Aust. J. Phys., 1974, **27**, 121–8

Structure of 194 Southern Declination Radio Sources from Interplanetary Scintillations

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Abstract

Interplanetary scintillation observations of 194 southern declination radio sources have been made at 327 MHz. The angular size and the fraction of the flux present in the scintillating component have been estimated. More than half of the observed sources scintillate and contain $\geqslant 10\%$ of their flux in angular size smaller than $0''\cdot 5$. About 75% of the quasars and $\sim 50\%$ of the galaxies and the blank field objects scintillate. For quasars the spectral index seems to be correlated with the strength of scintillation; most of the flat spectrum quasars are strong scintillators and are unresolved. The scintillating properties of blank field objects are consistent with Bolton's hypothesis that most of these are galaxies beyond the plate limit of the Sky Survey.

1. Introduction

Resolutions of less than a second of arc at radio frequencies can be achieved by very long baseline interferometry (VLBI) and also by the study of interplanetary scintillations (IPS). The VLBI technique has been used mainly at centimetre wavelengths and observations have been made only for a limited number of radio sources. The complexity of VLBI observations makes it impractical to carry out large surveys to detect compact components in radio sources. The IPS technique, on the other hand, achieves a fairly high resolution with a comparatively simple experimental setup. Unlike VLBI the resolution in IPS is relatively independent of the frequency of observation and this makes it more useful at long wavelengths. IPS surveys have been made at 81·5 MHz by Burnell (1972), at 178 MHz by Little and Hewish (1968) and at 430 MHz by Cohen *et al.* (1967) and Harris and Hardebeck (1969). These authors have derived the structure of about 500 radio sources in the declination range 0° to +40°. However, only a limited number of sources in the southern sky have been studied so far. In this paper we report the IPS observations of 194 radio sources between declinations 0° and −30°. The observations were made at 327 MHz with the Ooty radio telescope (Swarup *et al.* 1971).

2. Observation and Analysis

Observations were made during the periods March–April and August–December 1971. All sources between declinations 0° and −30° from the Parkes (Ekers 1969) and 4C (Gower *et al.* 1967) catalogues, which were expected to have flux densities greater than 2 f.u.* at 327 MHz, were selected for observations. Of about 500 in this category, only 194 could be observed owing to limited telescope time.

* 1 flux unit (f.u.) = $10^{-26}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$.

The methods of observation and analysis are only briefly described here as the details are given in the preceding paper by Rao *et al.* (1974; present issue pp. 105–20). The receiver bandwidth used for the observations was 4 MHz and the time constant was 0·1 s during March–April and 0·05 s in the second period of observations. The intensity fluctuations were recorded digitally on magnetic tape with a sampling rate of 50 s^{-1}. Normally 6 min of data were acquired with the telescope pointing at the source and 3 min with it pointing at a nearby cold region.

The scintillation index m and the second moment f_2 of the power spectrum were calculated. For sources found to be scintillating, the flux and the angular diameter of the scintillating component were estimated by comparing their m and f_2 values with those for a point source at the same elongation. A study of the scintillating properties of point sources at 327 MHz is described in the preceding paper. If the ratio f_2/f_0, where f_0 is the second moment of a point source at the same elongation, was less than about 0·8, the source was considered to be resolved and its angular diameter ψ was estimated using the relation (Cohen *et al.* 1967)

$$\psi = (v/1\cdot 2\pi f_2 z)\{1-(f_2/f_0)^2\}^{\frac{1}{2}},$$

where v is the velocity of the solar wind and z is the distance to the thin screen; v and z were assumed to have values of 350 km s^{-1} and 1 A.U. respectively. For the resolved sources the scintillation index was corrected for the finite diameter of the scintillating component using the relation (Cohen *et al.* 1967)

$$m_c = m\{1+0\cdot 36(z\psi/a)^2\}^{\frac{1}{2}},$$

where the scale size a of the irregularities producing scintillation was assumed to be equal to 100 km. If the ratio of the second moments f_2/f_0 was $\geqslant 0\cdot 8$, the source was considered to be unresolved and an upper limit on ψ was derived from

$$\psi \leqslant v/1\cdot 2\pi f_2 z.$$

For most of the unresolved sources this limit is about $0''\cdot 15$, although slightly better estimates are available for some. We have, however, used $0''\cdot 15$ as the upper limit for all unresolved sources.

The fraction μ of the total flux of the source in the scintillating component is given by the ratio of the scintillation index of the source to that of a point source at the same elongation from the Sun. For the resolved sources the corrected value of m was used in calculating μ. For sources which did not show any scintillation, upper limits on μ were estimated from the system noise and the elongation of the source.

From the detailed observations of point sources we find that the day to day fluctuations in m and f_2 have an r.m.s. value of the order of 15%. For most of the sources in the present survey there is more than one observation and so our estimates of μ and ψ are believed to be correct to within 15%.

3. Results and Discussion

The results on the structure of radio sources derived from the observations are given in Table 1, in which the sources are listed in order of increasing right ascension. Column 1 gives the source number in Parkes or 4C nomenclature and column 2 the

Table 1. Source structure from interplanetary scintilations at 327 MHz

(1) Source No.	(2) 3C No.	(3) Optical identi-fication	(4) Fraction μ of flux in scint. component		(5) Res. or unres.	(6) Cor-rected μ	(7) Angular diam. ψ ″	(8) Other IPS observations		
								μ	ψ ″	Freq. (MHz)
0003−00	3C2	Q	S	0·6	UR	—	⩽0·15	0·5	<0·1	178
								0·6	⩽0·06	430
0005−06	3C3?	G	S	0·7	R	0·8	0·25			
0013−00		Q?	S	0·6	R	0·7	0·2			
0016−12			N	<0·2	—	—	—			
0016−10			N	<0·2	—	—	—			
0018−09			N	<0·3	—	—	—			
0018−01			S	0·7	UR	—	⩽0·15	1·0	⩽0·15?	430
0019−00			S	1·0	UR	—	⩽0·15			
0020−08			N	<0·3	—	—	—			
0023−13			S	0·3	UR	—	⩽0·15			
0027−12			N	<0·4	—	—	—			
0029−01			N	<0·5	—	—	—			
0031−07		D	S	0·2	R	0·25	0·2			
0034−01	3C15?	E	N	<0·1	—	—	—	<0·2	—	178
								<0·1	—	430
0035−02	3C17?	E	N	<0·1	—	—	—	<0·2	—	178
0044−05			S	0·6	UR	—	⩽0·15			
0046−06			N	<0·4	—	—	—			
0047−02			N	<0·2	—	—	—			
0047−10			S	1·0	UR	—	⩽0·15			
0051−03	3C26	E	S	0·5	UR	—	⩽0·15			
0056−00		Q	S	1·0	UR	—	⩽0·15	1·0	⩽0·08	430
0115−01		N	S	1·0	UR	—	⩽0·15			
0117−15	3C38		N	<0·2	—	—	—			
0119−04		Q	S	0·8	UR	—	⩽0·15			
0122−00		Q	S	0·6	UR	—	⩽0·15	1·0	⩽0·2	430
0123−01	3C40	db	N	<0·1	—	—	—	<0·2	—	178
								<0·05	—	195
0129−07			S	1·0	UR	—	⩽0·15			
0131−00		E	S	0·75	UR	—	⩽0·15			
0140−07			N	<0·6	—	—	—			
0140−01			N	<0·2	—	—	—			
0144−05			S	0·4	UR	—	⩽0·15			
0144−02			S	0·6	UR	—	⩽0·15			
0148−09			S	0·3	R	0·35	0·15			
0150−03	3C53?		S	0·7	UR	—	⩽0·15			
0153−05			S	0·9	UR	—	⩽0·15			
0155−10		Q?	S	0·3	UR	—	⩽0·15			
0218−02	3C63	E	N	<0·1	—	—	—	<0·2	—	178
0222−00		S0(E)	S	0·45	UR	—	⩽0·15			
0232−04		Q	S	0·6	—	—	—			
0232−02			S	0·4	—	—	—			
0240−00	3C71	Sc	S	0·25	—	—	—	<0·3	—	178
								<0·1	⩽0·3	195
0300−00		E	N	<0·4	—	—	—			
4C−04·30			N	<0·3	—	—	—			
0919−14			N	<0·5	—	—	—			
4C−04·31			N	<0·2	—	—	—			
0939−11	3C224		N	<0·3	—	—	—			
0941−08		D	S	1·0	UR	—	⩽0·15			
0944−13			N	<0·7	—	—	—			
0955−01			S	0·5	UR	—	⩽0·15			
4C−00·37			N	<0·2	—	—	—			
1005−09			N	<0·4	—	—	—			
1006−11			S	0·5	UR	—	⩽0·15			
1007−07			N	<0·4	—	—	—			
1007−03			N	<0·4	—	—	—			
1008−01			N	<0·3	—	—	—			
1017−02			N	<0·6	—	—	—			
1025−07			N	<0·5	—	—	—			
1026−05			S	0·4	UR	—	⩽0·15			

Table 1 (*Continued*)

(1) Source No.	(2) 3C No.	(3) Optical identi-fication	(4) Fraction μ of flux in scint. component	(5) Res. or unres.	(6) Cor-rected μ	(7) Angular diam. ψ ″	(8) Other IPS observations μ	ψ ″	Freq. (MHz)
1028−09			N <0·4	—	—	—			
1031−11			S 0·6	R	0·65	0·15			
4C−04·36			S 1·0	UR	—	≤0·15			
1044−00			N <0·4	—	—	—			
1046−02			N <0·3	—	—	—			
1049−09	3C246?	Q	S 0·15	R	0·2	0·3			
4C−00·41			N <0·7	—	—	—			
1059−01	3C249		S 0·1	UR	—	≤0·15	<0·2	—	178
							0·3	≤0·3	195
4C−04·37			N <0·4	—	—	—			
4C−00·43			N <0·3	—	—	—			
1103−24		D	N <0·6	—	—	—			
1103−20		E3	N <0·2	—	—	—			
4C−05·46			N <0·4	—	—	—			
4C−02·45			N <0·4						
1110−01	3C253		N <0·3	—	—	—	<0·3	—	195
4C−02·46			S 0·3	UR	—	≤0·15			
4C−05·47			N <0·6	—	—	—			
1116−02	3C255		S 1·0	UR	—	≤0·15	—	<1·0	81·5
							0·7	<0·2	178
1127−14		Q	S 1·0	UR	—	≤0·15			
1131−19			N <0·4	—	—	—			
4C−00·45			S 1·0	UR	—	≤0·15			
1136−13		Q?	N <0·2	—	—	—			
1142−00			N <0·7	—	—	—			
1148−00		Q	S 1·0	UR	—	≤0·15			
1158−05		E4	S 0·75	R	1·0	0·3			
1212−00			N <0·5	—	—	—			
1229−02		Q	N <0·7	—	—	—			
1239−04	3C275		S 0·3	UR	—	≤0·15	1·0	0·5	81·5
							0·5	<0·2	178
1244−11		G	N <0·6	—	—	—			
1245−19			S 1·0	UR	—	≤0·15			
1247−19		D	N <0·5	—	—	—			
1252−12	3C278	db	N <0·2	—	—	—			
1253−05	3C279	Q	S 0·5	UR	—	≤0·15	—	0·3	81·5
							—	<0·002	2695
4C−00·49			N <0·5	—	—	—			
1306−09		D	S 0·5	R	0·7	0·3			
1309−22		G	S 0·8	UR	—	≤0·15			
1312−18			S 0·6	R	0·7	0·15			
4C−06·33			S 0·6	R	0·65	0·2			
1317−00			N <0·4	—	—	—			
4C−01·28			N <0·6	—	—	—			
1325−01		D	N <0·3	—	—	—			
1327−21		Q?	N <0·3	—	—	—			
1330−14			N <0·6	—	—	—			
1331−09			N <0·2	—	—	—			
4C−05·58			N <0·5	—	—	—			
1334−29		Sc	N <0·6	—	—	—			
1334−17		G	S 1·0	R	1·0	0·15			
1335−06		Q	N <0·3	—	—	—			
1339−12			S 1·0	UR	—	≤0·15			
1342−00		Q?	N <0·4	—	—	—			
1344−07			S 0·2	R	0·25	0·25			
1348−12			S 1·0	UR	—	≤0·15			
1358−11		E2	N <0·3	—	—	—			
1401−05			N <0·6	—	—	—			
1401−04			S 0·3	R	0·4	0·35			
1403−02			S 0·35	R	0·4	0·20	—	<1·0	81·5
1404−01		N	N <0·3	—	—	—			
4C−06·37			N <0·5	—	—	—			

Table 1 (*Continued*)

(1) Source No.	(2) 3C No.	(3) Optical identi- fication	(4) Fraction μ of flux in scint. component		(5) Res. or unres.	(6) Cor- rected μ	(7) Angular diam. ψ ″	(8) Other IPS observations μ	ψ ″	Freq. (MHz)
4C−03·49			N	<0·3	—	—	—			
1410−06		G	S	1·0	R	1·0	0·3			
1411−05			N	<0·3	—	—	—			
1412−10			S	0·8	UR	—	⩽0·15			
1412−14			S	1·0	R	1·0	0·2			
1414−21			N	<0·5	—	—	—			
1414−03			S	0·9	R	1·0	0·40			
1416−15		G	N	<0·6	—	—	—			
1417−19		N	N	<0·5	—	—	—			
1420−27		Q	S	0·2	R	0·25	0·25			
1422−29		Q	N	<0·7	—	—	—			
1424−11			N	<0·3	—	—	—			
1425−01	3C 300·1	N	S	0·15	R	0·2	0·25	—	<1·0	81·5
								<0·3	—	178
								~0·1	<0·3	195
1428−03			S	1·0	R	1·0	0·15			
1433−05			S	1·0	UR	—	⩽0·15			
1436−16		D	S	0·6	R	0·7	0·15			
1445−16			S	1·0	UR	—	⩽0·15			
1449−13		G	N	<0·2	—	—	—			
1452−04		G	N	<0·2	—	—	—			
1453−10		Q	S	0·35	R	0·5	0·35			
4C−02·62			S	1·0	—	—	—			
4C−00·58			N	<0·5	—	—	—			
1509−12			N	<0·5	—	—	—			
1510−08		Q	S	1·0	R	1·0	0·15			
4C−05·65			N	<0·5	—	—				
1514−16			N	<0·4	—	—	—			
1514−24*		N	S	0·8	UR	—	⩽0·15			
1518−29			N	<0·4	—	—	—			
1520−04			N	<0·5	—	—	—			
1524−13		Q?	S	1·0	UR	—	⩽0·15			
4C−04·56			N	<0·7	—	—	—			
1528−29			N	<0·2	—	—	—			
1534−12			S	0·5	R	0·55	0·15			
1537−14			N	<0·5	—	—	—			
1537−05			S	0·7	R	0·85	0·20			
1539−09			S	0·8	R	1·0	0·25			
4C−05·69			S	1·0	UR	—	⩽0·15			
1553−06			S	0·7	UR	—	⩽0·15			
1556−21			N	<0·3	—	—	—			
1602−28			N	<0·2	—	—	—			
1602−17			N	<0·2	—	—	—			
1602−09			N	<0·2	—	—	—			
1609−14			S	1·0	UR	—	⩽0·15			
1622−29			S	1·0	UR	—	⩽0·15			
1635−14			N	<0·5	—	—	—			
1640−15			N	<0·3	—	—	—			
1938−15			S	0·6	UR	—	⩽0·15			
1945−09			S	0·8	UR	—	⩽0·15			
2058−17			S	0·3	UR	—	⩽0·15			
2149−20			S	0·7	UR	—	⩽0·15			
2203−18		Q	S	1·0	UR	—	⩽0·15			
2223−05	3C 446	Q	S	0·8	R	1·0	~0·25 × <0·1†			
2234−17			S	0·75	UR	—	⩽0·15			
2235−12			N	<0·2	—	—	—			
2235−14			S	0·5	UR	—	⩽0·15			
2236−17		Q	N	<0·3	—	—	—			
2237−04			N	<0·2	—	—	—			
2239−10			S	1·0	UR	—	⩽0·15			

* Angular diameter details for PKS 1514−24 from Ananthakrishnan *et al.* (1972).
† Position angle of major axis ~260° (Rao *et al.* 1974).

Table 1 (*Continued*)

(1) Source No.	(2) 3C No.	(3) Optical identification	(4) Fraction μ of flux in scint. component		(5) Res. or unres.	(6) Corrected μ	(7) Angular diam. ψ ″	(8) Other IPS observations μ	ψ ″	Freq. (MHz)
2243−19			S	0·4	UR	—	≤0·15			
2243−03		G	S	0·4	R	0·45	0·15			
2300−18		N	N	<0·4	—	—	—			
2308−10			S	1·0	UR	—	≤0·15			
2313−18		G	S	0·5	UR	—	≤0·15			
2313−16			S	0·4	UR	—	≤0·15			
2318−16			S	0·6	R	0·7	0·2			
2322−12		E5	N	<0·3	—	—	—			
2325−15			S	0·15	R	0·25	0·45			
2329−16			S	0·9	UR	—	≤0·15			
2329−10			S	0·4	R	0·45	0·2			
2335−18		Q?	S	0·3	UR	—	≤0·15			
2337−06			S	1·0	R	1·0	0·15			
2338−16			S	0·2	UR	—	≤0·15			
2345−16		Q	S	0·5	UR	—	≤0·15			
2347−02			S	0·9	UR	—	≤0·15			
2348−16			N	<0·3	—	—	—			
2349−01		N	S	0·1	R	0·15	0·4			
2354−18			N	<0·7	—	—	—			
2354−11		Q	S	0·8	UR	—	≤0·15			

corresponding 3C number. The optical identification, if any, is listed in column 3; abbreviations used are: Q, quasi-stellar object; Q?, possible quasi-stellar object; D, db, E, N, S0, Sc, galaxies of the corresponding class; G, galaxy too faint to classify. Column 4 contains the symbols S and N, to indicate whether we have detected scintillations or not, and the fraction μ of the total flux in the scintillating component. Column 5 indicates whether the source is resolved (R) or unresolved (UR). Corrected values of μ for the resolved sources are given in column 6. The derived estimates of angular diameter are presented in column 7. In the last column other available IPS results are given for comparison. These results are taken from observations by Cohen and Gundermann (1969) at 2695 MHz, Harris and Hardebeck (1969) at 430 MHz and 195 MHz, Little and Hewish (1968) at 178 MHz and Burnell (1972) at 81·5 MHz.

In the present survey we find that about 50% of the sources observed contain scintillating components with more than 10% of the total flux in a size less than $0''\cdot 5$. For the nonscintillating sources the upper limits on μ are often higher than 0·2. It is possible that some of these are scintillating with $\mu \geqslant 0\cdot 1$ but scintillations have not been detected because of poor signal to noise ratio. Therefore the actual percentage of scintillating sources with $\mu > 0\cdot 1$ is likely to be higher than 50%. This result agrees with that found by Harris and Hardebeck (1969) from a scintillation survey of about 500 northern ecliptic radio sources.

In order to study the occurrence of fine structure in different kinds of radio sources we have divided the sources into quasars, galaxies and blank field objects and analysed the scintillation properties of each class. The optical identifications have been taken from the Parkes catalogue. The distribution of μ for the three classes is given in Table 2. It is seen that the percentage of quasars that scintillate is much higher than that for galaxies and blank fields, the percentages of the latter two being nearly equal.

The fraction of radio sources in any survey which can be identified with optical objects varies with the minimum flux limit of the survey. Typically in a survey that is complete down to about 2 f.u. only about half of the radio sources are optically identified. Various authors have tried to deduce the nature of blank field objects on the basis of observed properties of identified sources. Bolton (1966) has studied the distribution of high frequency spectral indices and distribution of radio and optical magnitudes for the three classes of objects and has concluded that most of the blank

Table 2. Distribution of μ for quasars, galaxies and blank field objects

Class of objects	Total No. of objects observed	Percentage of scintillating objects	Percentage of objects with: $0{\cdot}1 \leqslant \mu \leqslant 0{\cdot}3$	$0{\cdot}3 < \mu \leqslant 0{\cdot}6$	$0{\cdot}6 < \mu \leqslant 1{\cdot}0$
Quasars	27	74	15	22	37
Galaxies	39	49	10	11	28
Blank fields	105	53	8	15	30

field objects must be galaxies fainter than the plate limit of the Sky Survey. From a study of radio spectra and from source counts, Wall (1972) and Braccesi *et al.* (1970) have concluded that, at most, 25% of the blank fields could be quasars. The scintillation surveys can also be used to study the nature of blank field objects. In our survey the percentage of blank fields that scintillate is much closer to that of

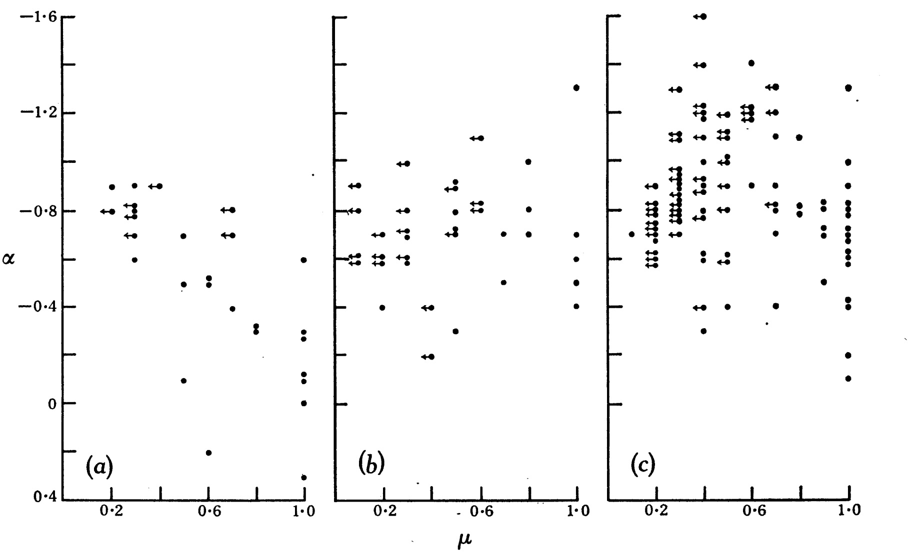

Fig. 1. Spectral index α plotted against the fraction μ of the flux in the scintillating component for (*a*) quasars, (*b*) galaxies and (*c*) blank field objects. The points with arrows refer to the upper limits on μ for the nonscintillating sources.

galaxies than that of quasars. On the basis of the assumption that the blank field objects consist only of quasars and galaxies, this implies that the blank fields are predominantly galaxies. To explain the observed percentages in Table 2 we would require blank field objects to be a mixture of galaxies and quasars in the proportion 5:1. Although better statistics are required before we can make a conclusive statement, we find support for the above result from the behaviour of angular size of the sources. If the blank field objects are distant galaxies beyond the plate limit we would expect them to be generally more compact than the sources identified with galaxies. There is evidence for such an effect in our data, where $\sim 70\%$ of the blank fields and only $\sim 50\%$ of the galaxies are unresolved at $0''\cdot 15$. The percentage of unresolved quasars in our survey is $\sim 75\%$.

In Fig. 1 the spectral index α is plotted against the fraction μ of the total flux of the source in the scintillating component for quasars, galaxies and blank field objects. The spectral index refers to the range 408–1410 MHz as given in the Parkes catalogue. For nonscintillating sources the upper limit on μ is plotted. It is seen that almost all the flat spectrum quasars show strong scintillations and are unresolved. The steep or normal spectrum quasars are mostly weak scintillators or nonscintillators. For galaxies and blank field objects there are not many sources with flat spectra in our sample, but even among the steep spectrum galaxies and blank field objects there is an appreciable fraction which scintillate strongly and therefore it is rather unlikely that a simple correlation exists between α and μ as found for quasars.

Acknowledgments

We thank Professor G. Swarup, Professor T. K. Menon and Mr V. K. Kapahi for helpful comments. One of us (S.M.B.) is indebted to Professor U. R. Rao, Physical Research Laboratory, for useful suggestions, and acknowledges financial support from the Department of Space, Government of India. We also thank Mr P. Govindaswamy and Mr J. Hilal for assistance in the tabulation of the data.

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Manuscript received 10 May 1973