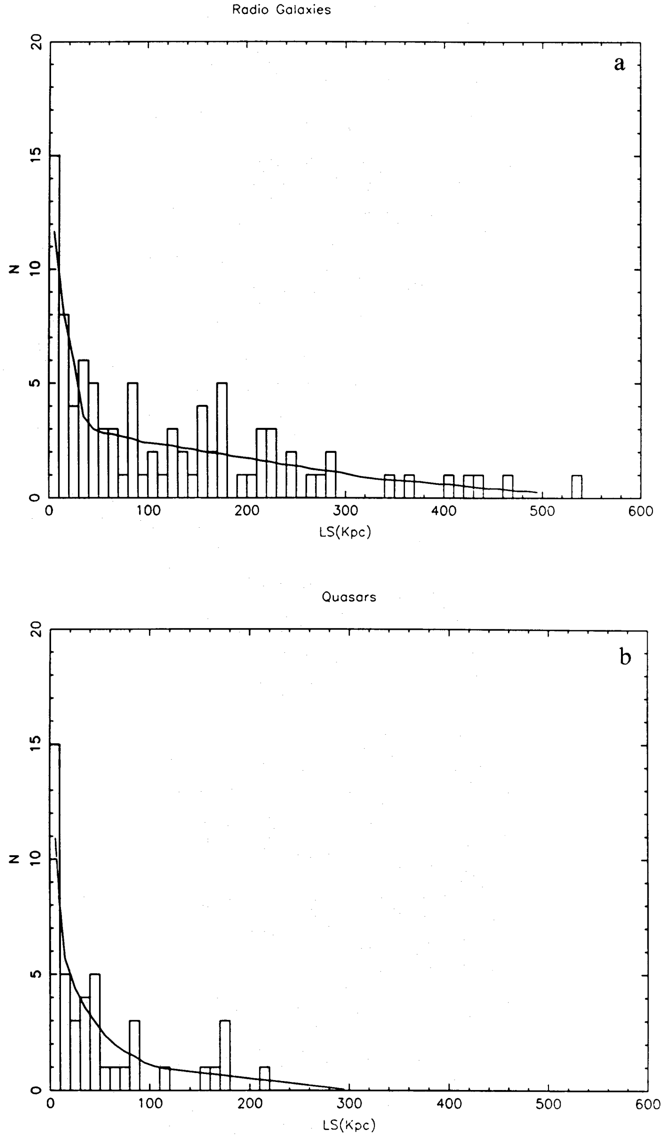

Fig. 12a and b. Distribution of projected Linear Sizes for radio galaxies and quasars of the 3 CR + PW sample (see Sect. 2), with $\log P_{178} > 26.5$. The continuous lines represent models for the intrinsic size distributions discussed in Sect. 4.1

luminosity, jet/total luminosity have to be consistent with the observed ones.

a) Boosted core emission

The cores of the CSS's account only for a tiny fraction of the CSS luminosity (Sect. 3b), and furthermore this fraction is totally consistent with that of large sources with radio luminosity comparable to that of CSS's. Therefore *boosting of the core radio luminosity alone is insufficient.*

b) Boosted lobe emission

This explanation is not appliable to quasars, since their lobes are not the major contributors to their luminosity.

On the contrary, boosting of the lobe luminosity is the only possibility for radio galaxies, since the lobes virtually account for their whole luminosity.

The lobe luminosity is certainly not significantly boosted in the large doubles (Longair and Riley, 1979; Katgert – Merkelijn et al., 1980) which, by projection should generate the CSS's. This is also true in our own data. In order to explain the peak in the size distribution of CSS radio galaxies by projection and boosting of the lobes, values of $\beta \gtrsim 0.5$ are required. However this would introduce a strong asymmetry in the observed lobe flux densities, with a median ratio between the two lobes $\gtrsim 20$, in contrast to the rather symmetric distribution observed for both Doubles and Triples, which has a median value ≈ 1.3 (Fig. 6). The distribution of flux density ratios excludes lobe velocities higher than 0.2c. Furthermore, in case of Doppler effects we would expect a relation between flux ratio and arm ratio of the lobes of the type $(S_1/S_2) = (d_1/d_2)^{3+\alpha}$. Such a relation is not consistent with the data in Fig. 8. Thus *boosting of the lobe luminosity of double sources is unlikely* to explain the size distribution of CSS's.

We may add another argument against the existence of the strong projection effects required for Doppler boosting of the lobes: the ratio of component transverse size to separation for the lobes of Doubles is ≈ 0.1, as is seen in the large doubles. Projection should make this ratio larger by at least a factor of 2.

This conclusion depends, of course, on the assumption that our Doubles are D 1 type and not Triples in which one of the lobes is missing (maybe due to Doppler effects) and the central component mistakenly considered a lobe. However the similarity of properties with lobes of Triples (Sect. 3.1), for which the above point does not apply, makes this argument implausible. On the other hand could the unresolved sources of our sample be *disembodied components* of doubles moving relativistically? This question must await for an answer from higher resolution observations. In any case, the unresolved sources are not numerous enough to explain the CSS excess.

c) Boosted jet emission

Another component of radio emission which could be boosted is the large scale jet emission. We have no proof that the kpc jet velocity is relativistic, although this has been invoked to explain the asymmetry of jets in high luminosity sources (see, e.g. Scheuer, 1987; Bridle, 1989).

This explanation is clearly not tenable for radio galaxies, which show little jet emission and whose luminosity is largely accounted for by the radio lobes.

The situation is less clear for quasars, where emission by the jet accounts for a large fraction of the observed luminosity. For the sake of argument, we tentatively identify a boosted jet as the component which increases the source luminosity to the required value. In order to evaluate the bulk Lorentz factor required for the Doppler boosting, the ratio of jet luminosity to total luminosity (R_j) for large size quasars (assumed to be at large angles to the line of sight) must be known. This parameter is, at present, rather uncertain. No reliable estimate of it can be found in the literature (the data available are very scarce; authors do not generally quote luminosities of jets). From the plot of jet luminosity versus extended emission luminosity for 98 radio sources shown in Bridle (1989) (neither a complete nor a representative sample), we estimate a median $R_\mathrm{j} \approx 0.1$ at most for large quasars. A value around 0.05 would seem more realistic. Taking $R_\mathrm{j} \approx 0.1$ (at 90°) with $\beta = 0.85$ and 0.9, we can reproduce, with the method described above, $\approx 50\%$ and $\approx 100\%$ respectively of the CSS peak, by projection and boosting of the jets in larger sources. However, for both values of β, the core-to-total luminosity median ratio would be $\gtrsim 0.1$, which is $\gtrsim 2\sigma$ above the observed value (Sect. 3.2) and for $\beta = 0.9$ the expected median ratio of jet to lobe luminosity would be ≈ 8, i.e. higher than observed in our data (≈ 2).

If we take R_j (at 90°) to be ≈ 0.05, there is no way to reproduce the peak in the CSS size distribution by projection, without exceeding the observed core-to-total luminosity and jet-to-total luminosity ratio by even greater margins.

Furthermore major projection effects in Triples are unlikely on the basis of the low median value of the transverse size to separation ratio of the lobes (≈ 0.1). Therefore, although the situation for CSS quasars is not as clear as for radio galaxies, *we conclude that it is more likely that they also are primarily intrinsically small objects.* Further work has to be done to clarify this point. In particular the cores and central components of CSS's need study, and, in addition, the distribution of jet luminosities in large size quasars should be determined more reliably.

Our present conclusion is therefore that *CSS's, as a class, consist mainly of a population of intrinsically small radio sources,* likely to be randomly oriented, plus a small minority of intrinsically larger ones ($\lesssim 25\%$) shortened by projection effects. The latter could be found amongst those with fat lobes and strong cores, and perhaps strong jets or those suspected of superluminal motion (e.g. 3C 216, Barthel et al., 1989).

4.2. CCS's and the Barthel unified model

We have attempted to model the relative proportions and structural radio properties of CSS quasars and radio galaxies, on the basis of the Barthel (1989) suggestion that the two classes of object derive from the same population, but are observed at different angles to the line of sight.

The size distribution and relative proportions of quasars and radio galaxies in Fig. 12 are consistent with random extraction from the same linear size distribution, at $\theta \lesssim$ and $\gtrsim 45°$ respectively. This is not surprising since $\approx 40\%$ of the sources of Fig. 12 are common to the sample used by Barthel.

One consequence of the Barthel model is that Doppler boosting should play a role in CSS quasars. However any Doppler boosting [of the jets] has to be modest (see Sect. 4.1) since this would cause too many faint sources to be raised above the flux density limit of the sample, even at moderate angles to the line of sight. This in turn would increase the proportion of smaller linear size sources (quasars) compared to larger ones (radio galaxies). For $R_j \gtrsim 0.05$, and a random distribution of projection angles, values of $\beta > 0.75$ for the jets are excluded for this reason. On the other hand, $R_j \gtrsim 0.05$ and $\beta \gtrsim 0.75$ would be required to explain the high jet luminosity of CSS quasars (Sect. 4.1), compared to that of their radio galaxy counterparts. It is hard to reconcile these conflicting requirements.

It may also not be easy to reconcile the considerable distortion found in CSS quasars with the moderate projection effects in the Barthel model, for $\theta \lesssim 45°$, if typical intrinsic distortions of less than 10° in the CSS radio galaxies are found to be the rule.

Furthermore the ratio of lobe size to total extent should be approximately twice as large in CSS quasars than in radio galaxies, an effect that we do not find in our data.

4.3. *Physical parameters*

Physical parameters for the radio source components have been computed assuming equipartition and using standard formulae (Pacholczyk, 1970). Proton and electron energies have been assumed equal, with a filling factor of unity; ellipsoidal geometry for the components and an average spectral index of 0.8 extending from 10 MHz to 100 GHz have been adopted. No corrections have been introduced for beaming due to relativistic motion (see Sects. 4.1 and 4.2).

Typical values obtained for minimum total energy ($U_{\min}$), minimum energy density ($u_{\min}$) and equipartition magnetic field ($H_{\rm eq}$) are:

$$\begin{aligned} U_{\min} &\approx 10^{56}\text{–}10^{57}\ \text{erg} \\ u_{\min} &\approx 10^{-7}\text{–}10^{-8}\ \text{erg cm}^{-3}\ \text{in the lobes}, \\ &\approx 10^{-6}\text{–}10^{-7}\ \qquad \text{in the hot spots}, \\ H_{\rm eq} &\approx 10^{-4}\text{–}10^{-3}\ \text{G}. \end{aligned}$$

The central components of Triples are generally characterized by internal energy densities higher than in the lobes, as they have larger luminosities and smaller sizes.

For comparison, the minimum energies stored in the lobes of large radio galaxies and quasars of similar radio power are 2–3 orders of magnitude larger and the corresponding energy densities are 3–4 orders of magnitude lower.

It is worth comparing the non-thermal pressure inside the CSS lobes with the pressure of the outer ambient medium. It is likely that the radio lobes are co-spatial with the narrow-line region (NLR) in the parent optical object. The current picture of the NLR is that of a dense ($\approx 10^4\,\text{cm}^{-3}$) clumpy and tepid ($10^4$ K) gas producing the lines, mixed with a more uniform, tenuous ($1\,\text{cm}^{-3}$) and hotter (10^7 K) gas, detectable by its X-ray emission (Canizares et al., 1987). The non-thermal pressure of the radio components is generally higher by one or two orders of magnitude than the thermal pressure of the diffuse gas component, which is the one likely to be interacting mostly with the radio components. Therefore lobe confinement by static pressure is unlikely.

Pressure equilibrium can be achieved by ram-pressure. Lobe velocities, v_l, can be estimated from the relation:

$$m_p n_e v_l^2 \approx p_{\min} \approx 0.5\, u_{\min}$$

where n_e is the external gas density and m_p the proton mass. If ϕ is the filling factor of the dense component ($\approx 10^{-3}$) and L the size of the NLR, interaction will occur for a path length $L(1-\phi) \approx L$ with the diffuse component and for ϕL with the denser one. Owing to the density ratio, the advance speeds in the two cases will be in a ratio of 100 to 1 and the times spent in travelling the two path lengths will be L/v_l (diffuse component) and $100(L/v_l)\,\phi$ (dense, clumpy component), where v_l is the velocity through the diffuse component. Therefore, if $\phi \approx 10^{-3}$ the travel time across the NLR will be determined by interactions with the diffuse component. If instead $\phi \approx 0.01$, the time-scale of the interaction with the dense component would be comparable to that with the diffuse medium and the travel time of radio plasmoids would be doubled. Furthermore, if the interaction with the dense clouds is limited to a few clouds, asymmetries may result in the two sides of the radio sources, which may explain the somewhat broad distribution (Sect. 3.1) of component distances from the core, as well as the observed complex structures.

We note that, if the NLR extends to $\gtrsim 10$ kpc and ϕ is not $\ll 10^{-3}$, a large luminosity in the emission lines is to be expected.

Assuming a particle density $n_{\rm hot} \approx 1\,\text{cm}^{-3}$ for the hot diffuse component and $p_{\min} \gtrsim 10^{-7}$ dyn cm^{-2} in the *hot spots*, the average advance speed of the lobes through the hot and diffuse component is found to be:

$$v_l \gtrsim 10^8\,\text{cm sec}^{-1}$$

This estimate of the speed of advance of the lobes indicates typical dynamical time scales for CSS's of $\approx 3\ 10^6$ yr.

4.4. *Radio source evolution*

In Sect. 4.1 we concluded that most CSS's are truly small objects. How do they relate to the general population of radio sources, and in particular are they an early stage in the evolution of radio sources, as suggested by Mutel and Phillips (1988) for radio galaxies? Based on the continuity of the properties of double sources, these authors proposed that Compact Doubles evolve into Double CSS's, which in turn evolve into classical FR II sources.

We examine now some of the implications of this scenario. The starting point is again the size distribution of Fig. 12. If all radio sources with similar initial conditions undergo a similar evolution in a similar environment and do not change their radio luminosity greatly during their life, the number, ΔN, of objects in each bin of given linear size, $\Delta(LS)$, is proportional to the time interval, Δt, spent in this size bin. The advance speed can be then evaluated as: $v \approx \Delta(LS)/\Delta t \propto \Delta(LS)/\Delta N$. If, during the evolution (and size increase) the source luminosity changes, the frequency distribution as a function of linear size has to be determined at intervals of corresponding luminosity. We argue, in the following, that this is not the case.

Information on source luminosity evolution is obtainable only on the basis of a reliable source evolution model. We adopt a class of model similar to that of Scheuer (1974), which assumes a constant supply of energy and momentum to the lobes via symmetric beams which propagate in a gaseous atmosphere of decreasing density (the decreasing density is the only difference from the original Scheuer model). A similar revision of the Scheuer model was carried out by Carvahlo (1985). The luminosity change in the course of the source expansion depends on a combination of the external density gradient and jet geometry. For a constant external density (as expected within a few kpc from the nucleus) and a conical jet, the luminosity is expected to increase as the square root of the linear size. At a distance of some kpc from the centre, however, the external density is likely to start decreasing. In this case the luminosity may decrease too. A full discussion of this model is beyond the scope of this paper, but we mention that, for reasonable parameters, in particular for an external density $\propto$ (distance)$^{-1.5}$, the luminosity can be expected to change by only half an order of magnitude in the two decades of linear size from ≈ 1 to a few hundred kpc. We therefore make no distinction between different luminosities and use Fig. 12 as it stands [note that Carvahlo derives a different behaviour for the radio luminosity evolution, as a consequence of his assumption that the external density is $\propto$ (distance)$^{-4}$; we consider however this assumption rather unrealistic].

From Fig. 12, and accounting for the few expected projections, it is clear that the time taken by a source to increase its size to 10 kpc is $\approx 15\%$ of the maximum life time for radio galaxies, and $\approx 20\%$ for quasars. If the maximum life time for all radio sources is $\approx 10^{7.5}$ yr (from spectral studies of radio galaxies: e.g. Alexander and Leahy, 1987) the ages for CSS radio galaxies are $\approx 5\ 10^6$ yr and therefore advance speeds cannot be larger than $2\ 10^8$ cm sec^{-1}, not inconsistent with the results of Sect. 4.3. Furthermore the size distribution also implies that the advance speed of the lobes increases with increasing size by a factor from ≈ 5–10 in the range of 10 to 100 kpc. This is possible in a decreasing density atmosphere accompanied by some recollimation of the fueling beams.

A similar scheme could apply both to radio galaxies and quasars. The main differences between the two populations are: (i) the larger fractional luminosity of the jets (central components) and (ii) a higher level of distortion in quasars. This may be seen as evidence, in quasars, of a denser and more turbulent medium (velocities up to a few thousand km sec^{-1} and larger filling factors) over scales of a few kpc,.which strongly perturbs the radio source structure and causes the jets to flare and become bright. Only when the radio emitting material emerges from such a region do the lobes start to be formed and the radio morphology becomes more regular.

An alternative view could be that CSS's are not related to the large sources, but are a separate class never able to grow to larger sizes, perhaps because they are trapped in a medium which is too dense, as is suggested to be the case for Seyferts (Wilson, 1983). In this case we would expect the properties of the interstellar medium to differ between large FR II radio sources and CSS's, the latter being characterized by denser and more turbulet gas. Information on this point is not available to our knowledge.

In view of the continuity of radio properties between CSS's and larger sources, as well as the fact that radio galaxies and quasars of large size do exist, in contrast to Seyferts, we favour the evolutionary scenario.

One should add that CSS's require, any way, a dense and dynamically important medium. Since they are a population which shows up at redshifts greater than 0.2, this points to a significant change in the properties of the interstellar medium at $z \approx 0.2$.

5. Conclusions

The main results of this paper are:

(a) By combining two samples from the 3 CR and PW we have constructed a representative sample of CSS's, for which data on radio structure are available for a statistical study.

(b) CSS galaxies and quasars have different morphological properties. The galaxies generally are double, with cores and jets weak, if they are present. CSS quasars have stronger cores (typically by a factor 10) and often are dominated by bright jets. These differences mimic those found in larger size sources of the two types.

(c) We have examined the possibility that CSS's are the result of projection effects of larger sources and conclude that this is unlikely. They must be mostly intrinsically small objects, plus a minority ($\lesssim 25\%$) of larger ones shortened by projection. The latter could be found amongst those with fat lobes and strong cores, and perhaps strong jets or those suspected of superluminal motion.

(d) CSS's are a large fraction (≈ 15–20%) of the powerful sources found at high redshift ($z > 0.2$). Their fraction is almost constant with redshift. We note, in contrast, that amongst the most powerful nearby ($z < 0.2$) radio galaxies, CSS's are relatively rare.

(e) On the assumption that CSS's are not a separate class, but represent an early stage of radio source evolution, they must spend a relatively long time, $\approx 5\ 10^6$ yr, in this phase, based on their rate of occurrence. This is consistent with arguments on the dynamics of radio plasmoids which have to drill their way through a dense, possibly clumpy, gaseous atmosphere extending out to ≈ 10 kpc from the centre. The speed of advance of the radio lobes through the NLR, must be relatively slow ($\approx 2\ 10^8$ cm sec^{-1}) in order to be consistent with the duration of this phase of evolution. There should be a gradual increase in speed when the lobes emerge from the dense central region.

(f) Although the size distribution and relative proportions of CSS quasars and radio galaxies are accounted for reasonably well by the Barthel unified model, the differences in radio morphology are not explained.

(g) It is important to collect as many data as possible on the ambient gas, which is likely to be the dominant influence on CSS properties, in order to verify the above ideas. We consider observations in the X-ray band and in the optical emission lines to be particularly relevant, since these probe hot/diffuse and dense/clumpy media respectively. This is important in order to distinguish between the evolutionary scenario which connects CSS's and large FR II radio sources and the one which, by analogy with Seyferts, indicates that CSS's are a separate class.

(h) It will be important to extend the statistical analysis to the unresolved CSS's in our sample to determine the properties of radio galaxies and quasars with sizes $\lesssim 0.4$ kpc and bridge the gap with the Compact Doubles of Phillips and Mutel. This requires studying with the appropriate angular resolution ($\lesssim 20$ mas) a representative sample, like that in Table 1, with sizes $< 0''.1$.

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