SPECTRA FOR 107 RADIO SOURCES SELECTED AT 408 MHz

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Abstract

Radio spectra are presented for 107 sources which have previously been examined for optical identifications based on 408 MHz positions obtained with the Molonglo cross. Flux density measurements are given at five frequencies from 318 to 2695 MHz. The relationship between spectrum and optical identification is discussed. For sources with peaked, flat, or complex spectra the identification rate with QSO candidates is very high. For the remaining sources, no significant difference between the spectral index distribution of QSOs and galaxies is found.

I. Introduction

Positions and identifications have been given by Hoskins *et al.* (1972; hereinafter referred to as paper 1) for 111 sources selected at 408 MHz in the declination range 0° to +19°. In the present paper we give spectral information for 107 of these sources. This information is not complete but is sufficient to enable the spectra to be classified and the types of spectra to be related to the nature of the optical objects. None of the sources occur in the 4C catalogue (Gower *et al.* 1967) since these were being studied in a separate program (see paper 1 for references). This selection produces a bias towards sources with flat or peaked spectra and hence results in a larger proportion of such sources than would be obtained from a complete sample at 408 MHz.

Table 1

observations and flux density errors

Observing frequency (MHz)	Telescope	Beam width (min arc)	Number of sources	Flux density errors: Flux independent (f.u.)	Flux density errors: Proportional (%)
318	Arecibo	16	25	0·2	6
408	Molonglo	3 × 4	107	0·05	5
606	Arecibo	10	99	0·1	8
1400	Green Bank 300 ft	10	103	0·045	5
2695	Green Bank 300 ft	5	87	0·035	5

II. Observations

Details of the observing instruments and the numbers of sources observed with each are given in Table 1. All observations were carried out by drift scans. The observed sources were all indistinguishable from point sources with the Molonglo 1 mile cross type radio telescope, which has a resolution of 2′·6 in right ascension and

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$2' \cdot 86 \sec(35° \cdot 5 + \delta)$ in declination. The source positions were known to $\sim 5''$ arc at 408 MHz, a higher precision than could be obtained at the other frequencies. The error estimates given in paper 1 are confirmed by comparison with precise positions from the Royal Radar Establishment (hereinafter designated RRE) for 11 sources (Gent *et al.* 1973).

The observations at Green Bank were made with the resurfaced 300 ft telescope during the period April–July 1971. At 1400 MHz, two beams separated in declination by $5'$ arc were available, their half-power beam widths being $10'$ arc. Both beams were polarized in position angle zero. The telescope was pointed in declination to observe each source mid-way between the two beams, thus giving a check on the pointing. At 2695 MHz two beams with orthogonal linear polarizations were obtained from a central feed. Two additional feeds each produced a single linear polarized beam and were pointed $+2' \cdot 5$ and $-2' \cdot 5$ in declination respectively. The flux density was taken from the mean of the two centre beams and the outer beams were used as a pointing check. The observations with the Arecibo 1000 ft reflector were made during the period February–April 1971. Single beams were available at 606 and 318 MHz. About half of the observations were repeated and no gross errors were detected.

The measurements at 318, 606, and 1400 MHz were all confusion limited whilst, at 2695 MHz, the noise error was greater than the confusion error. In all cases peak flux densities were used. This gave a better estimate of the true flux density than an integrated value since any observed extension at frequencies other than 408 MHz would be due to confusion. Where confusing sources were known to exist, allowance was made for this. The sources $1250+11 \cdot 9$A and $1250+11 \cdot 9$B were completely resolved at 408 MHz but were blended in the other beams. In this case integrated flux densities are quoted, and the spectrum can only be obtained for the sum of the two sources. Two other sources, $1621+13 \cdot 1$ and $1621+13 \cdot 2$, are separated by $7'$ arc in declination. At 606 MHz only the stronger source was measured and allowance was made for the presence of the other. However, the observation of each source with two beams separated by $5'$ arc enabled a flux density to be assigned to each source at 1400 MHz. Three sources listed in paper 1 were reobserved only at 606 MHz and are not included here. Since the original sources were randomly selected rather than giving a complete coverage of the area, nothing is lost by the omission of these three sources. The Arecibo data were reduced by hand. The primary reduction of the Green Bank data was carried out by means of a standard computer program provided by Dr. M. M. Davis which fits a Gaussian beam shape to the source.

III. Flux Density Calibration and Errors

At each frequency a number of strong sources were used as flux density calibrators. At 1400 and 2695 MHz the scale of Kellermann *et al.* (1969) was used. The Arecibo calibrators were expressed on the CKL scale (Conway *et al.* 1963) and, since it is now generally agreed that an upward revision of low frequency scales is necessary (Scott and Shakeshaft 1971; Baars and Hartsuijker 1972), we have tried to achieve compatibility with the Wyllie (1969) scale at 408 MHz. The 318 and 606 MHz results have accordingly been increased by 10% and 7% respectively. These corrections are somewhat arbitrary but are within $\sim 2\%$ of those suggested in the above-mentioned references. At 318 MHz it was found necessary to reduce the flux densities (after correction) by about $0 \cdot 15$ f.u. to achieve compatibility with the extrapolated spectrum based on measurements at the other frequencies. This was presumably due to a mean overestimation in the measurements. There is some evidence for a slight overestimation at 606 MHz for the stronger sources only, but no corrections have been applied. At 1400 and 2695 MHz the use of Monte Carlo sources showed that any mean estimation error was entirely negligible. The mean calibration error is estimated to be not greater than 3% at any frequency on the relevant adopted scale.

The adopted r.m.s. flux density errors are included in Table 1. The errors at 318 and 606 MHz have been taken from Condon *et al.* (1971), with slight increases to allow for errors in our fitting procedure. The errors at 408, 1400, and 2695 MHz were obtained by the Monte Carlo method but some increases have been made to allow for such factors as gain fluctuations and calibration uncertainty. Many of the measurements are means of two or more observations. The adopted error estimates given in Table 1 are believed to be slightly conservative since there is good agreement with Parkes measurements for five sources at 1400 MHz and for eight sources at 2695 MHz (Day *et al.* 1966; Wall *et al.* 1971) and also with RRE measurements for nine sources (H. Gent, personal communication). In some cases the observed flux density is as low as twice the standard error. Although the percentage error is necessarily high in such cases, with consequent appreciable error in the spectral index, there is no stricture against using such low values of signal to noise since the sources have been observed at 408 MHz with a signal to noise ratio of at least 10:1. Furthermore, since the flux densities at 408 MHz are obtained from reobservation with the Molonglo pencil beam, there is no mean overestimation at 408 MHz, as would be the case if the flux densities were obtained from the finding survey with the Molonglo fan beam (Williams and Stewart 1967; Murdoch and Large 1968).

IV. Table of Flux Densities and Spectra

The source list is given in Table 2. Column 1 lists the designation number of the source (as given in paper 1, which included references to other source catalogues). The flux densities at the observation frequencies are listed in column 2, in which the 408 MHz values are taken from paper 1 but quoted here to $0 \cdot 05$ f.u. The fitted spectral index* α and its standard error σ_α in column 3 have been obtained by a weighted least squares fit to a straight line in the $\log S, \log \nu$ plane and are quoted in all cases where they are meaningful within the range of tabulated flux densities. The standard errors σ_α have been calculated from the errors listed in Table 1. Errors calculated from the observed residuals would have been on average lower and hence we believe the quoted values to be slightly conservative. It would be difficult to further refine the error estimates because of two countervailing factors: on one hand, correlation between errors (especially at 606 and 1400 MHz) due to confusion will reduce the residuals, whilst departures from a straight spectrum will increase them.

* The spectral index α is defined by the relationship $S_\nu \propto \nu^\alpha$, where S_ν is the flux density at frequency ν.

TABLE 2

FLUX DENSITIES AND SPECTRA

(1) Source	(2) Flux density (f.u.) at indicated frequency (MHz) 318	408	606	1400	2695	(3) Spectrum α	σ_α	Class	(4) Suggested ident. m	Object	(5) Notes*
1034+16·0		1·05	0·85	0·41	0·28	−0·72	0·07	S	19·5	g	
1035+02·6		1·20	1·15	0·52	0·31	−0·72	0·06	C?			
1037+06·7		1·65	1·25	0·61	0·31	−0·86	0·06	C?			1
1042+11·2		0·85	0·45	0·24	0·14	−0·98	0·10	S			
1043+06·7		0·75	0·50	0·23	0·13	−0·94	0·11	S			
1044+15·2		0·80	0·60	0·40	0·25	−0·60	0·07	S			
1048+05·0		0·85	0·70	0·32	0·18	−0·81	0·09	S	19·5	blue g	
1049+12·7		0·95	0·65	0·32	0·13	−0·96	0·10	S			
1054+10·7		0·75	0·60	0·31	0·23	−0·65	0·08	S			
1057+10·0		1·20	0·85	0·41	0·19	−0·93	0·08	S	17·5	BSO	
1103+09·0		0·70	0·45	0·13	0·10	−1·13	0·14	S	18	cg	
1104+16·0		0·90	0·80	0·41	0·19	−0·75	0·08	S			
1107+03·6		1·95	1·40	0·57	0·24	−1·06	0·06	S	17	D	2
1109+07·8		0·90	0·65	0·31	0·18	−0·86	0·09	S			
1113+06·0		0·70	0·55	0·31	0·22	−0·63	0·08	S			
1122+10·4		0·90	0·75	0·39	0·14	−0·81	0·09	C?			
1123+11·7		0·65	0·45	0·26	0·16	−0·74	0·10	S			
1126+10·1	1·60	1·20	1·00	0·58	0·32	−0·68	0·06	S	18	cg?	
1129+15·9		0·80	0·45	0·14	0·09	−1·25	0·15	S			
1139+10·3	1·70	1·05	0·75	0·35	0·12	−1·05	0·09	S			
1144+02·1		1·00	0·80	0·42	0·15	−0·84	0·09	C?			
1145+07·9		0·80	0·80	0·40	0·21	−0·66	0·08	S	18	E	
1148+05·2		1·05	0·85	0·45		−0·69	0·10	S	18·5	cg	
1150+04·1		1·40	0·85	0·41	0·15	−1·08	0·08	S			3
1200+04·5		1·30	1·30	1·14	0·89	−0·19	0·04	X	**19**	**BSO?**	
1205+04·5	2·65	1·95	1·50	0·61	0·31	−0·98	0·05	S			4
1210+05·2		0·80	0·55	0·17		−1·22	0·20	S			
1216+05·5		1·15	1·05	0·58		−0·56	0·09	S	17	E	
1235+05·7		0·85	0·70	0·27	0·15	−0·92	0·10	S			
1241+05·5		0·60	0·55	0·27	0·13	−0·74	0·11	S	19	BSO?	
1250+11·9		2·20	1·60	0·80	0·40	−0·88	0·05	S	18	E	5
1304+06·7	2·80	2·30	1·75	0·70	0·38	−0·95	0·05	S	19·5	g	6
1310+00·4		0·55	0·35	0·11	0·06	−1·22	0·19	S			
1310+05·8		1·10	0·75	0·41	0·19	−0·87	0·08	S	20	g	
1312+02·6		1·30	1·05	0·47		−0·82	0·10	S			
1314+00·6		1·00	0·60	0·31	0·16	−0·96	0·09	S			
1323+03·7		1·15	0·90	0·38	0·20	−0·92	0·08	S	18	BSO	
1325+16·4		0·95	0·70	0·40	0·17	−0·81	0·08	S			
1333+16·8	1·50	1·05	0·90	0·50		−0·65	0·09	S			
1348+07·6		0·95	0·80	0·44	0·30	−0·62	0·07	S			
1350+14·8		0·95	0·90	0·47		−0·57	0·10	S	18·5	BSO	
1353+03·6		0·70	0·50	0·20	0·12	−0·96	0·12	S	19	g	
1355+01·0	4·35	3·95	3·90	1·96		−0·56	0·05	P			7
1355+03·2		0·90	0·75	0·31	0·18	−0·86	0·09	S			
1401+09·2		1·15	0·80	0·52	0·34	−0·64	0·06	S			

* See notes on particular sources at end of table.

TABLE 2 (*Continued*)

(1) Source	(2) Flux density (f.u.) at indicated frequency (MHz) 318	408	606	1400	2695	(3) Spectrum α	σ_α	Class	(4) Suggested ident. m	Object	(5) Notes*
1408+15·5	1·05	0·70	0·65	0·33	0·16	−0·74	0·09	S			
1413+13·5	3·05	2·60	2·35	1·13	0·67	−0·71	0·04	P	20	g	8
1415+17·2	1·05	1·05	0·70	0·41		−0·74	0·10	S	18	BSO	
1418+17·1		0·80		0·22	0·12	−1·02	0·11	S			
1421+12·2	1·95	1·90	1·55	0·99	0·71	−0·51	0·04	P	**18**	**BSO**	9
1422+12·3		1·20	1·00	0·54		−0·65	0·09	S	19	cg	
1425+04·5	2·50	1·65	1·40	0·54	0·27	−0·98	0·06	C?			10
1426+03·0		1·10	1·10	0·62	0·41	−0·53	0·06	C?	19	E	11
1435+03·1		0·80	0·50	0·19	0·13	−1·03	0·11	S			
1442+10·1	1·65	1·90	2·45	2·47				P	**18·5**	**St**	12
1451+11·8	1·05	1·10	0·90	0·39	0·22	−0·82	0·07	S			
1452+06·6		1·30	0·95	0·36		−1·03	0·11	S			
1456+09·2		1·30	1·20	0·55	0·39	−0·67	0·06	S	18	BSO	
1500+12·8		0·55	0·40	0·15	0·11	−0·91	0·14	S	18	cg	
1502+10·6	1·35	1·45	1·35	1·62	2·03	+0·18	0·04	X	**18·5**	**BSO**	13
1502+12·1		0·70	0·50		0·11	−0·98	0·15	S	20	BSO	
1504+07·4		0·90	0·75	0·28		−0·92	0·14	S	18·5	blue g	
1508+12·8		0·85	0·65	0·29		−0·87	0·14	S			
1512+12·7		0·95	0·65	0·31	0·15	−0·95	0·09	S			
1516+06·4		1·10	0·95	0·51		−0·62	0·09	S	17	E	
1517+06·6		1·15	0·80		0·15	−1·07	0·12	S			
1528+06·0		1·20	1·05	0·54	0·37	−0·64	0·06	S			
1528+07·1		0·60	0·40	0·16		−1·06	0·21	S	18·5	cg	
1531+07·3		1·20	0·75	0·25		−1·27	0·14	S			14
1532+13·9	1·70	1·90	1·20		0·43	−0·75	0·05	C?	18·5	E	15
1537+14·5		1·15	1·15	0·61	0·35	−0·61	0·06	C?			
1540+11·0	1·15	0·90	0·65	0·27	0·16	−0·94	0·09	S	18	BSO	
1543+02·1		1·15	0·60	0·24	0·12	−1·24	0·11	S			
1545+08·2	1·35	1·65	1·30	0·59	0·33			C			16
1547+03·2		1·15	1·00	0·48	0·22	−0·81	0·07	S			17
1550+14·1		0·90	0·80	0·32	0·18	−0·85	0·09	S	18·5	BSO	
1555+00·1		0·75						X	**19**	**BSO?**	18
1556+02·0		1·20	1·15	0·37				C			
1603+11·0	1·50	1·05	0·80	0·48	0·22	−0·77	0·07	S			
1604+10·0		0·75	0·50	0·24	0·11	−0·97	0·12	S			
1611+08·3		0·90	0·65	0·36	0·20	−0·78	0·08	S	19·5	BSO?	
1614+09·5		0·65	0·40	0·27	0·14	−0·77	0·11	S			
1616+06·3	1·30	1·80		1·06	1·02	−0·29	0·04	X	**19**	**BSO**	19
1616+00·3		0·75	0·55	0·27		−0·83	0·14	S	20	BSO	
1621+13·1		0·90		0·49	0·29	−0·57	0·07	S	16·5	E	
1621+13·2		1·40	1·10	0·48	0·25	−0·90	0·07	S	19·5	blue g	
1628+09·5		0·95	0·80	0·50	0·16			C			
1636+10·6	2·60	2·15	1·70	1·05	0·70	−0·60	0·04	S			20
1652+14·5		1·05	0·75	0·32	0·16	−0·98	0·09	S			
1652+04·0		1·40	1·00	0·57	0·35	−0·73	0·06	S	19·5	g	

* See notes on particular sources at end of table.

TABLE 2 (*Continued*)

(1) Source	(2) Flux density (f.u.) at indicated frequency (MHz) 318	408	606	1400	2695	(3) Spectrum α	σ_α	Class	(4) Suggested ident. m	Object	(5) Notes*
1653+18·3		0·90	0·80	0·44	0·29	−0·60	0·07	S			
1656+05·3		2·70	2·50	1·57	1·65			X	**17·5**	**St**	21
1701+05·1	2·10	1·90	1·35	0·48	0·24	−1·07	0·06	S	18·5	g?	22
1701+14·5		1·20	1·20	0·59	0·34			C	18	cg?	
1706+07·1		0·80	0·55	0·36	0·15	−0·76	0·09	S			
1707+11·7	1·95	1·45	0·95	0·59	0·31	−0·80	0·06	S			
1707+06·8		1·70	1·40	0·76		−0·65	0·08	S			23
1710+15·6		0·85		0·42	0·25	−0·62	0·07	S	17·5	E	
1716+00·6		5·50		2·20	1·19	−0·80	0·04	S	**20**	**g?**	24
1717+11·1		0·70		0·35	0·11			C	19·5	BSO	
1720+00·1		2·30	1·75	0·73	0·51	−0·84	0·05	C?	18	cg?	25
1723+11·1		0·80		0·27	0·19	−0·80	0·09	S			
1725+10·7	1·50	1·30	0·95	0·36	0·28	−0·86	0·06	S			
1730+04·2		0·55	0·55	0·42	0·09			C	19	g?	
1731+10·7	1·40	1·35	1·05	0·55	0·32	−0·73	0·06	S	18·5	E	
1743+17·3	0·60	1·05	1·45	1·17	0·88			P	**19·5**	**BSO**	
1754+15·9		0·75	0·75	0·69	0·53	−0·17	0·06	X	**18·5**	**BSO**	

* Notes on particular sources:

1. 1037+06·7 $S_{178} \lesssim 2$ f.u.
2. 1107+03·6 4C confused with 4C0321 and 4C0435.
3. 1150+04·1 Extrapolation of S spectrum suggests $S_{178} = 3 \cdot 0$ f.u.; 4C records not examined.
4. 1205+04·5 $S_{178} \approx 3 \cdot 5$ f.u.; close to 4C0440.
5. 1250+11·9 Spectral data refer to a blend of two sources resolved at 408 MHz. The identification refers to 1250+11·9B.
6. 1304+06·7 4C confused with 4C0645.
7. 1355+01·0 $S_{178} \lesssim 3$ f.u. Flux densities at 2700 MHz, 1·0 f.u. (Wall *et al.* 1971); 5000 MHz, 0·47 f.u. (Shimmins *et al.* 1969).
8. 1413+13·5 $S_{178} = 1 \cdot 9$ f.u.
9. 1421+12·2 $S_{178} = 1 \cdot 4$ f.u. (Wills 1968).
10. 1425+04·5 $S_{178} \approx 1 \cdot 8$ f.u.
11. 1426+03·0 Flux density at 5 GHz = 0·26 f.u. (Wall 1972). The peak in the spectrum given by Wall is due to an underestimated 635 MHz value.
12. 1442+10·1 Flux densities at 2·65 GHz, 1·7 f.u.; 3·2 GHz, 1·6 f.u.; 6·6 GHz, 1·1 f.u.; 10·6 GHz, 0·7 f.u. (Kraus and Andrew 1970); 2·695 GHz, 1·96 f.u.; 5·0 GHz, 1·22 f.u. (Witzel *et al.* 1971).
13. 1502+10·6 Flux densities at 3·2 GHz, 1·95 f.u.; 6·6 GHz, 3·1 f.u.; 10·6 GHz, 3·45 f.u. (Kraus and Andrew 1970); 5 GHz, 3·7 f.u. (Blake 1970); 7·8 GHz, 3·0 f.u. (Cohen *et al.* 1971).
14. 1531+07·3 Extrapolation of straight spectrum suggests $S_{178} \approx 2 \cdot 9$ f.u. 4C records not examined.
15. 1532+13·9 $S_{178} \lesssim 2 \cdot 5$ f.u. Occurs between 4C1355 and 4C1459.
16. 1545+08·2 $S_{178} \approx 1 \cdot 5$ f.u.
17. 1547+03·2 Flux density at 5 GHz, 0·14 f.u. (Shimmins and Bolton 1972). The peak in the spectrum given by Wall (1972) is due to an overestimated 635 MHz value.

18.	1555+00·1	Flux densities at 178 MHz, 0·4 f.u. (Wills 1968); 750 MHz, 1·7 f.u.; 1400 MHz, 2·2 f.u. (Davis 1967); 1400 MHz, 1·46 f.u. (Wall 1972); 2700 MHz, 2·0 f.u. (Wall *et al.* 1971); 5 GHz, 2·18 f.u. (Shimmins and Bolton 1972); 7·8 GHz, 2·24 f.u. (Cohen *et al.* 1971); 3·2 GHz, 1·85 f.u.; 6·6 GHz, 1·85 f.u.; 10·6 GHz, 2·55 f.u. (Bridle 1969).
19.	1616+06·3	$S_{178} = 1 \cdot 9$ f.u. Flux densities at 750 MHz, 1·2 f.u. (Davis 1967); 3·2 GHz, 0·7 f.u.; 6·6 GHz, 0·75 f.u.; 10·63 GHz, 0·5 f.u. (Bridle 1969).
20.	1636+10·6	$S_{178} \approx 2 \cdot 5$ f.u. Flux densities at 3·2 GHz, 0·7 f.u.; 6·6 GHz, 0·4 f.u.; 10·6 GHz, 0·3 f.u. (Conklin *et al.* 1972). These values confirm the present straight spectrum rather than the peaked spectrum of Conklin *et al.* which is based on a low 1400 MHz value.
21.	1656+05·3	Flux densities at 178 MHz, 3·0 f.u. (Wills 1968); 2·65 GHz, <1·3 f.u.; 3·2 GHz, 1·4 f.u.; 6·6 GHz, 3·3 f.u.; 10·6 GHz, 4·0 f.u. Possibly variable at high frequency (Wills *et al.* 1971).
22.	1701+05·1	$S_{178} = 4 \cdot 0$ f.u.
23.	1707+06·8	$S_{178} \approx 1 \cdot 8$ f.u.
24.	1716+00·6	$S_{178} = 10$ f.u. (Wills 1968).
25.	1720+00·1	Flux densities at 178 MHz, <2 f.u. (Wall 1972); 5 GHz, 0·29 f.u. (Wall 1972). Flux densities observed by Davis (1967) at 750 MHz, 1·9 f.u. and 1400 MHz, 1·5 f.u. are significantly higher than those reported here.

Also given in column 3 is the spectral classification of each source according to the following scheme: Sources with spectra which definitely rise at high frequency (3 cases) or which appear fairly flat, with $\alpha > -0 \cdot 4$ (3 cases), have been classified as X. Sources with spectra which on the available evidence have a single peak below 1000 MHz are classified P. Of the remaining sources, those with obviously curved spectra are classified C, those with a good fit to a straight line spectrum are classified S, and some intermediate cases are classified C?. The goodness of fit calculated from the residuals has been used as a guide in deciding between C, C?, and S but the boundaries are necessarily somewhat arbitrary. In many cases we have made use of additional published flux densities, generally for frequencies outside the range of the present observations, and these are given in the notes to individual sources indicated in column 5. Flux densities at 178 MHz, other than those attributed to Wills (1968), were obtained from examination of the 4C records, which were kindly made available to one of us (H.S.M.). These values are quoted on the CKL scale.

The spectra of X, P, and C sources are plotted in Figures 1(*a*), 1(*b*), and 1(*c*) respectively and the spectra of C? sources are plotted in Figures 1(*d*) and 1(*e*). The additional flux density information listed in the notes to Table 2 has been included and flux density values at 178 MHz have been increased by 10%. For C? sources the straight lines shown correspond to the results of the least squares fitting procedure, except in the case of 1426+03·0, where the 5000 MHz point suggests a steeper slope.

In column 4 the identification suggested in paper 1 is given although this has been modified where necessary by the results of Gent *et al.* (1973) on the basis of accurate RRE radio positions. Identifications which are confirmed by an accurate position are indicated by bold type. The symbols used to describe the optical objects are: E, elliptical galaxy; D, galaxy with diffuse envelope; cg, compact galaxy; g, galaxy of unspecified type; BSO, stellar image which is significantly brighter on the O (blue) than on the E (red) Palomar Sky Survey print; and St, stellar image other than BSO. A question mark indicates that the nature of the object is in doubt.

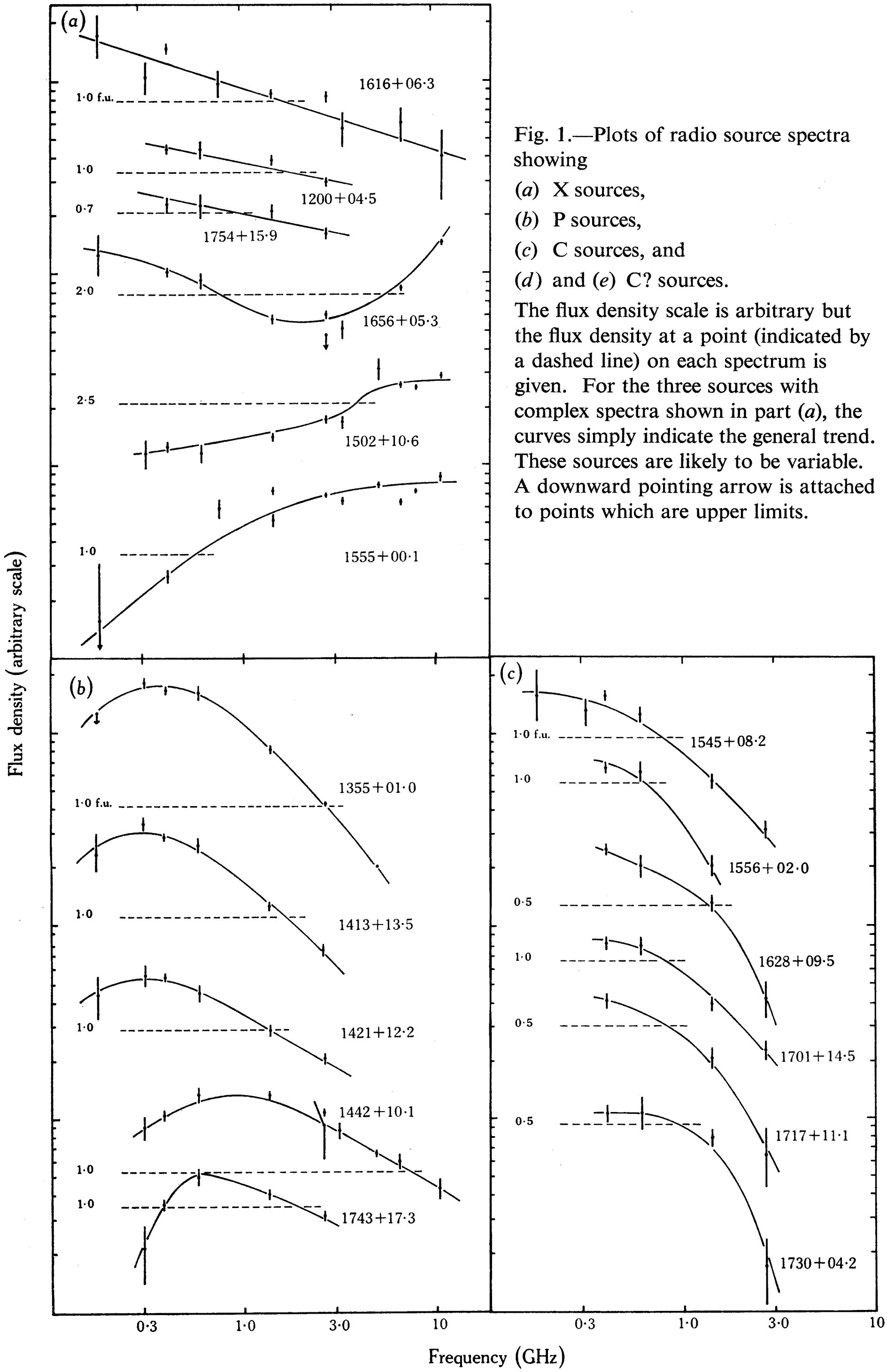
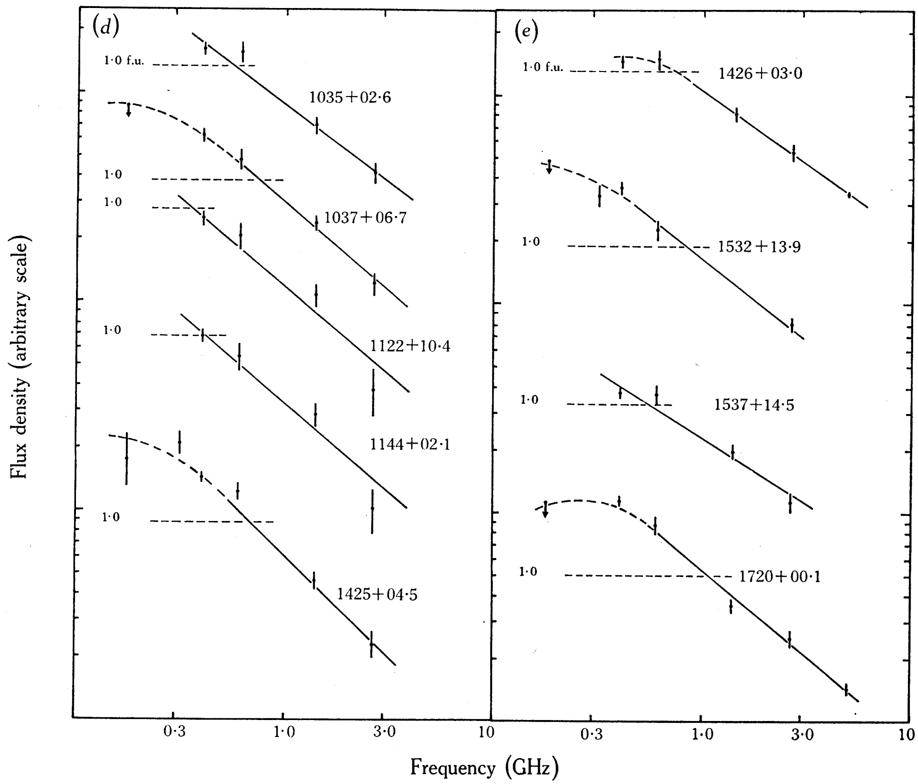


Fig. 1.—Plots of radio source spectra showing
(*a*) X sources,
(*b*) P sources,
(*c*) C sources, and
(*d*) and (*e*) C? sources.
The flux density scale is arbitrary but the flux density at a point (indicated by a dashed line) on each spectrum is given. For the three sources with complex spectra shown in part (*a*), the curves simply indicate the general trend. These sources are likely to be variable. A downward pointing arrow is attached to points which are upper limits.



Figs. 1(*d*) and 1(*e*).

V. Discussion

(*a*) *Relation of Identification and Spectrum*

In Table 3 the sources are grouped according to suggested identification and spectral classification. The classification QSO? includes BSOs, BSO?s, and the two neutral stellar objects suggested as identifications by Gent *et al.* (1973). Some of the faint galaxies are probably chance associations.

Table 3

Identifications for each spectral classification

Object	Spectral class					Total
	X	P	C	C?	S	
QSO?	6	3	1	0	11	21
Galaxies	0	1	2	3	24	30
Unidentified	0	1	3	6	46	56
Total	6	5	6	9	81	107

The striking feature of Table 3 is the high proportion of identifications of X and P spectrum sources with QSO candidates. We assume that the QSO confirmation rate will be high because of the good agreement (better than 1″ arc r.m.s. in each co-ordinate) with the RRE radio positions. Burbidge and Strittmatter (1972) have reported a red shift of 0·57 for one of the X sources, 1502+10·6, while Radivich and Kraus (1971) had reported a red shift of 1·8 as a personal communication from D. Wills. It is also interesting to note that the optical object is listed as 17^m by Radivich and Kraus, $18^m\cdot 5$ by paper 1, and $19^m\cdot 5$ by Blake (1970), all of whom have identified it independently from the Palomar Sky Survey.

In Table 4 we give the mean spectral index as a function of the identification for the S spectrum sources. It is possible that, with further information over a wide range of frequencies or with more precise flux density measurements, some of these sources would be assigned to other spectral categories.

TABLE 4

MEAN SPECTRAL INDEX FOR S SPECTRUM SOURCES

Object	No. of sources	Spectral index mean	stand. dev.
QSO?	11	$0\cdot 81 \pm 0\cdot 04$	0·13
Galaxies	24	$0\cdot 82 \pm 0\cdot 035$	0·17
Unidentified	46	$0\cdot 87 \pm 0\cdot 03$	0·19
All sources	81	$0\cdot 84 \pm 0\cdot 02$	0·18

For the sources in Table 4 there is a close similarity between the spectral index distribution for QSO candidates and galaxies. It has frequently been noted that unidentified sources have steeper spectra (Kellermann *et al.* 1969). Although the difference here is not significant, it is probably worth noting that the five steepest spectrum sources are all unidentified, and that these alone would be sufficient to account for the whole of the difference existing in the present sample. The mean spectral index for the S sources is no doubt slightly biassed by the exclusion of 4C sources.

It has generally been noted that there is a tendency on average for convex (negative) curvature (Kellermann *et al.* 1969) although Scott and Shakeshaft (1971) have raised the question of the extent to which this may be due to errors in the low-frequency flux density scales. Apart from some of the X spectrum sources, all curved spectra in the present sample are convex and, even among the sources classified as S, there is a mean convex curvature. Although the latter is only marginally significant, and the precise value would clearly depend on the choice of boundary between the classes S and C?, it no doubt represents the tail of a distribution of negative spectral curvature. In the present sample, positive curvature occurs only in sources whose spectra are fairly flat ($\alpha > -0\cdot 4$) at low frequency. Consequently our results indicate that an average negative spectral curvature exists between 408 and 2700 MHz, unless a much greater revision of flux density scales is required than has been suggested up to now. It is not of particular interest, however, to quote a mean curvature for the present biassed sample.

(*b*) *Methods of Classifying Sources*

There are several ways of classifying extragalactic radio sources, the most common being into QSOs (or QSO candidates) and galaxies. Bridle *et al.* (1972*a*) have suggested an alternative classification based on surface brightness as deduced from angular size. Although this requires high resolution observations, it enables all sources to be classified whether or not they can be optically identified. Bridle *et al.* find that bright sources have a much higher mean red shift and probably also a steeper exponent to the source count distribution, and this seems to suggest a physically real basis for their classification.

For the purpose of subsequent discussion, we combine the spectral classes defined in Section IV into two categories. Spectra classified as S or C? will be referred to as "normal" since the majority of sources which have been observed over a wide range of frequencies would be included in these two classes. Spectra classified as X or P will be referred to as "abnormal". The three sources whose spectra are fairly flat over the present limited frequency range are believed to be more properly included in the abnormal than in the normal category. Their spectral indices all differ by $\geqslant 3$ standard deviations from the mean of those classified as S. Also, Fanaroff and Blake (1972) find that in a sample of sources selected on the basis of having a flat spectrum over a limited frequency range, most show some spectral abnormality when information over a greater range of frequencies is examined.

The classification into normal and abnormal spectrum sources, is also one which can be made for all sources if observations are made over a range of frequencies although there will always be borderline cases such as those classified here as C. Observations over an increased range of frequency would settle some of these cases (e.g. some C sources no doubt have normal spectra with a steepening at high frequency) but might also place others in doubt. However, the situation is no worse than in the other classification schemes, as classification by identification omits the large number of unidentified sources and classification by surface brightness depends on an arbitrary boundary between high and low brightness that is based on observational convenience.

There remains the question whether classification by spectrum has any physical significance. Since spectral abnormality is believed to be due to synchrotron self-absorption in a compact source or source component, abnormal spectrum sources will generally be included in the bright classification of Bridle *et al.* (1972*a*). This class includes $\sim 50\%$ of all sources at 1400 MHz but does not consist entirely of abnormal spectrum sources since these are in a minority at frequencies below 5 GHz (Pauliny-Toth *et al.* 1972). The physical significance of the classification by normal and abnormal spectra is considered in the following two subsections.

(*c*) *Normal Spectrum Sources*

There is increasing evidence that galaxies and QSOs with normal spectra belong to the same class of objects. Miley (1971) has shown that normal spectrum QSOs are almost all resolved into at least two components and that there is a continuous relationship between angular separation and red shift z for both QSOs and galaxies, albeit with quite a spread at any given z. Bridle *et al.* (1972*b*) find the usual correlation between luminosity and spectral index for galaxies with normal spectra but they also conclude that the normal spectrum QSOs and galaxies probably form a common trend in this respect. The correlation between luminosity and steepness of spectrum also explains the tendency for steep spectrum sources to be unidentified. A similar result is reported by Veron *et al.* (1972). Strom (1972) has shown that for normal spectrum sources (sources with very steep spectra were excluded) there is a common relationship between Faraday depolarization and linear size for both QSOs and galaxies.

If normal spectrum galaxies and QSOs do belong to the same class of object, with the QSOs being generally at a greater distance, this would appear to suggest evolution in luminosity, although observational selection effects due to distance alone may play a part in the difference in appearance. There are three blue galaxies among our normal spectrum sources while some of the BSO?s may also be compact blue galaxies. Such objects may well represent an intermediate stage in appearance between galaxies and QSOs.

(*d*) *Abnormal Spectrum Sources*

As already pointed out in subsection (*a*) above, the identification rate is very high for abnormal spectrum sources. Similar results have been obtained by Blake (1970) and Fanaroff and Blake (1972) for sources with comparable spectra. Combining the three lists we obtain 32 sources of which 23 are identified with QSOs or QSO candidates, 6 with galaxies, and only 3 are unidentified. The high identification rate for these sources implies a high ratio of optical to radio luminosity.

Sources with flat or complex spectra have long been associated with QSOs (Bolton 1966). Bolton (1969), among others, has suggested that the flat spectrum QSOs may form a separate class. Hazard (1967) and Miley (1971) have drawn attention to an important phenomenological difference between QSOs with flat or complex spectra and those with normal spectra. The former usually have the optical object coincident with the radio source, or with the dominant component at high frequency (if the source is resolved). On the other hand, normal spectrum QSOs tend to have the optical object more or less centrally placed between two radio components.

Rowan-Robinson (1972) has suggested that very compact QSOs may comprise a separate class of object occurring locally. This would overcome many difficulties, as he points out, but would require a new mechanism for the red shift. On the other hand, Kellermann (1972) has emphasized the occurrence of galaxies among the compact objects. Even though we find these to be a minority, their existence may be important. There appears to be no way of deciding unequivocally between QSOs and galaxies on the basis of their radio properties alone. It seems a distinct possibility that QSOs and radio galaxies may form a common class and that the compact objects with abnormal radio spectra represent explosive events in the nuclei of these sources or possibly early stages in their evolution as suggested by Hazard (1967). However, the last part of the discussion in this and the preceding subsection has necessarily been speculative. It is desirable to have detailed information on many more sources before firm conclusions can be drawn.

VI. Conclusions

Considering only those sources in our sample whose spectra are straight or slightly curved, the spectral index distributions for galaxies and QSO candidates are very similar. This conforms with a considerable amount of other evidence that these objects are not distinguishable on the basis of radio properties. For sources with spectra which are peaked, flat, inverted, or complex the identification rate with optical objects visible on the Palomar Sky Survey prints is very high ($\sim 90\%$). Most of these are blue (or in some cases neutral) stellar objects. It is important to find more identifications with neutral stellar objects and to determine whether these are QSOs in a particular range of red shift (for example, $z > 2 \cdot 5$).

Note added in proof

One of the neutral stellar objects discussed here ($1442+10 \cdot 1$) has been found to have a red shift of $3 \cdot 53$ (Wampler *et al.* 1973).

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