Mon. Not. R. astr. Soc. (1976) **176**, 571–588.

COMPACT FEATURES IN A COMPLETE SAMPLE OF RADIO SOURCES

A. C. S. Readhead and A. Hewish

Mullard Radio Astronomy Observatory, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE

(Received 1976 March 25)

SUMMARY

The occurrence of compact features in a complete sample of 3CR sources, as revealed by interplanetary scintillation at 81·5 MHz, is described. It is found that ' hot spots ' having a typical size of 5 kpc commonly exist in sources of high luminosity. Hot spots account for at least half the total radiation in many high luminosity sources when the overall extent of the source is around 100 kpc. Sources having an extent exceeding about 200 kpc do not usually contain prominent hot spots and are of lower luminosity. The significance of these facts is discussed in relation to the beam model of extragalactic radio sources.

1. INTRODUCTION

A radio source which exhibits strong interplanetary scintillation must contain one or more compact features, the angular size of which cannot exceed about 1″–2″ in *any* direction. This is true even for a one-dimensional line source. Scintillation therefore provides a method of studying radio source components whose size, even at the greatest distances, is less than about 10 kpc. Surveys to detect such features using the scintillation method have been carried out at frequencies in the range 81·5–611 MHz (Cohen, Gundermann & Harris 1967; Little & Hewish 1968; Harris & Hardebeck 1969; Burnell 1972; Harris 1973; Readhead & Hewish 1974; Bhandari, Ananthakrishnan & Pramesh Rao 1974). These have shown that (i) more than half of the 3C sources contain compact features, (ii) quasars generally have more pronounced compact features than radio galaxies, (iii) there is a high correlation between scintillation and redshift.

A survey at 81·5 MHz has recently provided scintillation data on 1500 sources (Readhead & Hewish 1974) and in this paper we discuss the compact features in a complete sample of 3CR sources, roughly 70 per cent of which are optically identified. A study of this sample by Readhead & Longair (1975) has shown that the correlation between scintillation and redshift cannot be explained by geometrical effects alone as suggested by Harris (1973). Sources which contain a large fraction of their total flux density in components of small *physical* size are characterized by a high radio luminosity.

We first describe the occurrence of compact features in radio galaxies, quasars and unidentified sources. We then present the angular and linear size distributions of the compact features and discuss them in relation to the overall source morphology revealed by other measurements.

2. THE OCCURRENCE OF COMPACT FEATURES

2.1 *The source sample*

The complete sample of 3CR sources (Bennett 1962) is confined to the region $\delta > 10°$ and galactic latitude $|b| > 10°$ and contains 199 sources. A few sources in this sample have been excluded from the present analysis for one of the following reasons, (a) near the galactic centre, interstellar scattering can cause a significant increase in the apparent angular size unless $|b| > 20°$, (b) uncertainty in the total flux density arising from a large angular extent, (c) confusion in the 81·5-MHz survey. The remaining sample contains 181 sources.

2.2 *The scintillation data*

A full account of the scintillation method has been given by Readhead & Hewish (1974). During the survey each source was observed over a wide range of solar elongation and the scintillation index was plotted as a function of elongation. The resulting curve has a slope which depends upon the angular size of the source. In the calculations it is assumed that the sources have a circularly-symmetrical gaussian distribution of brightness, but the results are not sensitive to the model adopted.

The value of the angular diameter obtained depends upon a model of the interplanetary plasma, and that adopted by Readhead (1971) was based upon observations of the spatial correlation of the scintillation diffraction pattern using spaced receivers. It is sometimes thought that the scintillation method provides only a crude estimate of angular size owing to factors such as day-to-day variations of the solar plasma. Our experience has shown, however, that the curves of scintillation versus elongation are repeated from year to year with excellent agreement. The time-averaged properties of the solar plasma are remarkably constant and, at distances exceeding 0·5 AU which are relevant to the present survey, there is little evidence for any variation due to the solar cycle. The lack of solar cycle effects has also been noted in spacecraft measurements.

There may be small systematic errors arising from inaccuracies in the calibration curves due to the adoption of an incorrect model of the solar plasma. These may, in principle, be checked by comparing scintillation results with other measurements. Unfortunately few data of sufficient angular resolution at metre wavelengths exist, but our results for 3C 48 and 3C 144 are in good agreement with *VLBI* data. Another check can be made by comparison with source maps obtained with the 5-km telescope. Combining both methods gives confidence that any systematic errors are less than about 25 per cent over the range 0″·3–1″·5. These checks will be described more fully elsewhere.

When the angular size has been measured it is possible to determine the fraction, R, of the total flux density which is contained in the compact feature. If a source contains several scintillating components spaced by at least 1″, the derived value of R underestimates the flux contained in the compact components, and the angular size is a weighted average of the values of the individual components (Hewish & Readhead 1976). If the components are contained within an overall angular size of less than 1″, the derived angular size will tend to the overall size of the group.

2.3 *The flux density in compact features*

It is convenient to classify sources as strong, intermediate or weak scintillators when the fraction R of the total flux in the scintillating component falls in the

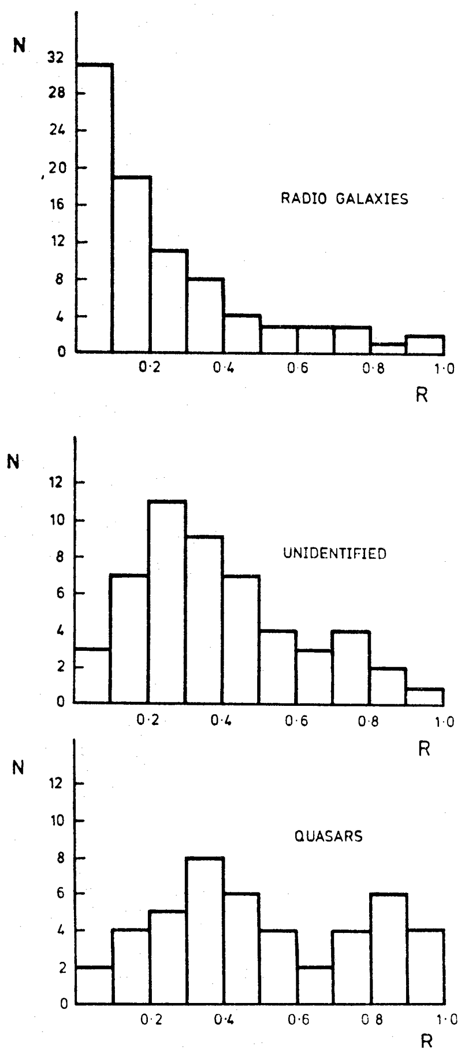

FIG. 1. *The distribution of the fraction* (R) *of the flux density in hot spots.*

TABLE I

		Radio galaxies	Unidentified sources	Quasars
$R \leqslant 0{\cdot}25$	Weak scintillators	55	15	7
$0{\cdot}25 < R < 0{\cdot}4$	Intermediate	12	15	11
$R \geqslant 0{\cdot}4$	Strong scintillators	18	21	27

ranges $0{\cdot}4 \leqslant R$, $0{\cdot}25 < R < 0{\cdot}4$, $R \leqslant 0{\cdot}25$ respectively. The distributions of R for the 181 sources are shown in Fig. 1 separately for radio galaxies, unidentified sources and quasars. Those sources for which we have only an upper limit on R (e.g. $R \leqslant 0{\cdot}2$) have been evenly distributed in the bins below this limit. There are relatively few such cases, and they have little effect on the overall shapes of the histograms.

The histograms clearly indicate, as has been noted before, that radio galaxies are generally weak scintillators whereas quasars are generally strong scintillators. The numbers of sources in each class are shown in Table I. The unidentified sources have a distribution similar to that of quasars. This would, however, be consistent with the unidentified sources being radio galaxies since, if they have the linear dimensions characteristic of radio galaxies (but are more distant) we would

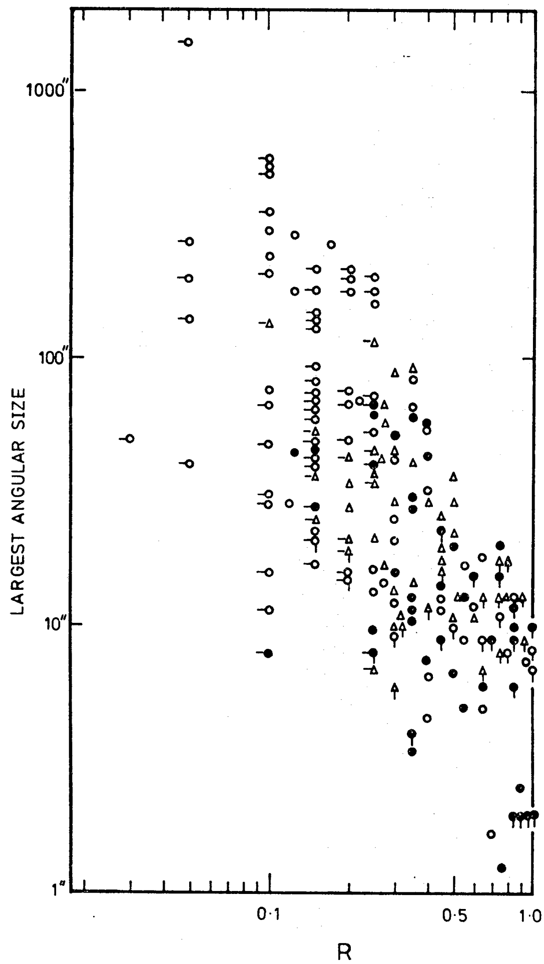

FIG. 2. *The fraction (R) of the flux density in hot spots related to overall angular size.* ○ *Radio galaxies;* △ *unidentified sources;* ● *quasars.*

expect them to scintillate more strongly. However, we cannot rule out the possibility that they are mainly quasars by a similar argument, since the identified quasars range in redshift from about 0·3 to 2·0 and in this range the apparent angular size is almost independent of redshift on most cosmological models.

It is also of interest to investigate the extent to which scintillation is related to the overall angular size of radio sources. We shall return to this topic later when discussing the source morphology and the physical sizes of compact components. In Fig. 2 the values of R are plotted against the largest angular size of individual sources derived independently. Fig. 2 shows a strong correlation between R and largest angular size. In particular, apart from 3C 236, sources for which $R > 0{\cdot}5$ have an overall angular extent which never exceeds 20″.

Finally we present the relation between R and the absolute luminosity of sources for which redshifts are available. The distribution is shown in Fig. 3 from which it is clear that strong scintillators are also sources of high luminosity. This result has been discussed in detail by Readhead & Longair (1975) who have shown that it cannot be explained by the fact that the more distant sources subtend a smaller angle and are therefore more likely to scintillate. Compact features of the type found in sources of high luminosity are rarely a prominent feature of low-luminosity sources.

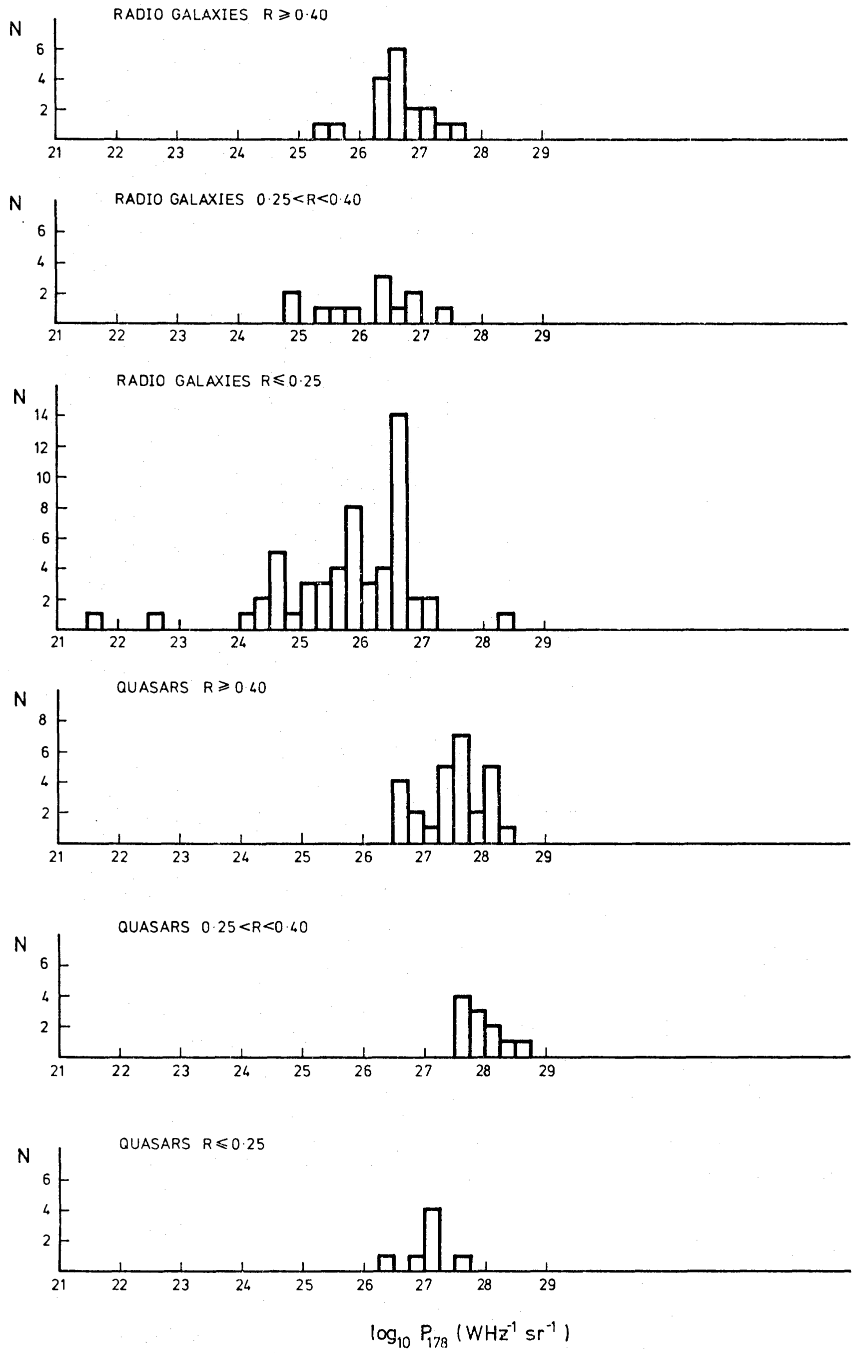

FIG. 3. *The luminosity distributions of weak, intermediate and strong scintillators.*

3. THE ANGULAR SIZES OF COMPACT FEATURES

The accuracy with which the angular size of a scintillating source may be determined depends upon the flux density of the compact feature. For a discussion of the distribution of angular sizes we consider a limited sample of 49 sources for which the measurements are accurate to ±0″·1–0″·2, all of which sources are intermediate or strong scintillators.

The angular diameter distributions for radio galaxies, quasars and unidentified sources are shown in Fig. 4, where θ refers to the diameter (to e^{-1}) of a circularly-symmetrical Gaussian source.

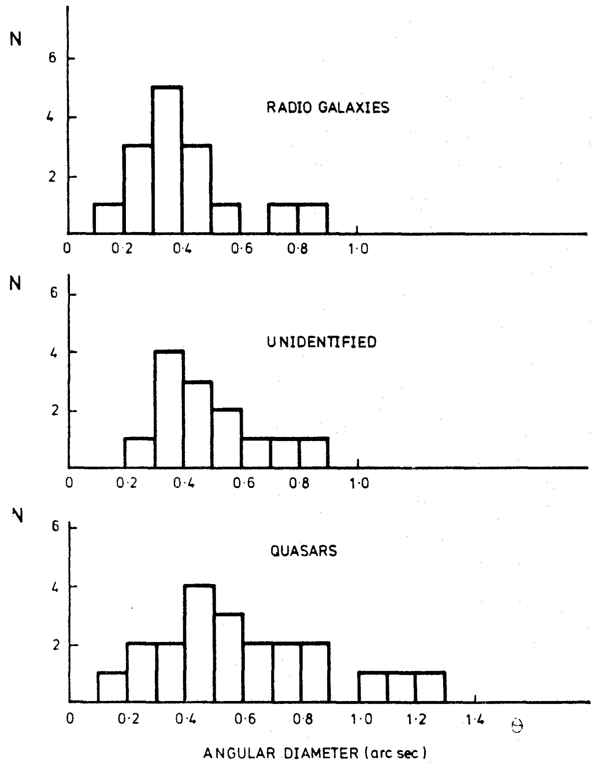

FIG. 4. *The distribution of angular size of hot spots.*

There is a marked similarity in these distributions but both the radio galaxies and the unidentified sources peak at a slightly lower value of angular diameter than do the quasars. The quasar distribution also appears to be broader and to extend to larger values of angular diameter than the other two classes. The numbers of sources in all three classes are small but, if we follow the suggestions of various authors (e.g. Rees 1972) that most of the unidentified sources are radio galaxies, combine the distributions for radio galaxies and unidentified sources, and then compare this composite distribution with the distribution for quasars, the differences are more striking.

We have seen that the quasars are more distant and more luminous than the radio galaxies, thus the implication of Fig. 4 is that the average angular size of hot spots increases with luminosity. This point is discussed again in Section 4.2.

The most striking feature of Fig. 4 is the cutoff in the number of small sources ($\theta \lesssim 0''\cdot 35$). The similarity in this cutoff for the three samples is surprising and suggests that instrumental effects, e.g. the bandwidth and time constant of the receiver; observational selection; source broadening due to interstellar scattering (Harris, Zeissig & Lovelace 1970; Readhead & Hewish 1972) or some other spurious effect, may be at work.

For sources of a given flux density the scintillation index increases steadily with decrease of the angular size until the resolution limit is reached. The latter is set, at 81·5 MHz, by the bandwidth and time constant of the receiver (1 MHz and $0^{s}\cdot 1$), whose combined effect limits the maximum resolution to $0''\cdot 07$.

Hence there is strong observational selection which favours the detection of sources having the smallest angular size. Since the observed distributions all exhibit a maximum near $0''.4$, this cannot be explained by selection arising from the scintillation technique.

Another factor to be considered is source broadening due to interstellar or intergalactic scattering. This was checked by comparing angular sizes derived by scintillation at different wavelengths, since angular scattering due to a plasma varies as λ^2. Additional scintillation measurements at 151 MHz showed that the 81·5-MHz diameters were not significantly increased by interstellar scattering for sources at galactic latitudes $|b| > 10°$ (Duffett-Smith & Readhead 1976). This shows that interstellar scattering is not large enough to explain the observed distributions, although it is clearly an important consideration for high resolution measurements at low frequencies. We can similarly rule out the possibility of significant intergalactic scattering along the line of sight to these sources.

A possibility, suggested by Swarup & Bhandari (1976), is that blending may occur when a source contains components having sizes of, say, $0''.2$ and $2''$, such that the measurements refer to a weighted mean of these values. This point has been considered in detail elsewhere (Hewish & Readhead 1976), where it is shown that confusion effects only become important when R is not large. In most cases R is too large for confusion effects to matter. The geometrical scaling of source structure envisaged by Swarup & Bhandari is not supported by the scintillation observations. An independent confirmation of this conclusion can be obtained, in a few cases, by direct mapping and interferometric methods, and such examples will be mentioned presently.

A final possible explanation of the lack of sources in the range $0''.2$–$0''.3$ is that they are self-absorbed. If synchrotron self-absorption set in at, say, 150 MHz so as to remove sources from the sample at 81·5 MHz, then the typical sources, which have a surface brightness of about $15/(0.25)^2$ Jy arcsec^{-2}, would require magnetic fields of 0·1–1·0 G (Scheuer & Williams 1968). Such high fields seem very unlikely, as the equipartition fields are typically 10^{-4} G. The radio spectra also provide evidence against self-absorption since very few 3C sources exhibit low-frequency cutoffs below 178 MHz.

No other spurious effects have been envisaged and we therefore believe that the angular size distribution is real. The deficit of identified sources near the resolution limit is particularly significant at the largest redshifts. This point has been discussed in terms of possible cosmological effects by Hewish, Readhead & Duffett-Smith (1974), and we return to it in Section 4.2.

4. COMPACT FEATURES AND THE SOURCE MORPHOLOGY

4.1 *The location of compact features*

Radio sources of moderate or high luminosity generally consist of two main components situated on opposite sides of a central optical source which is also frequently a radio emitter. The outer components typically have steep radio spectra (with spectral index $\alpha \gtrsim 0.6$), whereas the central components have flat or complex spectra.

When such double sources are close enough to be mapped in detail, it is often found that they exhibit a characteristic structure in which ' hot spots ' are embedded in the outer components (see Fig. 8). The hot spots are regions of high surface brightness having a size of a few kpc and they are usually situated near the outer extremities of the larger components. The latter have typical dimensions of

20–200 kpc and are of much lower surface brightness (Hargrave & Ryle 1974; Fanaroff & Riley 1974; Pooley & Henbest 1974). It is interesting to note that components of size exceeding 20 kpc can never produce a large scintillation index, even at the largest redshifts. This follows from the angular size versus redshift relation for standard cosmological models. Hot spots, on the other hand, like those in Cygnus will scintillate strongly for $z > 0.1$. It is thus highly likely that the compact features revealed by scintillation are similar to the hot spots which have been found in Cygnus A.

Since many radio sources are known to contain central cores of very small angular size it is possible that these might also contribute to the observed scintillation. Pooley & Henbest (1974) have, however, shown that at 5 GHz the central cores usually account for less than 40 per cent of the total flux density in the 3CR sample, and it is also well known that the cores have much flatter spectra than the outer components. Therefore central cores are unlikely to contribute significantly to the scintillation at 81·5 MHz. In order to produce appreciable scintillation, a core must have a flux density comparable to that of the outer components and this implies that the spectrum of the core would have to steepen considerably between 5 GHz and 81·5 MHz. This would be evident as a steepening of the total source spectrum at low frequencies. Examination of the spectra of 66 strong scintillators reveals only three cases (3C 153, 3C 254, 3C 280) for which the low-frequency spectra might be sufficiently steep, and it follows that the scintillating features must generally be associated with the outer components of radio galaxies. In fewer than 10 per cent of the strongly-scintillating sources the scintillating component may be close to the optical source, e.g. 3C 48, 3C 147, 3C 286, 3C 287. These sources all have $R \geqslant 0.85$, and they are all known to be compact with overall sizes less than or comparable to a few arcsec.

4.2 *The physical sizes of the compact features*

Since many of the scintillating sources have large redshifts ($z > 0.5$), the linear sizes deduced from the angular diameters will depend significantly upon the cosmological model adopted. It has already been shown that there is a tendency for the mean angular size to increase at the largest redshifts (Hewish *et al.* 1974) and the larger source sample described in this paper reinforces our earlier result. This effect can be explained either by adopting a sufficiently high value of the deceleration parameter q_0, or by assuming that the linear size increases with z. For convenience we here adopt an Einstein–de Sitter model, $q_0 = \frac{1}{2}$, with $H = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

The distribution of linear diameters of hot spots for intermediate and strongly scintillating sources is shown in Fig. 5(a). The mean value of roughly 3·5 kpc is similar to that of the hot spots which have been found in the outer components of Cygnus A (Hargrave & Ryle 1974). Since we have shown that the scintillating components generally reside in the outer components of double sources, it follows that hot spots like those in Cygnus A must be common features of powerful radio sources.

Fig. 5(b) shows the relation between the size and absolute luminosity of the scintillating components themselves. At high luminosities ($P_{178} > 10^{27} \text{ W Hz}^{-1} \text{ sr}^{-1}$) it is seen that the sizes are scattered over the range 1–10 kpc with a median value of 5·5 kpc. The less luminous sources ($P_{178} < 10^{27} \text{ W Hz}^{-1} \text{ sr}^{-1}$) have a median value of 2 kpc. There is thus a tendency for hot spots of the highest luminosity

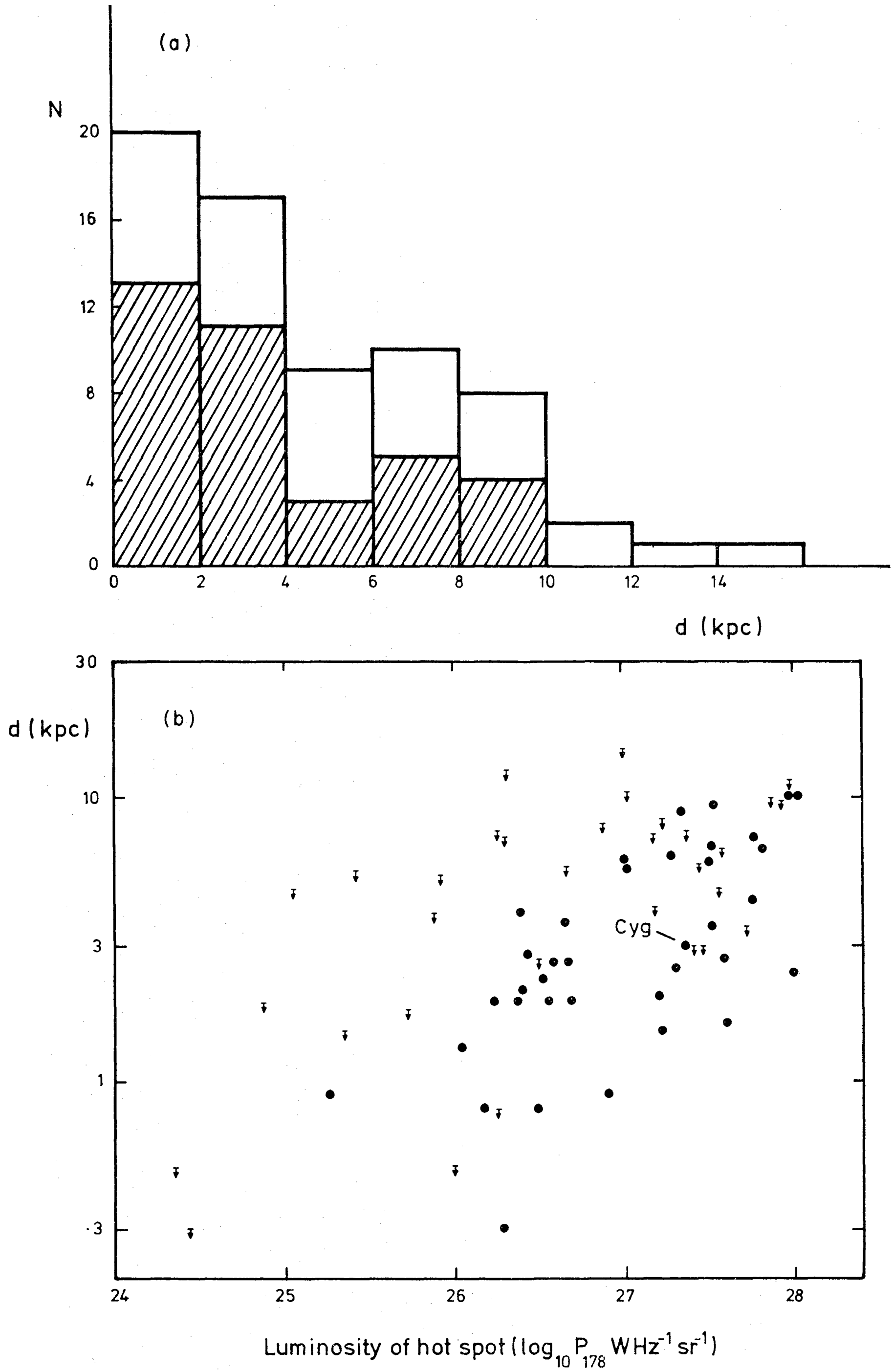

FIG. 5. (*a*) *The distribution of physical sizes of hot spots in intermediate and strongly scintillating sources. Hatched—actual values, unhatched—upper limits.* (*b*) *The relation between physical size and luminosity of the hot spots.*

to have a larger average size, but it is important to see whether this could be explained by selection arising from the upper resolution limit of the scintillation technique, which rules out the detection of larger hot spots in the nearer and less powerful sources. We return to this point at the end of this section.

It is convenient that the upper resolution limit for the scintillation measurements lies close to the resolving power of the 5-km telescope. This means that compact

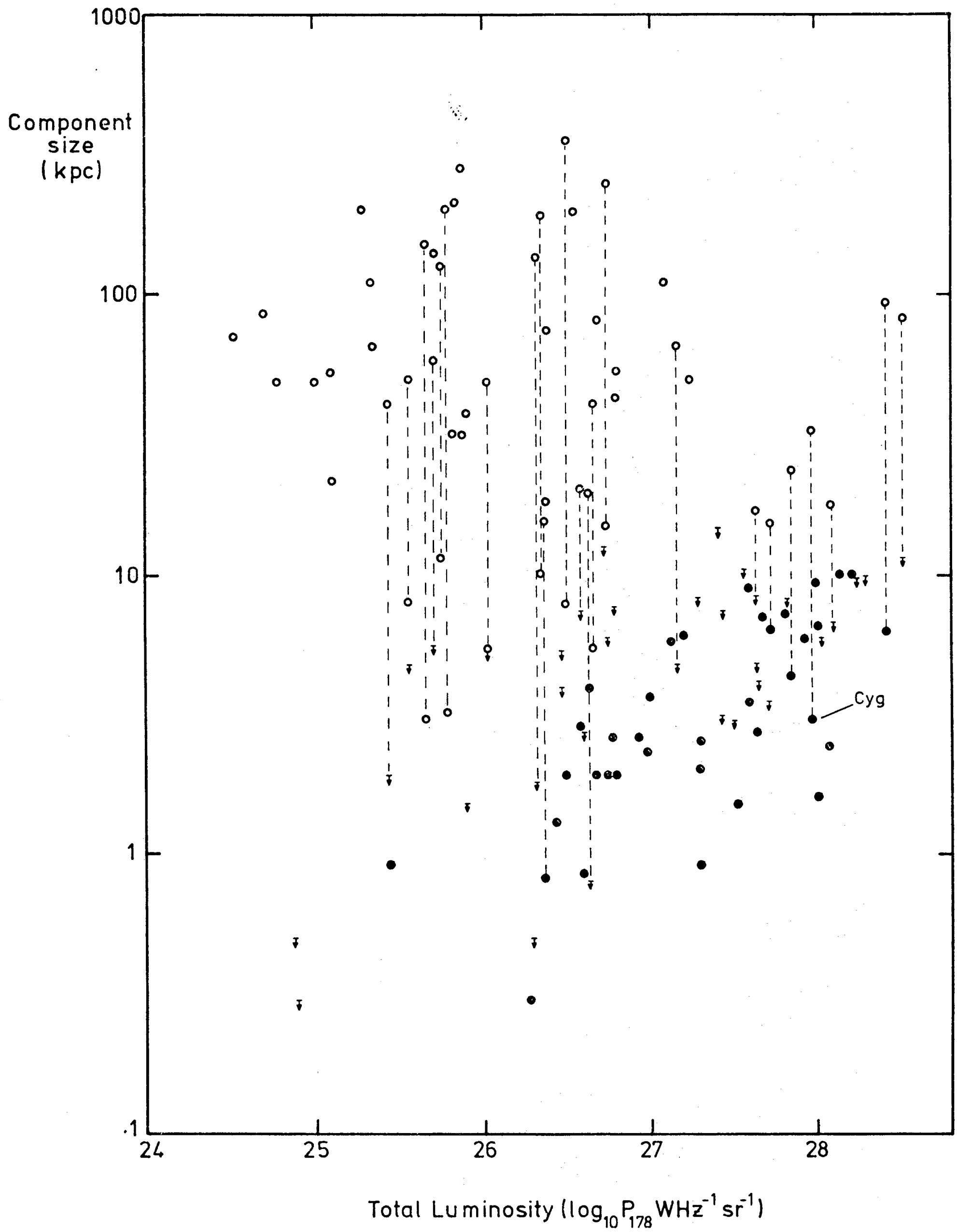

FIG. 6. *The relation between the physical sizes of extended outer components and hot spots in 3CR sources and the total source luminosity. Dashed lines connect extended components and hot spots for individual sources;* ● *from interplanetary scintillation;* ○ *from synthesis maps.*

features which are just too large to scintillate should be detected by direct mapping. In Fig. 6 the scintillation results have therefore been combined with component sizes derived from mapping (Macdonald, Kenderdine & Neville 1968; Mackay 1969; Pooley & Henbest 1974; Hargrave & McEllin 1975; Riley & Pooley 1975). The data are here plotted against the *total* source luminosity and all identified sources with $P_{178} > 10^{24}$ W Hz^{-1} sr^{-1} in the 3CR sample have been included. Results derived from mapping are only given when there is definite evidence for resolved structure. In each case we have plotted only the brighter component.

For some of the nearest sources both the hot spots and the outer components are resolved by mapping, but in most cases the hot spots are unresolved except by scintillation. At the highest luminosities ($P_{178} > 10^{27}$ W Hz^{-1} sr^{-1}) even the extended outer components are unresolved or lie close to the limit for mapping. Components of size >20 kpc would, however, be resolved at any distance by the 5-km telescope. The results for the intermediate and strongly scintillating sources plotted in Fig. 6 are set out in Table II. In all cases a correction for interstellar scattering has been made using the formula derived by Duffett-Smith & Readhead (1976). Such corrections are only important at the smallest angular sizes and the uncorrected value is also given. For identified sources where no redshift has been measured, a redshift has been assigned by assuming an absolute visual magnitude $M_V = -23$. The K corrections from Schild & Oke (1971) have been applied to these sources. In these cases the redshift is quoted to two significant figures only.

Two things are immediately apparent in Fig. 6. First, in many sources there is a clear distinction between the hot spots seen in the scintillation measurements and extended features. This is shown by the sources in which the two types of feature are easily distinguished and which have been joined by dashed lines in Fig. 6. Thus this type of structure, which is also observed in Cygnus, is common in high luminosity sources. Secondly, for the most powerful sources ($P_{178} \gtrsim 10^{27}$ W Hz^{-1} sr^{-1}), the extended components are generally close to the resolution limit of the 5-km telescope and therefore have sizes $\lesssim 20$ kpc. Since the hot spots account for roughly half or more of the total flux density at 81·5 MHz, the extended components are far less important in these cases. Since hot spots are seen in *all* the most powerful sources, selection is unimportant, yet there is still an increase of mean hot spot size with luminosity.

Amongst the weaker sources ($P_{178} < 3.10^{26}$ W Hz^{-1} sr^{-1}) there is a tendency for some hot spots to be smaller and this cannot be explained as a selection effect arising from the scintillation technique.

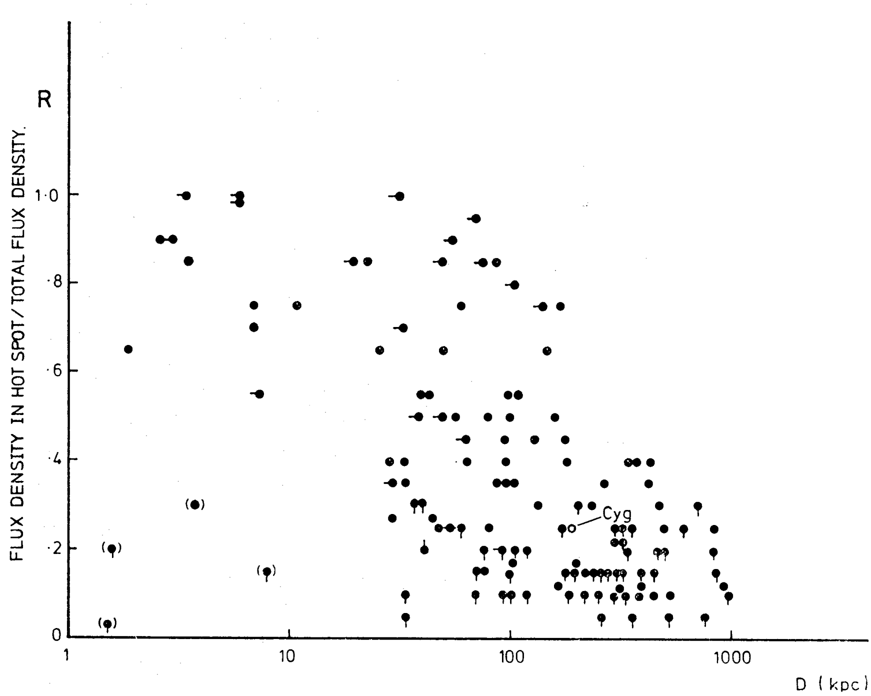

FIG. 7. *The fraction of the flux density in hot spots vs overall physical size of the sources. The points in brackets are for the nearby galaxies M82, M84, M87 and 3C 305.*

TABLE II

Source 3C	Identification	Redshift (z)	Luminosity P_{178} ($WHz^{-1}\,sr^{-1}$)	Angular size (θ)	Fraction of flux density in scintillating component (R)	Galactic latitude (b)	Angular size corrected for interstellar scattering (θ_c)	Component size in kpc (d)	Total source size in kpc (D)	Notes and references
9	Q	2.012	28.50	<1".40	0.10 - 0.45	-47°	<1".39	<11.4	82	8,15
42	G	0.3952	26.79	<1".20	0.15 - 0.45	-33°	<1".18	< 7.6	160	6,12
43	Q	0.38	26.76	0".45	0.85	-39°	0".41	2.6	< 76	15
48	Q	0.367	27.30	0".45	1.00	-29°	0".40	2.5	< 6	8,15
67	G	0.3102	26.50	0".40	0.75	-31°	0".34	1.9	11	11,15
68.1	Q	1.237	28.01	<0".70	0.20 - 0.35	-24°	<0".66	< 5.70	500	12
93.1	G	0.244	26.30	<0".30	0.50	-16°	<0".10	< 0.5	< 50	1,12,15
138	Q	0.759	27.51	<0".50	0.90	-11°	<0".37	< 3.0	< 3.0	1,8,15
147	Q	0.545	27.71	<0".60	1.00	10°	<0".48	< 3.5	< 3.5	1,4,8,15
153	G	0.2771	26.65	<0".35	0.40	13°	<0".15	< 0.8	34	1,9,15
171	G	0.2387	26.65	0".85	0.55	22°	0".81	3.9	42	8,9
173	Q	0.50	26.93	0".45	0.45	18°	0".36	2.6	< 64	14
181	Q	1.382	28.00	0".80	0.65	15°	0".75	6.5	51	8,15
186	Q	1.063	27.84	0".55	0.85	26°	0".50	4.3	23	8,15
191	Q	1.946	28.28	<1".20	0.25 - 0.75	21°	<1".17	< 9.7	< 49	8,15
194	G	0.38	26.66	0".40	0.55	32°	0".34	2.1	100	6,7,14
196	Q	0.871	28.20	1".20	0.55	33°	1".18	9.9	41	8,15
197.1	G	0.1302	25.73	<1".80	>0.2	35°	<1".79	< 5.5	41	9,15
204	Q	1.112	27.73	0".75	0.35	36°	0".72	6.2	270	8,15
205	Q	1.534	28.09	<0".80	0.20 - 0.40	37°	<0".77	< 6.6	135	8,15
208	Q	1.110	27.92	0".70	0.35	33°	0".67	5.8	90	8,15
210	G	0.64	27.20	0".80	0.65	39°	0".78	6.0	148	5,6
212	Q	1.063	27.83	<0".90	0.20 - 0.55	35°	<0".88	< 7.6	473	12,15
213.1	G	0.29	26.48	<0".75	0.15 - 0.35	40°	<0".73	< 3.9	< 54	15

220.2	Q	1.157	27.64	<0".50	0.25 - 0.45	47°	<0".47	< 4.0	103	13
236	G	0.0988	25.45	0".40	0.65	54°	0".36	0.9	1.9	9,17
244.1	G	0.29	26.75	0".40	0.30	51°	0".36	1.9	238	15
245	Q	1.029	27.57	<1".20	0.15 - 0.50	56°	<1".19	<10.2	30	8,15
249.1	Q	0.311	26.59	<1".30	0.30 - 0.70	38°	<1".29	< 7.3	130	8,15
254	Q	0.734	27.60	1".10	0.55	66°	1".09	8.8	110	8,15
263	Q	0.652	27.30	0".20	0.40	50°	0".11	0.9	345	8,15
265	G	0.38	26.98	0".40	0.35	75°	0".36	2.3	422	15
268.3	G	0.38	26.64	0".20	0.70	52°	0".12	0.8	8	12
268.4	Q	1.400	27.83	0".85	0.85	71°	0".83	7.1	87	8,15
270.1	Q	1.519	28.00	0".25	0.40	81°	0".19	1.6	65	8,15
275.1	Q	0.557	27.27	<1".10	0.20 - 0.65	79°	<1".09	< 8.1	96	8,15
277.1	Q	0.320	26.61	<0".50	0.65 - 0.85	60°	<0".47	< 2.7	7	8,15
277.3	G	0.0857	25.44	<0".90	0.15 - 0.45	89°	<0".90	< 1.9	48	9,15
280	G	0.38	27.00	0".60	0.45	70°	0".58	3.6	95	6
280.1	Q	1.659	28.13	1".20	0.75	77°	1".18	10.0	170	8,15
284	G	0.2394	26.33	<0".40	0.20 - 0.30	86°	<0".37	< 1.8	840	3,15
286	Q	0.846	27.59	0".45	0.85	81°	0".42	3.5	3.5	8,15
287	Q	1.054	27.64	0".35	0.90	81°	0".31	2.7	2.7	8,15
288.1	Q	0.961	27.52	0".25	0.50	56°	0".18	1.5	57	8,15
293	G	0.0453	24.90	<0".30	0.30 - 0.40	76°	<0".26	< 0.3	96	9
293.1	G	0.29	26.47	<1".00	0.15 - 0.40	72°	<0".99	< 5.3	81	15
295	G	0.4614	27.68	1".00	0.70	61°	0".78	6.9	29	9,15,18
299	G	0.367	26.69	0".35	1.00	67°	0".31	1.9	< 6	11,15
303	G	0.141	25.92	<0".5	0.20 - 0.35	58°	<0".47	< 1.5	45	12
303.1	G	0.22	26.28	0".20	1.00	38°	0".06	0.3	< 32	15
305	G	0.0416	24.88	<0".50	0.25 - 0.35	49°	<0".47	< 0.5	3.8	6
309.1	Q	0.905	27.63	<0".60	>0.70	41°	<0".57	< 4.8	< 20	3,8,15
318	G	0.753	27.30	0".30	0.80	55°	0".25	2.0	<105	12,15
321	G	0.096	25.58	<2".00	0.10 - 0.70	54°	<1".99	< 4.7	34	12
322	G	0.29	26.44	0".3	0.40	49°	0.24	1.3	180	15
324	G	0.38	26.77	0".35	0.60	49°	0.30	1.9	75	8,15
330	G	0.549	27.40	<2".00	0.25 - 0.85	41°	<1".99	<14.7	435	6,12
336	Q	0.927	27.63	<1".00	0.25 - 0.60	42°	<0".98	< 8.3	180	8,15
343	Q	0.988	27.42	<0".40	>0.85	39°	<0".35	< 3.0	< 70	10,12

TABLE II—*continued*

Source 3C	Identification	Redshift (z)	Luminosity P_{178} (W Hz^{-1} sr^{-1})	Angular size (θ)	Fraction of flux density in scintillating component (R)	Galactic latitude (b)	Angular size corrected for interstellar scattering (θ_c)	Component size in kpc (d)	Total source size in kpc (D)	Notes and references
343.1	G	0.46	26.75	<0″.85	>0.60	39°	<0.83	< 5.7	< 55	12
351	Q	0.371	26.72	<2″.00	0.25 – 0.90	36°	<1.99	<12.3	370	8,15
380	Q	0.691	27.99	1″.20	0.35	24°	1″.17	9.3	< 30	8,15
405	G	0.057	27.97	2″.00	0.25	6°	–	3.0	190	9,15,16
432	Q	1.804	28.26	<1″.20	0.20 – 0.70	-23°	<1″.18	< 9.9	100	8,15
454	Q	1.756	28.06	0″.35	0.85	-36°	0″.29	2.4	< 50	8,15
454.3	Q	0.860	27.43	<0″.90	0.35 – 0.90	-39°	<0″.88	< 7.4	< 7.4	8,15
455	Q	0.543	27.13	0″.80	0.75	-41°	0″.78	5.7	<140	
460	G	0.264	26.37	0″.25	0.65	-35°	0″.15	0.8	26	6,11

Notes and references

1. Upper limit for θ, since the effect of interstellar scattering is very large.
2. Arp *et al.* (1972).
3. Burbidge & Strittmatter (1972).
4. Elsmore & Mackay (1970).
5. Grueff & Vigotti, private communication.
6. Kristian, Sandage & Katem (1974).
7. Mackay (1969).
8. Minkowski (1975)
9. Moffet (1975).
10. Sandage, private communication.
11. Sargent, private communication.
12. Spinrad, private communication.
13. Wills & Lynds (1972).
14. Wlérick, Lelièvre & Véron (1971).
15. Wyndham (1966).
16. θ taken from synthesis maps.
17. Dimensions given are for the inner double.
18. Combined IPS measurements over 3 yr give $\theta = 1''\cdot 0 \pm 0''\cdot 3$.

4.3 *Compact features and total source size*

It was shown in Section 2 that the occurrence of scintillating components is strongly correlated with the overall angular extent of radio sources. The relation between R and the corresponding overall linear size is shown for identified sources in Fig. 7. It can be seen that the fraction of the total flux of a source contained in hot spots is closely related to the linear size, and that hot spots become far less prominent when the overall size exceeds about 200 kpc.

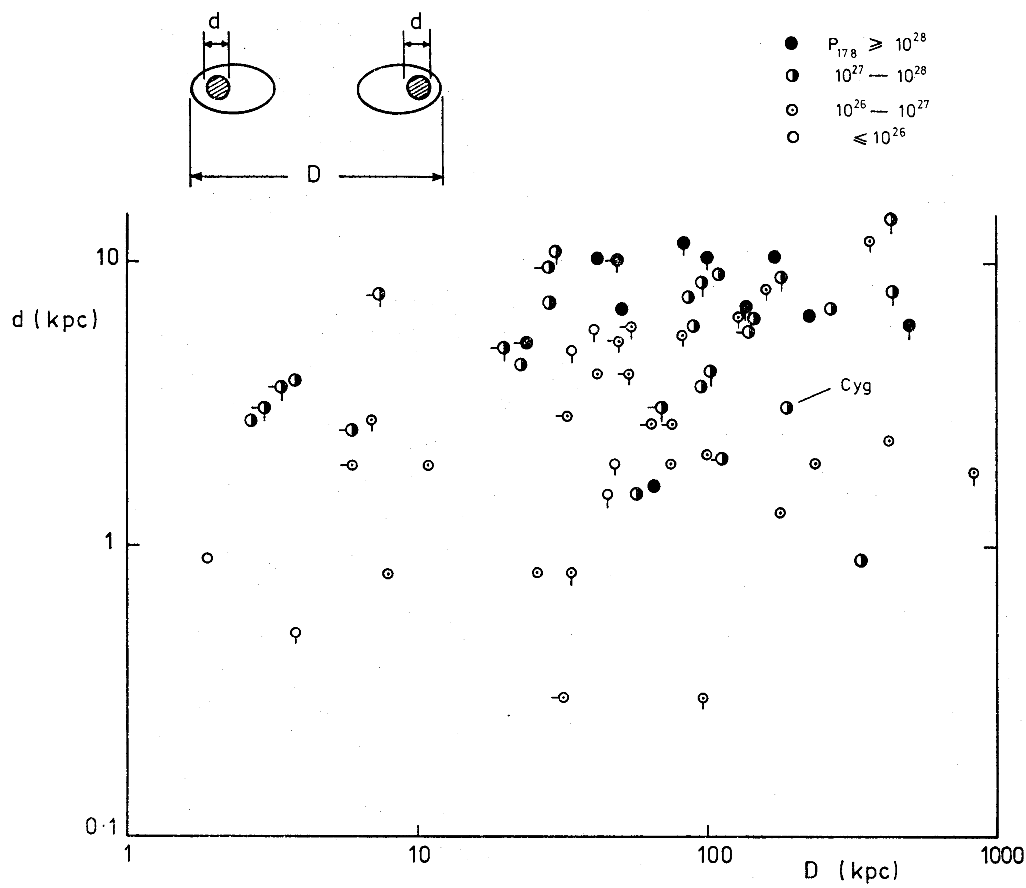

FIG. 8. *Hot spot size (d) vs overall size (D) from intermediate and strongly scintillating 3CR sources in different luminosity classes.*

The data of Hargrave & Ryle (1974) show that the hot spots in Cygnus A contain 25 per cent of the total flux and are separated by 186 kpc. If this source were ten times more distant it would scintillate giving $R \sim 0{\cdot}2$. This agrees with the general behaviour shown in Fig. 7 and adds further support to our conclusion that the compact features revealed by scintillation are similar to the hot spots in Cygnus A.

The linear size of hot spots is shown in relation to overall source size in Fig. 8. A remarkable feature of this plot is the comparatively small variation in the size of the hot spots of the most luminous sources ($P_{178} \gtrsim 10^{27}$ W H^{-1} sr^{-1}) in relation to the total source size, which varies widely. This is not a selection effect since, as we have seen in Fig. 6, hot spots have been detected in all the most luminous sources. Good examples of this behaviour are the sources 3C 295 and 3C 280.1. The hot spots have sizes ≈ 7 and 10 kpc respectively but the overall separations are 29 and 170 kpc. These sources have been fully resolved by interferometric measurements (Wilkinson, Richards & Bowden 1974) which confirm our data.

In Fig. 8 there is a significant trend for sources of the highest luminosity ($P_{178} > 10^{28}$ W Hz^{-1} sr^{-1}) to have overall sizes in the range 50–200 kpc. It has already been shown that weak and intermediate scintillating sources typically have $P_{178} < 10^{27}$ W Hz^{-1} sr^{-1} (see Fig. 3) and so the total luminosity falls as the hot spots become less prominent and the overall size exceeds 200 kpc.

When the total extent is less than about 10 kpc the scintillation results cannot easily distinguish component separation from component size and the points in Fig. 8 may well be overestimates.

5. DISCUSSION

Our study of compact structure in a complete sample of 3CR sources using the scintillation technique has led to the following new facts:

(a) The compact features which scintillate in steep spectrum ($\alpha > 0 \cdot 6$) sources are similar to the hot spots which have been found in the extended outer components of Cygnus A.

(b) Hot spots are a typical feature of sources of high radio luminosity ($P_{178} > 10^{26}$ W Hz^{-1} sr^{-1}) but are rarely found in low-luminosity sources.

(c) The most powerful sources ($P_{178} > 10^{28}$ W Hz^{-1} sr^{-1}) have hot spots of typical size 5 kpc, separated by 50–200 kpc. The hot spots account for at least half the total flux density at 81·5 MHz in these sources.

(d) The physical size of hot spots increases with luminosity if $q_0 = \frac{1}{2}$.

(e) The slightly less powerful sources ($P_{178} < 10^{27}$ W Hz^{-1} sr^{-1}) show structure in which there is a clear distinction between hot spots of size < 10 kpc and more extended components of lower surface brightness having typical sizes of 20–200 kpc.

(f) Hot spots are rarely prominent in sources having an overall extent greater than about 300 kpc.

(g) The size of the hot spots shows no significant dependence upon the overall extent of the source when this exceeds 20 kpc.

Hargrave & Ryle (1974) have suggested that the structure of Cygnus A may be explained by a continuous-flow model in which energy is beamed from the central core towards the outer components. In this model the hot spots are identified with regions in which the beam interacts with intergalactic material and from which relativistic particles are supplied to the extended outer components. Our scintillation results show that this model may be applicable to most high-luminosity sources.

On the assumption that double sources expand outwards from the central core we can envisage an evolutionary sequence as sketched in Fig. 9. The typical dimensions are taken from the results that have been described in this paper and actual sources which correspond roughly to the model are indicated. When the overall size is less than 10 kpc, the hot spots are smaller than 5 kpc and the source has moderately high luminosity (3C 147, 3C 138). As the separation increases beyond 10 kpc the hot spots reach their maximum size of about 5 kpc and the luminosity increases (3C 67, 3C 295), reaching a maximum when the separation is 50–150 kpc (3C 9, 3C 280.1). The accumulation of particles which have escaped from the hot spots is beginning to form extended components but these are not yet

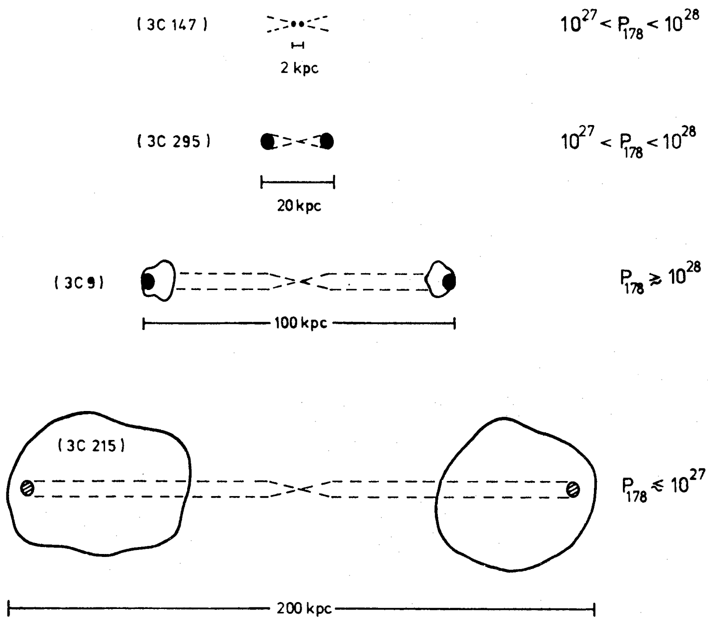

FIG. 9. *Schematic diagram of the evolution of a double radio source. Sources which roughly correspond to the model are indicated.*

a dominant feature. Finally the beam fades as the separation increases beyond 200 kpc and the luminosity falls; the accumulated particles in extended components now dominate the source (3C 47, 3C 215).

If the beam model is correct it appears that an effective collimation mechanism is at work in order to account for the more or less constant size of the hot spots as their separation increases from 10 kpc to more than 100 kpc. Scheuer (1974) has discussed such a model (his model B) in which a beam of relativistic material is focused by the external pressure of the intergalactic medium. He also points out the limitations of this model. The major problem is that if we identify the hot spot size (~ 5 kpc) with the width of the beam at the interface with the intergalactic medium, ~ 100 kpc from the source, then the beam width very near the source is ~ 1 kpc. This is much larger than the size of central components observed by *VLBI*. Scheuer's model C, in which the thermal pressure due to a hot intracluster gas balances the pressure in the radio source, is most successful in producing the type of structure observed.

It therefore appears that the most fruitful attack on this problem may be to combine Scheuer's model C with a beaming mechanism in which the beam spreads very slowly as it pushes outwards into the intergalactic medium.

ACKNOWLEDGMENTS

We thank Dr M. S. Longair for valuable discussions. ACSR is indebted to the Royal Society for a fellowship supported by the Weir Foundation.

REFERENCES

Arp, H. C., Burbidge, E. M., Mackay, C. D. & Strittmatter, P. A., 1972. *Astrophys. J. Lett.*, **171**, L41.

Bennett, A. S., 1962. *Mem. R. astr. Soc.*, **68**, 163.

Bhandari, S. M., Ananthakrishnan, S. & Pramesh Rao, A., 1974. *Austr. J. Phys.*, **27**, 121
Burnell, S. J. B., 1972. *Astr. Astrophys.*, **16**, 379.
Burbidge, E. M. & Strittmatter, P. A., 1972. *Astrophys. J. Lett.*, **172**, L37.
Cohen, M. H., Gundermann, E. J. & Harris, D. E., 1967. *Astrophys. J.*, **150**, 767.
Duffett-Smith, P. J. & Readhead, A. C. S., 1976. *Mon. Not. R. astr. Soc.*, **174**, 7.
Elsmore, B. & Mackay, C. D., 1970. *Mon. Not. R. astr. Soc.*, **146**, 361.
Fanaroff, B. L. & Riley, J. M., 1974. *Mon. Not. R. astr. Soc.*, **167**, 31P.
Hargrave, P. J. & Ryle, M., 1974. *Mon. Not. R. astr. Soc.*, **166**, 305.
Hargrave, P. J. & McEllin, M., 1975. *Mon. Not. R. astr. Soc.*, **173**, 37.
Harris, D. E., 1973. *Astr. J.*, **78**, 369.
Harris, D. E. & Hardebeck, E. G., 1969. *Astrophys. J. Suppl.*, **19**, 115.
Harris, D. E., Zeissig, G. A. & Lovelace, R. V., 1970. *Astr. Astrophys.*, **8**, 98.
Hewish, A., Readhead, A. C. S. & Duffet-Smith, P. J., 1974. *Nature*, **252**, 657.
Hewish, A. & Readhead, A. C. S., 1976. *Astr. Astrophys.* (submitted).
Kristian, J., Sandage, A. & Katem, B., 1974. *Astrophys. J.*, **191**, 43.
Little, L. T. & Hewish, A., 1968. *Mon. Not. R. astr. Soc.*, **138**, 393.
Macdonald, G. H., Kenderdine, S. & Neville, A. C., 1968. *Mon. Not. R. astr. Soc.*, **138**, 259.
Mackay, C. D., 1969. *Mon. Not. R. astr. Soc.*, **145**, 31.
Minkowski, R., 1975. *Stars and stellar systems*, 9, eds G. P. Kuiper and B. M. Middlehurst.
Moffet, A., 1975. *Stars and stellar systems*, 9, eds G. P. Kuiper and B. M. Middlehurst.
Pooley, G. G. & Henbest, S. N., 1974. *Mon. Not. R. astr. Soc.*, **169**, 477.
Readhead, A. C. S., 1971. *Mon. Not. R. astr. Soc.*, **155**, 185.
Readhead, A. C. S. & Hewish, A., 1972. *Nature*, **236**, 440.
Readhead, A. C. S. & Hewish, A., 1974. *Mem. R. astr. Soc.*, **78**, 1.
Readhead, A. C. S. & Longair, M. S., 1975. *Mon. Not. R. astr. Soc.*, **170**, 393.
Rees, M. J., 1972. IAU Symposium 44 on *External galaxies and quasi stellar objects*, ed. D. E. Evans.
Riley, J. M. & Pooley, G. G., 1975. *Mem. R. astr. Soc.*, **80**, 105.
Scheuer, P. A. G., 1974. *Mon. Not. R. astr. Soc.*, **166**, 513.
Scheuer, P. A. G. & Williams, P. J. S., 1968. *A. Rev. Astr. Astrophys.*, **6**, 321.
Schild, R. & Oke, J. B., 1971. *Astrophys. J.*, **169**, 209.
Swarup, G. & Bhandari, S. M., 1976. *Astrophys. Lett*, **17**, 31.
Wilkinson, P. N., Richards, P. J. & Bowden, T. N., 1974. *Mon. Not. R. astr. Soc.*, **168**, 515.
Wills, D. & Lynds, C. R., 1972. *Astrophys. Lett*, **11**, 189.
Wlérick, G., Lelièvre, G. & Véron, P., 1971. *Astr. Astrophys.*, **11**, 142.
Wyndham, J. D., 1966. *Astrophys. J.*, **144**, 459.