Hotspots and radio lobes of quasars

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Summary. Observations are described of 31 quasars mapped with the VLA which provides a resolution of about 0.4 arcsec at 4.87 GHz. The sources were selected from those lying near the upper envelope of the largest angular size (LAS) – redshift (z) diagram for the 3C, 4C and B2 samples of quasars. The outer lobes of about a quarter of these quasars have no significant hotspots, which may imply that the lobes are not currently being supplied with energy. About 60 per cent of the sources have at least one compact hotspot with size < 4 kpc transverse to the source axis, containing at least 20 per cent of the lobe flux density. For two-thirds of such hotspots, the magnetic field is perpendicular, within about $\pm 30^\circ$, to the source axis. For extended hotspots, the magnetic field tends to be circumferential. No marked dependence is found of the linear size of hotspots on z , LAS or radio luminosity, but the fraction of the flux density from the hotspots to that from the radio lobes is strongly correlated with radio luminosity.

On average, about 90 per cent of the flux density of the central radio component coincident with the optical quasar appears to come from a compact unresolved core, and the balance from extended features, a few kiloparsecs in size.

1 Introduction

Much observational effort has been devoted to investigating whether certain radio structural parameters of double radio quasars depend on redshift. Particularly, it is found that the upper envelope to the largest angular size (LAS) – redshift (z) diagram follows the line $\text{LAS} \propto z^{-1}$

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(Miley 1971; Wardle & Miley 1974). Correlations have also been reported between the angular sizes of the hotspots and redshift (Readhead & Hewish 1976), and their compactness with radio luminosity (Jenkins & McEllin 1977). It is conceivable, however, that selection and projection effects might influence the observed parameters whose dependence on redshift and on any other quasar characteristic is being investigated.

To minimize the potential confusion caused by such selection and projection effects, one may study complete samples of quasars located close to the upper envelope of the LAS- z diagram. We expect these to be oriented at large angles to the line of sight. Such a choice also implies more detailed mapping for a given angular resolution. This paper describes observations of 31 such quasars made with the Very Large Array (VLA), which provides a resolution of about 0.4 arcsec at a frequency of 4.87 GHz. This resolution is usually adequate to separate the hotspots from the surrounding diffuse emission of the outer radio lobes. Preliminary results of this study have been reported by Swarup, Sinha & Salter (1982b). The observed sample and the observations are described in the next section. The following two sections outline the results obtained and a discussion of them.

2 Observations and data reduction

The selection criterion for the sample of 31 quasars described here is as follows: Firstly, from the 3CR and 4C complete samples (Hooley, Longair & Riley 1978; Stannard & Neal 1977; Wills 1979) we selected 28 quasars as being representative of all those lying near the upper envelope of the LAS- z diagram. These quasars are distributed roughly uniformly over the seven successive redshift ranges of < 0.25 , $0.25-0.5$, $0.5-0.75$, $0.75-1$, $1-1.5$, $1.5-2$ and > 2 . Secondly, we selected all six quasars with $z > 0.8$ from the B2 sample (Fanti *et al.* 1977, with redshifts taken from Hewitt & Burbidge 1980), three of which are already present in our 4C sample. In order to minimize the scatter in radio luminosity of the selected quasars of similar angular size, preference was given to the 3CR sources at lower redshifts and to the 4C and B2 samples at higher redshifts. The LAS- z distribution of the selected sample as well as of the complete 3CR, 4C and B2 samples is given in Section 6.

The observations were made with 22 antennas in the VLA 'A' configuration (Thompson *et al.* 1980) on 1981 March 17, 24 and 25 at 4873 MHz using a bandwidth of 25 MHz. Each source was observed in two or three different scans of 4 or 5 min duration, separated by a few hours. To calibrate the amplitude and phases of the observed visibilities, one of 12 point sources was observed about every 15 min.

The primary flux density calibration was made by observing 3C 286 whose flux density at 4.87 GHz was taken as 7.41 Jy on the scale of Baars *et al.* (1977). For polarization calibration, the radio sources 3C 138 and 3C 286 were observed. A uniform grading was applied across the aperture during the data reduction in order to obtain the highest possible resolution. Most of the sources were 'cleaned' (Högbom 1974) using the Westerbork software package at Leiden. Thirteen of the observed sources were self-calibrated (Schwab 1980). In order to estimate the flux density of the extended radio lobes, the dirty maps and the dirty beams of most of the observed sources were smoothed to a resolution of about 1–2 arcsec, and then cleaned using the Groningen GIPSY software at Ootacamund. As shown in Table 1, the estimated flux densities of the radio lobes agree reasonably well with the measurements by other workers at 5 GHz, excepting a few sources which have relatively large diffuse lobes.

3 Results

3.1 OBSERVATIONAL RESULTS

The results for the 31 quasars are summarized in Table 1, which is arranged as follows:

Source	Other name	Comp	Right Ascension	Declination	R	Resolution	Flux Density	Polariza-	Size	Size	Size	R	LAS	PA	e	f						
(1)	(2)	(3)	h m s	° ' "	(4)	"	Peak (VLA) mJy	Peak PA	Hot spot	Radio lobe	major minor PA	(5)	"	deg	"	deg						
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)
*0118+03	4C 03.02	OPT	01 18 26.05	+03 28 32.2	M	.98	4	112	173	M	1.2											
	3C 39	NW	24.69	+ 37.9		.98	29	33	23	M	1.2											
		CN	26.11	+ 30.8		.98	8	141	128	M												
		SE	27.56	+ 27.5		.98	Total=286	273	M													
*0133+20	3C 47	OPT	01 33 40.42	+20 42 10.2	S	.56	98	392 ^a	560	P	23	28	.74	.42	34	4.1	1.3	96				
		SW	38.92	+ 41 38.4		.56	47	64	57	72	80	P	<.5									
		CN	40.41	+ 42 10.5		.56	6	180 ^a	420	P	.8	33	.22	.12	57	15	11	117	P			
		NE	41.77	+ 42 36.1		.56	Total=	1090	K													
*0229+34	3C 68.1	OPT	02 29 27.24	+34 10 34.1	J	.46	39	110	144	J	39	104	.81	.23	58	5.2	3.8	100				
		NW1	26.93	+ 55.9		.46	39	110	40	J	22	171	.68	.32	76							
		NW2	27.13	+ 55.1		.46	39	110	< 2	J												
		CN	27.24	+ 34.1		.46	39	110	< 3	J												
		SW	27.1	+ 00		.46	39	110	Total=	820	K											
*0312-03	4C-03.11	OPT	03 12 52.04	-03 27 49.8	W	.44	43	44	32		6.4	136	.31	.26	135	3.2	2	80				
		SW1	51.59	- 28 11.8		.44	43	44	59		10.6	62	.26	.21	38							
		SW2	51.72	- 28 11.6		.44	43	44	4		1.7	0	.33	.25	23	5.1	1.7	8				
		CN	52.02	- 27 50.1		.44	43	44	6													
		NE	52.24	- 27 30.7		.44	43	44	32		340	K										
							Total=	338														
*0808+28	B2	OPT	08 08 32.18	+28 54 02.2	H	.49	36	116	< 2		14	F	<.15									
		NW	31.20	+ 32.6	F	.49	36	116	25		42	F										
		CN	32.15	+ 02.1		.49	Total=	56														
*0835+58	3C 205	OPT	08 35 10.02	+58 04 51.4	A	.48	48	0	163		37	63	.29	.17	120	2.8	0.9	150				
		SW1	09.78	+ 43.1		.48	48	0	52		10	90	.82	.55	60							
		SW2	09.89	+ 41.8		.48	48	0	24		30	P	<.5									
		CN	10.07	+ 51.4		.48	48	0	71		203	190	.41	.27	105	1.2	.6	0				
		NE	10.32	+ 58.3		.48	48	0	Total=	677	660	L										
0901+28	B2	OPT	09 01 30.64	+28 31 30.8	F	.47	38	93	4		<.75		.20	<.15	83	1.1	.47	10				
		SW	30.00	+ 23.2		.47	38	93	28		<.75		.29	<.2	49							
		CN	30.65	+ 30.4		.47	38	93	13													
		NE	31.39	+ 37.9		.47	38	93	Total=	89	80	F										
*0903+16	3C 215	OPT	09 03 44.15	+16 58 15.7	S	.47	39	91	2		<1		.28	.24	4	8.4	4.8	90				
		NW	43.29	+ 34.2		.47	39	91	17		<1		.36	.18	108	8.8	5	105				
		CN	44.13	+ 15.9		.47	39	91	5				.51	.43	1							
		E	44.37	+ 16.6		.47	39	91	5													
		SE	44.81	+ 13.0		.47	39	91	Total=	410	410	K										
*0911+05	4C 05.38	OPT	09 11 24.00	+05 20 17.0	M	.83	64	115	48		74	200	M									
		CN	23.93	+ 17.0			Total=	74														
0922+14	4C 14.31	OPT	09 22 22.41	+14 57 23.2	M	.49	41	90	9		85	69	M									
		SW	21.92	+ 06.3		.49	41	90	35		26	54	M									
		CN	22.36	+ 23.6		.49	41	90	19		116	115	M									
		NE1	22.84	+ 45.2		.49	41	90	27													
		NE2	22.89	+ 44.9		.49	41	90	Total=	227	175	M										
*0932+02	4C 02.27	OPT	09 32 42.93	+02 17 39.6	M	.50	50	0	5		105	147	M									
		SW	40.91	+ 13.9		.50	50	0	82		<.5		2.1	.99	.65	71	9	6	30			
		CN	42.93	+ 40.9		.50	50	0	20		156	M	<.5									
		NE	43.30	+ 44.7		.50	50	0	54		2.6	82	M	.29	.18	50	5	2.5	50			
							Total=	256	300	M												

Table 1 — continued

Source	Other name	Comp	Right Ascension	Declination	R f	Resolution	Flux Density			Polarization	Size			R f	PA	R f	deg				
(1)	(2)	(3)	h m s	° ' " (5)	(6)	"	mJy (8)	mJy (9)	mJy (10)	PA (11)	Hot spot Y1 (14)	Y2 (15)	major (16)	minor (17)	PA (18)	(19)	(20)	(21)	(22)	(23)	
• 0957+00	4C 00.34	OPT	09 57 43.84	+00 19 50.0	M	.58	.44 63 17	136	144	M	3.0 145	.64 .49 150	3.2	1.2	100						
		NW1	42.53	+ 50.8		.58	.44 63 14	14			3.0 30	.79 .49 130	1.7	0.5	0						
		NW2	42.58	+ 50.3		.58	.44 63 10	10			<1	.64 .45 41	1.7	0.5	0						
		NW3	42.69	+ 50.2		.58	.44 63 7	125	80	M	<1	<.2	3	2	115						
		CN	43.80	+ 49.1		.58	.44 63 7	97	108	M	<1										
		SE	44.70	+ 43.0		.58	.44 63	Total=358	330	M											
• 1004+13	4C 13.41	OPT	10 04 45.05	+13 03 37.7	M	.77	.68 84 < 1	10	13	M	<.3										
		NW	40.84	+ 04 08.7	M	.77	.68 84 < 1	9	9	M											
		CN	45.03	+ 03 36.9	M	.77	.68 84 < 1	141	M												
		SE	47.89	+ 03 17.2	M	.77	.68 84	Total=	579	M											
• 1011+28	4C 28.25	OPT	10 11 46.07	+28 03 58.3	PW	.48	.48 0	8	34		<1.5										
		NW	45.44	+ 04 01.7		.48	.48 0	56	71		<1	.27 <.2	95	2	120						
		CN	46.02	+ 03 58.4		.48	.48 0	20	140		2.3 125	.71 .48 90	2.5	2	120						
		SE	46.47	+ 03 56.7		.48	.48 0	Total=245	331	F											
• 1100+77	3C249.1	OPT	11 00 27.44	+77 15 08.2	P	.40	.39 130	21	590	M	3.3 65	1.24 .81 110	6.5	4.5	100						
		NW	22.78	+ 11.4		.40	.39 130	70	100	M	<.8	.17 <.15	77	4.5	1.5	90					
		CN	27.42	+ 08.3		.40	.39 130	7	266	M	<1										
		SE1	28.97	+ 07.6		.40	.39 130	8	266	M	<1										
		SE2	29.19	+ 07.7		.40	.39 130	50	790	K	11 85	.35 <.15	2								
		SE3	29.73	+ 08.2		.40	.39 130	Total=956	790	K											
† 1137+66	3C263	OPT	11 37 09.30	+66 04 27.0	P	.59	.40 68	12	152	P		.37 .28	21	7	2.5	120					
		NW	05.21	+ 36.8		.59	.40 68	164	169	P	<.15	<.15	164	3	1	130					
		CN	09.30	+ 26.9		.59	.40 68	400	688	P	19 101	.31 <.15	164	3	1	130					
		SE	11.79	+ 20.8		.59	.40 68	Total=1009	1030	K											
• 1221+18	4C 18.34	OPT	12 21 14.66	+18 37 43.5	W	.59	.40 63	10	63	M	2.8 42	1.26 .55 151	2.4	1.8	120						
		NW	13.80	+ 50.6		.59	.40 63	20	16	M	1.2 44	<.2									
		CN	14.63	+ 43.7		.59	.40 63	9	52	M	0.9 53	.67 .47 107	3.8	1.4	135						
		SE	15.16	+ 37.3		.59	.40 63	Total=161	128	M											
• 1244+32	4C 32.41	OPT	12 44 55.40	+32 25 22.8	PW	.87	.82 135	6	38	F	<1										
		SW	54.80	+ 11.7		.87	.82 135	44	71	F	<2	.58 .22 90	5	2	60						
		CN	55.43	+ 22.3		.87	.82 135	6	44	F	<2	.46 .20 135									
		NE1	55.52	+ 28.6		.87	.82 135	10	44	F	<1										
		NE2	56.22	+ 28.3		.87	.82 135	Total=170	170	F											
• 1248+30	4C 30.25	OPT	12 48 0.12	+30 32 59.3	PW	.54	.51 90	21	58	F	3.5 25	.53 .29 26	3.5	2.5	50						
		SW	47.99.17	+ 32 49.4		.47	.46 133	3	3	F											
		CN	48 0.14	+ 32 58.7		.47	.46 133	5	43	F											
		NE	48 0.99	+ 33 05.4		.47	.46 133	Total=104	133	F											
• 1305+06	4C 06.45	OPT	13 05 22.48	+06 58 12.9	M	.47	.41 61	< 2	115	M	<0.8	.30 .18 25	5.0	2.5	35						
		SW	22.48	+ 57 46.9	M	.47	.41 61	12	15	M	2.5 5	.49 .40 3	5.0	2.5	35						
		CN	22.46	+ 58 13.8		.47	.41 61	19	160	M											
		NE	22.71	+ 58 30.4		.47	.41 61	Total=	314	M											
• 1435+31	B2	OPT	14 35 31.40	+31 31 58.0	U	.40	.40 0	5	11 ^a		1.8 62	<.15	2	1	0						
		NW	31.12	+ 32 02.2		.40	.40 0	94	107												
		CN	31.48	+ 31 57.9		.40	.40 0	Total=118	135	F											

* 1545+21	3C323.1	OPT	15 45	31.09	+21 01	27.5 S	.39	.39	9	229	278	M	3.1 160	.34	.30 135	3.5	2	35	70.5	21		
		SW1		30.05	+	00 50.4	.39	.39	14				3.6 33	.77	.51 100							
		SW2		30.08	+	00 49.1	.39	.39	13				3.6 45	.56	.39 30							
		SW3		30.11	+	00 49.8	.39	.39	32	45	30	M	3.7 170	.16	<.15							
		CN		31.12	+	01 27.4	.39	.39	25	402 ^a	516	M	2.9 88	1.13	.64 10							
		NE1		31.85	+	01 55.1	.39	.39	17													
		NE2		31.88	+	01 54.5	.39	.39		Total=	910	K										
* 1602-00	4C-00.63	OPT	16 02	22.11	-00 11	00.2 W	.47	.43	53	54	80		8.6 83	.23	<.15 155				26.5	86		
		W		20.90	-	11 01.1	.47	.43	53	165	165		<1.6									
		CN		22.11	-	10 59.8	.47	.43	53	30	50		<1.6	.31	.21 30							
		E1		22.61	-	11 00.4	.47	.43	53	20												
		E2		22.66	-	10 59.4	.47	.43	53		Total=	295										
* 1606+28	4C 28.40	OPT	16 06	09.95	+28 56	55.7 W	.39	.36	132	27	71	75	R	2.5 165	.35	<.15 40	1.4	0.9	40	29.8	142	
		NW		09.31	+	57 06.8	2	2	0	6	13											
		CN		10.06	+	56 57.1	.39	.36	132	14	78	75	R	5.6 132	.36	.23 62	2.6	1.6	145			
		SE		10.72	+	56 43.4	.39	.36	132		Total=	162	160	R								
*†1618+17	3C 334	OPT	16 18	07.28	+17 43	30.1 J	.40	.38	96	4	146 ^a	310	J	1.0 13	<.20	<.20 0	5.5	3.5	130	45.6	130	
		NW		05.76	+	47.8	.40	.38	96	152	159	170	J	<.5								
		CN		07.29	+	30.3	.40	.38	96	5	22	200	J	1.1 159	.73	.26 76						
		SE		08.21	+	18.5	.40	.38	96		Total=	720	J									
*†1622+23	3C 336	OPT	16 22	32.21	+23 52	02.0 S	.39	.36	97	57	230	240	P	4.0 0	.43	.35 105	4.5	2.9	22	22.7	33	
		SW1		31.98	+	31 54.4	.39	.36	97	25	29	30	P	<.5	.44	.15 56						
		SW2		32.01	+	31 55.3	.39	.36	97	26	29	30	P	<.5	.24	.21 0						
		CN		32.21	+	52 01.3	.39	.36	97	47	440	490	P	4.1 20	1.07	.59 49	4.9	3.6	60			
		NE		32.68	+	52 13.5	.39	.36	97		Total=	699	690	K								
* 1704+60	3C 351	OPT	17 04	03.49	+60 48	30.9 L	.45	.34	0	80	685 ^a	650	L	9.0 15	.93	.74 62				59.0	34 R	
		SW		01.50	+	08.0 R	.45	.34	0	140	201 ^a	310	L	27.5 64	.21	.19 90						
		CN		03.55	+	31.2 L																
		NE1		03.64	+	33.6																
		NE2		03.95	+	48.7																
*†1739+18	4C 18.51	OPT	17 39	55.43	+18 28	43.5 W	1.45	1.32	27	3	114		<.5	1.35	1.30 99	17	5	0	212.2	158		
		NW1		52.81	+	30 25.2	1.45	1.32	27	3	31		<.5									
		NW2		53.23	+	30 21.5	1.45	1.32	27	21	107		<.5	2.34	.77 143	14	5	135				
		CN		55.39	+	28 43.8	1.45	1.32	27	5	107		<.5	1.59	<.2 151							
		SE1		56.19	+	27 11.0	1.45	1.32	27													
		SE2		56.38	+	27 08.4	1.45	1.32	27													
									Total=		253											
*†2131+17	4C 17.87	OPT	21 31	55.51	+17 33	32.4 W	.51	.44	52	4	35		<1.7							31.0	37	
		SW1		54.86	+	18.3	.51	.44	52	9					.41	.34 29						
		SW2		55.04	+	32.1	.51	.44	52	20	19				.28	.23 80						
		CN		55.49	+	32.6	.51	.44	52	7	39				.86	.54 38	2.8	2	40			
		NE		56.16	+	43.1	.51	.44	52		Total=	93										
* 2318+02	4C 02.58	OPT	23 18	14.40	+02 40	34.4 W	.65	.49	131	5	56		80 ^b W							59.0	0 W	
		A		13.71	+	40 04.8	1.9	1.3	67	<2			150 ^b W									
		B		13.76	+	39 07.6																
				13.77	+	40 06.0					Total=	56	230 ^b W									
*†2325+29	4C 29.68	OPT	23 25	42.23	+29 20	38.6 M	.58	.35	82	4	114	150	M	<.5						50.0	116	
		NW		40.50	+	51.1	.58	.35	82	34	37	24	M	<.5	<.15	<.15	5.5	4.5	127			
		CN		42.30	+	38.5	.58	.35	82	6	213	228	M	<.5	.78	.38 119	3.4	2.4	120			
		SE1		43.82	+	30.6	.58	.35	82	91					.67	.37	.21 165					
		SE2		43.94	+	29.3	.58	.35	82		Total=	364	382	M								

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(1) Source name. An asterisk (*) before the source name indicates that a note is given in Section 3.3. A dagger (†) indicates that the map was self-calibrated.

(2) 3C, 4C or B2 name.

(3) Component designation.

(4) and (5) RA and Dec (1950.0). The optical positions are accurate to about ± 0.5 arcsec. The radio positions are accurate to about ± 0.1 arcsec for peak values of flux density > 10 mJy, although the errors are larger for smaller peak values.

(6) Reference for optical positions.

(7) Size of the antenna beam and its position angle.

(8) Peak values of flux density per beam area for the hotspots and for the core of the central components.

(9) Integrated flux density of each component obtained from the VLA maps, typically accurate to about 10 per cent. The superscript 'a' indicates that extended features are resolved out by the VLA and therefore the flux density is underestimated.

(10) and (11) Integrated flux density at 5 GHz from the literature and reference. Superscript 'b' refers to values at 2.7 GHz by Wills (1979).

(12) and (13) Peak value of the linearly polarized intensity and its position angle.

(14), (15) and (16) De-convolved full width to half-power (FWHP) of the hotspot or the central component along its major and minor axis in arcsec, and the position angle.

(17), (18) and (19) Approximate FWHP and position angle of radio lobes obtained from the low-resolution maps by removing the contribution of hotspots by eye estimates.

(20) Reference for FWHP of the radio lobes taken from the literature.

(21), (22) and (23) Largest angular size in arcsec, and position angle of the radio source, with reference when the values are from the literature.

3.2 THE MAPS

Fig. 1(i–xxviii) give contour plots of 28 quasars. No maps are given for the quasars 0808 + 28, 0911 + 05 and 1004 + 13 because the extended features are found to be resolved out fully at 4.87 GHz by the VLA 'A'-configuration (see Section 3.3). The figure captions describe the maps.

3.3 NOTES ON THE SOURCES

0118 + 03. The source has a relaxed morphology with a weak hotspot in the SE component.

0133 + 20. The source has an 'S'-shaped geometry (Pooley & Henbest 1974). The diffuse features of the source are resolved out by the VLA, particularly for the NE component. According to Pooley & Henbest (1974), the peak feature in the NE component has a size ~ 15 kpc.

0229 + 34. Only the north-west component of this source is seen in the VLA map. In addition there exists a very faint radio component 46 arcsec to the south of the NW component (Mackay 1969). The quasar lies between these two components.

0808 + 28. The source has a strong central component coincident with the quasar and a weak diffuse NW component about 13 arcsec west and 30 arcsec north of the central component (Fanti *et al.* 1977). This latter component is resolved out by the VLA 'A' configuration. The flux density of the central component is found to be only $\sim 2/3$ of the value measured by Fanti *et al.* (1977), so either it is variable or it may have been partially resolved by the VLA beam. No other components are seen in the VLA maps obtained by smoothing

Figure 1. Total-intensity contour maps of 28 quasars at 4.87 GHz. The broken lines indicate negative contours. The values of contour levels and the angular size of the VLA beam are given below each map, and the size of the beam is also indicated by a shaded ellipse. The superposed vectors represent the linearly polarized flux density, whose scale is given on the top right-hand side. In the maps of components, the arrows indicate the direction of the quasar nuclei, the optical positions of which are shown by crosses, if full maps are published.

Figure 1 — continued

(vii)

(viii)

(ix)

(x)

Figure 1 – continued

(xiv)

(xv)

(xvi)

Figure 1 – continued

(xvii)

(xviii)

(xix)

(a) CONT. LEVS. = -6, 6, 12, 24 mJy/B B = "47, "43, 55°

(b) CONT. LEVS. = 6, 12, 24, 48 mJy/B B = "47, "43, 55°

(xx)

(a) CONT. LEVS. = 1, 2, 4, 8 mJy/B B = "39, "36, 130°

(b) CONT. LEVS. = -1, 1, 2, 4, 8, 16, 24 mJy/B B = "39, "36, 130°

(xxi)

(a) CONT. LEVS. = 0.5, 1, 2 mJy/B B = "40, "38, 96°

(b) CONT. LEVS. = 0.5, 1, 2 mJy/B B = "40, "38, 96°

(xxii)

Figure 1 — continued

(xxiii)

(xxiv)

M=McEwen et al, 1977; G=Ghigo & Owen, 1973.

W-A & W-B = Wills 1979, Comps. A & B

Figure 1 – continued

and cleaning the data with beams of ~ 0.5 , 0.8 and 2 arcsec, giving 2σ limits of ~ 1.5 , 3.5 and 8 mJy respectively.

0835+58. The SW2 component is more diffuse than the SW1 component. Using an interferometer with a base line of 1.26×10^6 wavelengths, Kapahi & Schilizzi (1979) detected a compact hotspot in the SW component which has a maximum correlated flux density of 317 mJy at 1.4 GHz; assuming a spectral index of about -1 , we estimate its peak flux density to be about 100 mJy at 4.87 GHz and its size to be < 0.1 arcsec. This implies that the minimum energy density of the SW1 hotspot has a value appreciably higher than the 3×10^{-8} erg cm $^{-3}$ given in Table 2.

0903+16. The radio structure of this quasar is considerably distorted, similar to that of low-radio luminosity sources located in clusters (Miley 1980). Gopal-Krishna & Swarup (1977) have compared occultation observations at 327 MHz made by Kapahi, Gopal-Krishna & Joshi (1974) with the 5 GHz map by Pooley & Henbest (1974). This comparison indicates that there is diffuse structure with a rather steep spectrum between the two outer lobes.

0911+05. Our cleaned VLA map shows only a central component of peak flux density ~ 48 mJy located near the quasar; the maximum visibility at antenna spacings of about 6000 wavelengths is found to be about 90 mJy. Miley & Hartsuiker (1978) report a double structure at 6 cm with a flux density of ~ 100 mJy in each of the outer components and an overall size of 95 ± 20 arcsec. Our observations indicate that their result could be in error, perhaps due to the low declination. Wardle & Miley (1974) report 0911+05 to be a double source with LAS of 55 arcsec and component sizes of ~ 3 arcsec for the stronger and ~ 7 arcsec for the weaker. Thus there is uncertainty about the angular structure of this low-red-shift quasar and it is not considered further in this paper.

0932+02. The source has a highly asymmetric structure, with the NE lobe located relatively close to the QSO. The resolution of earlier observations was insufficient and it was wrongly classified as a D2 source by Kapahi (1981).

0957+00. A smoothed and cleaned map with 1.7×1.7 arcsec 2 resolution shows an additional component ~ 5 arcsec east and 2 arcsec south of the SE component producing ~ 30 per cent of the flux of the SE component given in Table 1.

1004+13. The outer components of this source are fully resolved out at 5 GHz to < 2 mJy/beam with a resolution of about 0.8×0.7 arcsec 2 . A weak central component is present with a peak flux density of ~ 10 mJy. VLA observations by Fomalont (1981) at 5 GHz and Westerbork observations by Miley & Hartsuiker (1978) at 5 GHz with resolutions of about 4.3×3.3 and 6×26 arcsec 2 respectively show that this source has a prominent

radio lobe located about 70 arcsec to the west of the central component and a radio jet flaring up to a diffuse lobe about 45 arcsec to the east.

1011+28. By combining VLA data at 5 GHz with the interferometric measurements made at 2.7 and 8 GHz by Potash & Wardle (1979), it is seen that the central component has an extended feature of steep spectrum, superimposed on a compact component whose flux density increases towards higher frequency. The full source has a spectral index of -0.96 between 0.4 and 1.4 GHz and -0.27 between 1.4 and 5 GHz.

1100+77. The VLA map indicates a possible radio jet between the quasar and the eastern hotspot. The NW component seems to have a circumferential magnetic field. A recent MERLIN map at 408 MHz made at Jodrell Bank shows a weak diffuse component farther out from the SE component at a distance similar to that of the NW component (Lonsdale & Morison 1983; Miley & Hartsuiker 1978).

1221+18. The radio lobes of this source are relatively relaxed and there are no prominent hotspots at their extremities. The degree of polarization is small.

1244+32. A curved elongated structure is present in the NE lobe, lying between the outermost hotspot and the strong central component of the source. Since the cleaning of the source was poor, our values of the flux densities of the components are not included in Table 1.

1248+30. In a manner similar to the SW component, the NE lobe is also bent towards NW as seen in a map obtained with a resolution of 1.5×1.4 arcsec².

1305+06. The SE component reported by Miley & Hartsuiker (1978) seems to be diffuse, because it is resolved out in the VLA map.

1435+31. The source seems to have a D2 structure, as is also seen by Fanti *et al.* (1977) who report its LAS as 12 arcsec. From maps made with resolutions of 0.4×0.4 arcsec² (see Table 1) and 1.7×1.7 arcsec² (Fig. 1xviii), it is seen that the central component has an unresolved compact core of about 94 mJy with diffuse emission of about 13 mJy. In addition, there exists a NW component whose flux density is greater than 11 mJy. Using a 1.7×1.7 arcsec² resolution, it is found that the central component has a polarized flux density of 1.8 mJy at 54° PA. The spectral index of the source between 408 MHz and 5 GHz is -0.27 .

1545+21. In the map by Pooley & Henbest (1974) made with the Cambridge 5-km radio telescope at 5 GHz, the NE radio lobe is appreciably extended towards the west. The redshift of the quasar is 0.264 which is close to that of a nearby cluster of galaxies (Oemler, Gunn & Oke 1972; Baldwin 1975).

1602+00. This QSO is clearly a triple source, although Wills (1979) reported it to be only a double. The flux density of the central component given by him is likely to be the sum of the values for our central and eastern components. The quasar has a strong central component and is known to be a variable source at cm wavelengths (Wall 1972; McEwan, Browne & Crowther 1975).

1606+28. A map with a 2×2 arcsec² beam shows a central component with 6 mJy peak value at about 3 or 4 rms level, but a map with a 0.4×0.4 arcsec² beam shows only a peak value of < 2 mJy. This indicates that the central component may be extended without a compact region, which is unusual.

1618+17. A radio jet is seen between the SE component and the QSO by Wardle & Potash (1982), and their map also reveals that the direction of energy-flow bends by about 90° beyond the SW hotspot to form a diffuse lobe. This is not seen in our map because of the limited dynamic range.

1704+608. A low-resolution map made with a 20×23 arcsec² beam at 1.4 GHz shows a weak south-western component (Mackay 1969; Kronberg, Clarke & van den Bergh 1980), and a weak central component is seen by Riley & Pooley (1975), Laing (1981) and Kronberg *et al.* (1980).

1739+18. The VLA 'A' configuration with a smoothed beam of 0.74×0.65 arcsec² shows only a compact component of size < 0.3 arcsec with a peak of 21 mJy and a total flux density about 31 mJy. The map given in Fig. 1(xxv) was observed with the 'B' configuration of the VLA in 1982 August by D. J. Saikia. It has two extended lobes with weak hotspots and has a 'C'-shaped geometry.

2318+02. Fig. 1(xxvii) shows a map made with a beam of 1.9×1.32 arcsec². The feature seen in the map has a compact component with an extended tail, and corresponds to the component B of Wills (1979). No other radio component with a brightness above 2 mJy/beam area is seen within ± 60 arcsec of this feature. The QSO lies about 34 arcsec to the north-east of this feature. The centroid of the radio source at 365 MHz (Ghigo & Owen 1973) is only ~ 7 arcsec to the north of the feature seen by us. At 365 MHz, Cotton, Owen & Ghigo (1975) report it to be either a double radio source of separation 40 ± 15 arcsec along PA $170^\circ \pm 10^\circ$, or an elliptical source with a size 51 ± 17 arcsec in PA $= 106^\circ \pm 15^\circ$. The size of the double radio source given by Wills (1970) is 68 arcsec. These data might indicate that the radio source is a D2 quasar. In that case the linear size of the radio source would be unusually large for a quasar at $z = 1.968$. Also D2s tend to have prominent central components associated with the quasar (Kapahi 1981) while here a central component is not detected. However, it is possible (Wills 1979) that the QSO may not be associated with this radio source. To determine the overall structure and identification of this radio source, it should be mapped with a lower resolution than used here. For the present, we do not consider it as a confirmed quasar.

3.4 DERIVED PARAMETERS OF QUASARS

Table 2 gives derived physical parameters for 31 quasars. Data for quasars 0017+15 (3C9) and 1258+40 (3C 280.1) given by Swarup *et al.* (1982a) are also included, but not the sources 0911+05 and 2318+02 described in Section 3.3, for the reasons given there. Values of $q_0 = 0$ and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ have been assumed. Table 2 is arranged as follows:

- (1) The source name.
- (2) 3C, 4C or B2 name.
- (3) Redshift.
- (4) The flux density at 178 MHz, S_{178} . The values have been taken from Jenkins, Pooley & Riley (1977) and Gower, Scott & Wills (1967), and have been multiplied by correction factors of 1.05 and 1.11 respectively as determined by Kühr *et al.* (1979). For B2 sources, the flux densities were extrapolated from 408 to 178 MHz using the known values for the spectral indices.
- (5) The radio luminosity, P_{178} , at the emitted frequency of 178 MHz. This is derived from S_{178} and the value of the low-frequency spectral index, the latter taken mostly from Hooley *et al.* (1978) and Wills & Lynds (1978). For some cases the spectral index was found by plotting the known flux densities at different frequencies.
- (6) Component designation.
- (7) Estimated flux density, S_h , of the hotspot derived by multiplying its observed peak flux density (Table 1, column 8) by the ratio of the observed area of the hotspot (based on the measured FWHP before deconvolution) to that of the VLA beam used for mapping the source. An asterisk (*) indicates that only the peak value is given and is the same as in column 8 of Table 1; this is the case for central components and very weak hotspots.
- (8) The first row against each source gives the total flux density at 5 GHz, S_t . The value given against each component is its estimated flux density, S_1 (Table 1, columns 9 or 10).

Table 2. Derived parameters of the quasars.

Name	Other name	z	P_{178} 10 ²⁶ W Hz ⁻¹ Jy	Comp	S_h mJy	S_t mJy	C_s C_h	f_c f_n	ℓ_1 kpc	ℓ_2 kpc	ℓ_3 kpc	Type	Q_{15} deg	L kpc	u_{min} 10 ⁻⁹ erg cm ⁻³	B 10 ⁻⁴ G	τ 10 ⁴ yr	PA deg	PA Comp	PA Pol	RM deg	PA intr.	ΔPA deg
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
0017+15	3C 9	2.012	18.7	1031	NW CN SE1 SE2	50 3* 30 160	360	.43 .25 .08 .44	<.01	9.1	7.8	8.4	M	5	162	2.8	1.7	9				-22	
0118+03	4C 03.02 3C 39	0.765	6.8	25	NW CN SE2	4* 29* 13	286 112 33 141	.07 .04 .88 .09	.12				L	9	438							-5	
0133+20	3C 47	0.425	27.7	25	SW1 CN NE	225 57* 6*	1052 560 420	.24 .40 .01	.07 .79	5.5	3.1	4.3	H	9	514	0.5	0.7	46				-23	33 + 5
0229+34	3C 68.1	1.238	13.4	157	NW1 NW2 CN SE	358 94* 3* 3	800 700 100	.57 .13 <.03	<.01	9.4 7.9	2.7 3.7	6.1 5.8	H M	11	675	13.3 4.7	3.8 2.2	5 9	170 173	104 171		-63	118 -62 185 +12
0312-03	4C-03.11	1.072	7.1	57	SW1 SW2 CN NE	47 76 4* 47	338 167 6 165	.51 .28 .46 .28	.02 .66*	3.5 2.9 2.9	2.9 2.3	3.2 2.6	H H	7	471	5.5 10.2	2.4 3.3	7 5	17 12	136 62	+15*	133 -64 59 +47	
0808+28	B2	1.910	0.5	17	NW CN	< 2 25*	56 42	<.04 .60	.75				L L		436						+20*		
0835+58	3C 205	1.534	13.2	285	SW1 SW2 CN NE	202 149 24* 106	677 450 24 203	.70 .45 .33 .52	.04 .45 1.0 5.0	3.6 10.1 3.3	2.1 6.8 4.2	2.9 8.5	H M	1	193	30.7 3.7	5.7 2.0	2 9	15 8	63 90	-15	66 +51 93 +85	
0901+28	B2	1.121	0.4	3	SW CN NE	4* 28* 14	89 21 33 35	.32 .19 .85 .40	.37	7.9	1.9	4.9	H	2	264	1.4	1.2	27				-9*	58 +42
0903+16	3C 215	0.411	12.0	10	NW CN E SE	2* 17* 7 11	410 160 20 150	.05 .01 .85 .07	.04				L	40	221						31		
0922+14	4C 14.31	0.896	5.9	34	SW CN NE1 NE2	9* 35* 49 36	227 85 26 116	.47 .10 1.34 .31	.11	7.6 4.4	4.3 1.6	5.9 3.0	M			1.8 >.4	1.4 >2.6	16 < 8	18 20	85 38	+16*	82 +64 35 +15	

Table 2 — continued

Name	Other name	z	S ₁₇₈ 10 ²⁶ W Hz ⁻¹	P ₁₇₈ 10 ²⁶ W Hz ⁻¹	Comp	S _h mJy	S _t mJy	S _c mJy	f _c f _n	ℓ ₁ kpc	ℓ ₂ kpc	ℓ ₃ kpc	Type	Q _{mis} deg	L kpc	u _{min} 10 ⁻⁹ erg cm ⁻³	B 10 ⁻⁴ G	τ _{10⁴ yr}	PA Comp Pol	PA RM	PA intr	PA APA	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
0932+02	4C 02.27	0.659	4.1	10	SW	13	256	.24	.38	9.2	6.0	7.6	H	8	438	0.3	0.6	67	48	147	149	-79	
					CN	82*	105	.12	.85	2.7	1.7	2.2	H			4.2	2.1	10	56	82	84	+28	
					NE	25	54	.46															
0957+00	4C 00.34	0.907	6.8	36	NW1	39	358	.45	.35	6.3	5.2	5.7	M	19	352	1.4	1.2	20	95	145	146	+21	
					NW2	37	136	.27	.23	8.3	5.2	6.8	M			1.2	1.1	25	94	30	31	-63	
					NW3	22	125	.16	.59	6.7	4.7	5.7	M			1.1	1.1	26					
					CN	74*	97	.07					M										
					SE	7*																	
1004+13	4C 13.41	0.240	5.7	1	NW	10*	579	.02					L	2	356							-16	
		0.241			CN		206		.77				L										
					SE		141						L										
1011+28	4C 28.25	0.899	2.8	13	NW	8*	245	.34	.29				L	7	153							21*	
					CN	56*	34	.24	.78	7.5	5.0	6.3	L			1.5	1.3	20	106	125	120	+14	
					SE	51	140	.36					M										
1100+77	3C 249.1	0.311	13.1	6	NW	158	956	.29	.10	7.5	4.9	6.2	H	>10	141	0.7	0.9	43	101	65	71	-30	
					CN	70*	590	.27	.70				M										
					SE1	7	266	.03	.03														
					SE2	8		.27		2.1	<.9	<1.5	H			>6.6	>2.7	<9	91	85	91	0	
					SE3	71																	
1137+66	3C 263	0.652	15.9	36	NW	18	1009	.61	.17				H	0	407							6	
					CN	164*	152	.12	.97				L										
					SE	516	688	.75		2.9	<1.4	<2.1	H			>28	>3.5	<3	112	101	100	-12	
1221+18	4C 18.34	1.401	2.3	36	NW	41	161	.43	.12	15.1	6.6	10.9	M	10	282	1.3	1.2	23	120	42	42	-78	
					CN	20*	83	.55	1.0	8.1	5.6	6.9	M			1.4	1.2	15					
					SE	20	78	.26															
1244+32	4C 32.41	0.949	2.8	14	SW	6*	170	.33	.42				H	20	282							-4*	
					CN	44*	38	.16	.62				L										
					NE1	11	71	.25		6.2	2.4	4.3	H			1.8	1.4	20					
					NE2	15	44	.34		4.9	2.1	3.5	H			2.8	1.7	14					
1248+30	4C 30.25	1.061	2.9	25	SW	34	104	.39	.03	5.9	3.2	4.6	H	6	317	2.9	1.6	13	53	25	28	-25	
					CN	3*	56	.59	1.0				L										
					NE	5*	43	.12															
1258+40	3C 280.1	1.639	12.5	399	NW	175	312	1.0	.09	11.3	6.9	9.1	M	15	288	4.1	2.1	8	107	36	41	-66	
					CN	26*	175	1.0	1.0				M										
					SE1	10	26	.09		6.3	<1.9	4.1	M			>5.0	>2.3	<9					
					SE2	30		.27		17.0	4.3	10.8	M			2.6	1.8	18					
					SE3	33	111	.37		22.7	8.2	15.5	M			0.7	0.9	32					
					SE4	41		.74		27.7	8.2	15.5	M			0.7	0.9	32					

1303+06	4C 06.45	0.599	6.1	11	SW CN NE	< 2 12* 39	314 115 160	.13 <.02 .24	.05 .80	4.3	3.5	3.9	H	3	356	1.4	1.3	21	13	5	-6°	7	-6
1435+31	B2	1.366	0.32	3	NW CN	5* 94*	135 28 107	.18 .18 .88	.79 .88				L		143						+9		
1545+21	3C 323.1	0.264	11.1	3	SW1 SW2 SW3 CN NE1 NE2	15 50 32 32* 74 100	910 278 30 516	.30 .05 .18 .12 .14 .18	.03 .05 .18 .12 .14 .18	1.8 4.2 3.0 3.0 6.1	1.6 2.8 2.1 2.9 3.5	1.7 3.5 2.6 3.0 4.8	H	1	383	1.2 0.8 1.1 1.2 0.8	1.2 1.0 1.1 1.1 0.9	27 39 33 27 43	22 21 20 21 21	160 39 33 170 88	+14	157 36 15	-45 15
1602-00	4C-00.63	1.625	5.7	154	W CN E1	63 165* 40	295 80 50	.79 .79 .80	.56 1.0	2.9 3.9	<1.9 2.6	<2.4 3.2	H	11	320	>22.2 9.8	>4.9 3.3	< 2 4	86 83		-1	83	-3
1606+28	4C 28.4C	1.989	3.9	169	NW CN SE	39 6* 23	162 71 78	.42 .55 .29	.08 .46	4.5 4.6	<1.9 3.0	<3.2 3.8	H	13	385	>17.1 7.6	>4.3 2.9	< 3 5	135 148	165 132	+27*	159 126	+24 -22
1618+17	3C 334	0.555	11.4	19	NW CN SE	4* 152* 13	720 310 200	.03 .01 .07	.24 .89	6.2	2.2	4.2	L	1	390				129 132	13 159	+41	4	+55
1622+23	3C 336	0.927	12.1	64	SW1 SW2 CN NE	116 41 26* 265	699 230 29 440	.63 .50 .18 .60	.04 .90	4.6 4.7 11.4	3.7 1.6 6.3	4.1 3.1 8.8	H	13	241	4.8 6.9 2.5	2.3 2.7 1.6	8 8 15	25 27 37	0 172 20	+33	-7 165 13	-32 -42 -24
1704+60	3C 351	0.371	14.4	9	SW CN NE1 NE2	15 444 179	1250 200 650 310	.50 .01 .68 .56	.01	6.3 1.4	5.0 1.3	5.7 1.4	M	12	395						0*	15 64	-19 +19
1739+18	4C 18.51	0.186	5.6	1	NW1 CN SE1 SE2	5 21* 11 10	253 114 31 107	.12 .04 .08 .09	.12	5.7 9.8 6.7	5.5 3.2 <0.8	5.6 6.5 <3.8	L	4	891	0.1 0.1 >0.7	0.2 0.4 >0.8	270 210 <84			+50*		
2131+17	4C 17.87	1.215	2.4	28	SW1 SW2 CN NE	4 14 20* 20	93 35 19 39	.51 .11 .40 .51	.20	4.7 3.2 10.0	3.9 2.7 6.3	4.3 3.0 8.1	M	11	359	1.9 0.9	1.4 1.0	15 27			-38*		
2325+29	B2 4C 29.68	1.015	7.4	52	NW CN SE1 SE2	4* 34* 13 70	382 114 37 213	.27 .04 .06 .33	.10 .92	8.6 4.1	4.2 2.3	6.4 3.2	L	5	561				30 6	113 67	(-199*)	(110)(-3)	

(9) The first row against each source gives a 'compactness parameter', C_s , equal to the fraction of the total flux density in various hotspots to the integrated flux density of the source minus the value of the central component. In the subsequent rows for each source, the fraction, C_h , of the flux density of the hotspot to that of the corresponding radio lobe is given.

(10) The first row gives the fraction, f_c , which is the ratio of the flux density of the central component to that of the entire source as measured at 4.87 GHz. The value, f_n , given in the row marked CN (central component), is the ratio of the peak value to the total flux density of the central component. It is generally < 1 as expected, but is > 1 for three sources (0922 + 14; 1545 + 21; 2131 + 17) perhaps arising from errors of measurement.

(11), (12) and (13) Linear sizes l_1 and l_2 of hotspots derived from the observed FWHP values ψ_1 and ψ_2 (Table 1) along their major and minor axes respectively. Column 13 gives the mean sizes l_3 .

(14) Classification of the quasars and the type of each hotspot, according to the scheme described in Section 4.1

(15) The 'mis-alignment' angle between the lines joining the central component to the brightest hotspots on opposite sides of the quasars or to the centre of the extended lobe if no prominent hotspot is seen.

(16) The physical projected size of the quasar derived from its LAS.

(17) and (18) The minimum energy density, $u_{\min}$, and the equipartition value of the magnetic field, B , using the equations given by Pacholczyk (1970). The volume of the hotspot has been taken as $\pi l_1 l_2^2/4$, assuming a cylindrical geometry. A filling-factor of unity is assumed for the volume occupied by the relativistic particles and magnetic fields. The ratio of the energy of protons to that of electrons is taken as unity. A spectral index of -0.65 has been assumed for all the hotspots, as the spectral index of a hotspot is generally flatter than that of the entire radio source (Laing 1981).

(19) The lifetime, τ_s , considering both the synchrotron and inverse Compton losses incurred by the electrons radiating at 4.87 GHz, using equations given by van der Laan & Perola (1969).

(20) The position angle, PA, of the line joining the hotspot to the central component of the quasar.

(21) The polarization position angle of the observed peak polarized intensity of the hotspot.

(22) The rotation measure, RM, of the quasar obtained from Simard-Normandin, Kronberg & Button (1981). Using their measurements, for quasars for which no values of RM are available, a value of the foreground RM has been estimated by averaging the RMs of other extragalactic radio sources located within a radius of 10° of the quasar. Such values are marked by an asterisk.

(23) The intrinsic position angle of the peak polarization vector of the hotspot, after correcting the values given in column 21 for the Faraday rotation corresponding to the measured or estimated RM.

(24) The difference of the intrinsic position angle of the polarization vector of the hotspot and the line joining the hotspot to the central component (column 23—column 20).

4 Discussion

4.1 THE STRUCTURE OF RADIO LOBES

As seen in Fig. 1, prominent hotspots are located near the outer edges of the radio lobes of many steep-spectrum quasars in our sample. In some cases, multiple hotspots are found

within the same radio lobe. Also, in some of the sources, hotspots are found to occur prominently in just one lobe. Although the spatial resolution attained can be expected to influence the observed shape of fine structure in radio lobes, the present observations do reveal several examples of sources where the two radio lobes have structures showing an inversion symmetry about the nucleus. A precession of the energy beams emanating from the nucleus might give rise to such inversion-symmetric structure, the broader portions of which could be the remnants of older hotspots (see Miley 1976; Bridle *et al.* 1976; Ekers *et al.* 1978). According to Laing (1983) on the other hand, even such broader components are probably being fed currently with energetic particles continuously flowing out of the compact hotspots, the latter marking the regions where the beam of particles emanating from the nucleus impinge on the intergalactic medium. By a parallel argument, the less compact hotspots of size ~ 10 kpc seen in some sources might result from beams having relatively large opening-angle and thus need not necessarily be much older than compact hotspots existing in the same source (Laing 1983). The present observations do not show any obvious inconsistency with these morphological aspects.

We shall now examine if, for our sample of quasars, the compactness parameter, polarization and size of the hotspots (Section 3.4) vary appreciably as a function of radio luminosity, LAS or redshift of the quasar. It should first be noted that the angular resolution of about 0.4 arcsec attained in the present observations corresponds to a linear resolution of 2.1, 3.2, 4.4 and 5.2 kpc at $z = 0.25, 0.5, 1$ and 2 respectively. To reduce this disparity we have smoothed the maps to a resolution of 0.8 arcsec which corresponds to a linear resolution of 4.2 kpc at $z = 0.25$, close to that provided by the full-resolution beam of 0.4 arcsec for sources $z \sim 0.9$. However, this degrading of angular resolution for sources at smaller redshifts did not appreciably alter the value of the compactness parameter C_h taken over all the hotspots given in a radio lobe (Table 2, column 9). Therefore, for simplicity, we shall only consider the parameters given in Tables 1 and 2, which are mostly derived from the full-resolution maps except for the cases when only lower-resolution data are given in Table 1. In order to examine any trends of the types mentioned above, we have divided the quasars broadly into three categories depending upon the size and compactness parameter of their hotspots:

(1) High-brightness quasars (type H): Quasars falling in this category have at least one compact, prominent hotspot with $l_2 < 4$ kpc and $C_h \geq 0.2$. For such quasars, Fig.2(a) displays the distribution of ΔPA (Table 2, column 23), the difference between the position angles of the intrinsic linear polarization vector and the line joining the hotspot to the quasar nucleus. It is seen that, for nearly two-thirds of such hotspots, the intrinsic direction of magnetic field lies within $\pm 30^\circ$ of the perpendicular to the axis joining the hotspot to the nucleus. This supports the idea that such prominent hotspots are formed as a result of compression of magnetic field at the point where the energy beam from the nucleus impinges on the intergalactic medium (see Laing 1980). The degree of polarization appears to be generally high for hotspots of this type.

(2) Medium-brightness quasars (type M): The hotspots in this category of quasars are defined to have $4 \leq l_2 \leq 10$ kpc and $C_h \geq 0.1$. We have also included in this category a few quasar lobes (0229 + 34 NW2; 0901 + 28 SW; 1545 + 21 NE1–NE2, 1622 + 23 SW2; 2131 + 17 SW2) containing a hotspot which is compact ($l_2 < 4$ kpc) but not very prominent ($0.1 < C_h < 0.2$). As seen from Fig. 2(b), the values of ΔPA for the medium-brightness quasars are more or less uniformly distributed between 0° and 90° , in contrast to the peaked distribution found for the high-brightness quasars. In some of the well-resolved hotspots, the magnetic field is found to be circumferential (1100 + 77 NW; 1545 + 21 NW; 1622 + 23 NE; 1704 + 60 NE1).

Figure 2. The distribution of ΔPA giving the difference between the position angles of the intrinsic linear polarization vector and the line joining the hotspot to the quasar nucleus: (a) for type H (high brightness) hotspots and (b) for type M (medium brightness) hotspots. The hotspots with clearly seen circumferential magnetic fields are shown by open boxes.

(3) Low-brightness quasars (type L): In these quasars, no prominent hotspots of size < 10 kpc and $C_h > 0.1$ are seen. The radio lobes of this category may be considered to have a relaxed morphology. The absence of prominent hotspots may imply that the extended regions are not now being supplied with energy.

4.2 THE DEPENDENCE OF HOTSPOT SIZE ON z , P_{178} AND LAS

Although the measured size can depend weakly on angular resolution, any marked variation of angular sizes of hotspots with z , P_{178} or LAS should still be discernible in our data. In Fig. 3 the angular sizes ψ_2 of hotspots belonging to the high- and medium-brightness categories (indicated by crosses and dots respectively) are plotted against redshift. The circled points refer to upper limits. Points representing different hotspots in the same quasar are joined by a vertical line. The angular sizes plotted are those measured along the minor axes of the hotspots (Table 1, column 15), as these may be less subject to projection effects. The letters A and B in Fig. 3 refer to 3C 280.1 and 3C9 which show intense extended jets containing a few knots; the angular sizes of the most prominent knots have also been plotted in these cases.

The plotted data points have been compared with the expected variation of angular size with redshift for standard rods having projected lengths of 2.5 and 5 kpc (assuming $q_0 = 0$). These are shown in Fig. 3 as full and broken curves respectively. At first glance, the observed sizes of hotspots at high z appear to be somewhat larger than expected for a standard rod. This seems, however, more likely to be an artefact of the degradation of linear resolution with increasing redshift, which might tend to blend multiple hotspots into a single feature. It seems that the size of the hotspots is independent of redshift (Duffett-Smith & Purvis 1982). Our observations also indicate that sizes of hotspots do not depend on LAS.

In Fig. 4 we have plotted the average physical size l_3 of hotspots (Table 2, column 13) versus P_{178} of the observed quasars. The symbols are as for Fig. 3. Apparently, the value of l_3 shows no marked increase with P_{178} , nor is l_2 dependent on P_{178} . This is in contrast to the inference made by Readhead & Hewish (1976) from their interplanetary scintillation (IPS) observations at 80 MHz. It is likely that the IPS sizes are affected by the increasing

Figure 3. Plot of angular size, ψ_2 , of hotspots versus redshift z . Hotspots of type H and M are indicated by crosses and dots respectively. The circled values refer to upper limits. Values for the same quasar are joined by a vertical line. The full and broken curves are expected variations for linear sizes of 2.5 and 5 kpc respectively.

blending of multiple hotspots and radio lobes with z , owing to the expected degradation of the IPS resolution at higher redshift in terms of linear size (Swarup & Bhandari 1976; Kapahi 1978; Duffett-Smith & Purvis 1982). The blending is likely to be much less severe for the present observations which have been made with higher resolution. It is also likely that compact hotspots seen in quasars of high radio luminosity are self-absorbed at 80 MHz

Figure 4. Plot of I_3 versus $\log_{10} P_{178}$. The symbols are as in Fig. 3.

Figure 5. The compactness parameter C_s is plotted against z in (a) and $\log_{10} P_{178}$ in (b). The crosses, dots and open circles refer to hotspots of type H, M and L (low brightness) respectively.

(Laing 1981), which could lead to a positive correlation of l_2 with P_{178} as found by Readhead & Hewish (1976).

4.3 DEPENDENCE OF C_s ON P_{178} , z AND PHYSICAL SIZE L

From Fig. 5(a, b), the value of the compactness parameter for the entire source, C_s , appears to increase significantly with z and hence also with P_{178} , for a flux-density limited sample. Actually, C_s seems to be better correlated with P_{178} than with z . The correlation between C_s and P_{178} is in accordance with the findings of Jenkins & McEllin (1977).

Macklin (1982) has noted a trend for the compactness parameter to decrease with the overall physical size L for 99 3CR double radio sources, but we find no significant dependence of C_s on L for our sample of 31 quasars located near the upper envelope to the LAS- z diagram.

4.4 THE RELATION BETWEEN LAS AND z

Fig. 6 is a plot of LAS versus z for 199 quasars selected from 3CR, 4C and B2 samples (Hooley *et al.* 1978; Stannard & Neal 1977; Wills 1979; Fanti *et al.* 1975, 1977). The circled numbers near the bottom edge of the diagram refer to the quasars with $LAS < 7$ arc-sec falling in the various ranges of redshift described in Section 2. The quasars for which VLA maps were not available are shown by small circles, while those mapped with the VLA are shown by circles, triangles and squares depending upon their radio luminosities falling in the ranges < 10 , $10-100$ and $> 100 \times 10^{26} \text{ W Hz}^{-1} \text{ sr}^{-1}$, respectively. The indicators are shown filled, half-filled and unfilled for quasars belonging to the high-, medium- and low-brightness categories respectively. Note that VLA data are available for a total of 34 quasars, 29 being taken from the present sample (see Section 3) and five from other sources (Swarup, Sinha & Saikia 1982a; Stocke, Christiansen & Burns 1982; Neff 1982). The new data have significantly improved the information for sources near the upper envelope to the LAS- z diagram.

The expected variation of LAS with z for a quasar of $L = 600$ kpc in a Friedmann universe with $q_0 = 0$ is shown by a continuous curve in Fig. 6. The broken line gives the relation $LAS \propto z^{-1}$ expected for a quasar having $L = 1000$ kpc in a Euclidean universe. These two curves are consistent with the upper envelope of the plotted data points at lower z , although at redshifts beyond ~ 1.5 a deficiency of large quasars is found relative to the prediction for the Friedmann universe. The deficiency could, however, be merely an artefact of a possible anti-correlation between P_{178} and L (e.g. Jackson 1973; Richter 1973; Stannard & Neal 1977; Hooley *et al.* 1978; Masson 1980; Macklin 1982).

It may be expected that radio sources located near the upper envelope to the LAS- z diagram at any z are in a comparatively advanced stage of evolution, in which case the energy supply from the nucleus may decrease and prominent hotspots may not be present in many of these sources. Although we do not find prominent hotspots (type L) for nine out of the 34 quasars for which the VLA data are plotted in Fig. 6, the quasars of low-brightness category (type L) occur not only near the upper envelope but also at smaller values of LAS. To investigate whether there is an inverse correlation between L and P or a linear-size evolution with z (Wardle & Miley 1974; Kapahi 1975), it would be desirable to make high-resolution observations of a larger sample of high-redshift quasars whose flux densities are well below those of the 4C sample, so that the radio luminosities of these objects are comparable with those of low-redshift quasars.

Figure 6. Plot of Largest Angular Size against z . Quasars with $\log_{10} P_{1.78} < 10$, $10-100$ and $> 100 \times 10^{26} \text{ W Hz}^{-1} \text{ sr}^{-1}$ are shown with circles, triangles and squares respectively. The symbols are filled, half-filled and open for type H, M and L hotspots. Quasars for which no VLA data are available are marked with small circles.

4.5 THE CENTRAL COMPONENTS

In several quasars of the present sample, the central component is partially resolved, indicating a size of 1–2 kpc. In fact the general trend is that the ratio of the peak to integrated flux density of the central components, f_n , is significantly less than 1, the average value being 0.87 for 25 quasars with central components (Table 2, see column 10 against the row CN). The same value of f_n is found for sources having the self-calibrated maps and hence

this estimate is unlikely to be a consequence of any atmospheric phase-deviations arising across the aperture of the VLA during our observations. It appears therefore that the extended emission accounts for nearly 10 per cent of the total radio output from the central components at 5 GHz, on average. This estimate is unlikely to have been much affected by any Doppler boosting of the nuclear emission due to relativistic motions, as the overall angular sizes of the sources in the present sample are among the largest known at any given redshift and hence their radio axes are expected to lie well away from the line of sight.

The fraction, f_c , of the flux density of the central component to the total flux density of the 31 quasars (Table 2, column 10) is found to have a median value of ~ 0.1 at 5 GHz. The median value of f_c for 23 quasars with $f_c < 0.25$ is 0.08. There seems a trend for f_c to increase with redshift, as seven out of the eight quasars having $f_c > 0.25$ lie at $z \gtrsim 0.9$. The higher f_c for high-redshift quasars may be a consequence of relativistic beaming if their axes lie closer to the line of sight (Ulvestad *et al.* 1981; Orr & Browne 1982). For quasars with higher f_c , Kapahi & Saikia (1984) have shown that the degree of misalignment of the outer lobes with respect to the central core is, on average, higher. A similar trend is noticed for some quasars with higher f_c in our sample (0957+00; 1244+32; 1602+00) as may be seen from Fig. 1 and Table 2.

From high-resolution observations of 32 3CR quasars, Orr & Browne (1982) have estimated the ratio R_T of the flux density of the beamed central component ($\alpha = 0$) to that of the unbeamed extended components ($\alpha = -1$) when the radio axis is transverse to the line of sight. They have estimated that $R_T = 0.024$ at 5 GHz (emitted) and the Lorentz factor $\gamma = 5$. Assuming that the 23 quasars in our sample located near the upper envelope to the LAS- z diagram, and having $f_c < 0.25$, subtend an angle to the line of sight uniformly distributed between 60° and 90° , the average Doppler-enhancement factor is 1.32 for $\gamma = 5$. The median value of z for the 23 quasars is 0.8. Hence, we estimate R_T (5 GHz emitted) $\cong (1.32)^{-1} \bar{f}_c \bar{f}_n (1 - \bar{f}_c \bar{f}_n)^{-1} (1+z)^{-1} \cong 0.033$, taking the averages $\bar{f}_c = 0.08$ and $\bar{f}_n = 0.9$ according to our observations at 5 GHz. This estimate is comparable to, though on the higher side of, the value of $R_T = 0.024$ estimated by Orr & Brown (1982).

5 Conclusions

High-resolution observations have been made of 28 quasars selected from the 3C and 4C complete samples and three from the B2 sample of quasars. It is found that:

(1) About a quarter of the quasars located near the upper envelope to the LAS- z diagram show only relaxed lobes in which no prominent hotspots are seen. This may imply that their radio lobes are currently not being supplied with energy.

(2) About 60 per cent of the quasars contain at least one compact hotspot of size < 4 kpc in the direction of minor axis and having a compactness parameter $C_h > 0.2$. For nearly two-thirds of these hotspots, the magnetic field directions are found to be nearly perpendicular to the lines joining the hotspots to the quasar nuclei, supporting the hypothesis that a prominent hotspot is formed as a result of compression of magnetic field at the point where the energy beam from the nucleus impinges on the intergalactic medium.

(3) The linear sizes of hotspots show no marked dependence on z , LAS or P_{178} , but the fraction of flux density in the hotspots to that of the radio lobes, C_s , is well correlated with P_{178} , confirming the trend noticed by Jenkins & McEllin (1977).

(4) There seems to be a deficiency of large quasars relative to the prediction of a Friedmann universe, for $z \gtrsim 1.5$. This may arise either from an inverse correlation between L and P , or from the evolution of linear size with z . High-resolution observations for a sample

of high-redshift quasars, complete to much lower flux density level than that of the 4C sample, may allow a choice between these possibilities.

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