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RADIO SOURCES WITH FLAT SPECTRA

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ABSTRACT

The spectra of sixty-three radio sources discovered in surveys conducted at 1.4 GHz are studied in the frequency range 0.6–10.6 GHz. Many of the spectra are flat at high frequencies, and very few show evidence of having more than one spectral component. It is argued that a large fraction of the population of sources with flat high-frequency spectra are optically thin sources with low values of the electron-energy distribution index γ.

I. INTRODUCTION

In radio surveys conducted at higher frequencies, such as the Ohio survey at 1415 MHz, many radio sources are found which do not appear in surveys made at lower frequencies. These sources tend to have spectra above 0.5 GHz which are flat or which have a maximum (Kraus *et al.* 1968). Recent work (e.g., Kellermann, Pauliny-Toth, and Davis 1968; Pooley and Kenderdine 1968) has indicated that at a given flux level there is a significant increase in the proportional number of radio sources with flat spectra.

In examining the statistics of radio-source spectra it is usual to work with a sample of sources which (for a given area of sky) is complete down to a specific flux density at a certain frequency. The sources examined in this paper do not represent a complete sample in this sense. The sixty-three sources chosen for analysis were all first detected in source surveys at 1.4 GHz and were not previously detected in any surveys at lower frequencies. The sample is therefore strongly biased against sources with normal spectra, i.e., $\alpha \sim 0.7$, where $S \propto \nu^{-\alpha}$. The sources should, however, be a representative sample of the population of flat-spectrum sources provided that the distribution of spectra is not strongly dependent upon flux density.

Of the sixty-three sources examined, fifty-four were discovered in the Ohio survey. These sources are listed in Table 1. Their flux densities, published in a companion paper (Kraus and Andrew 1970), have been measured at 612, 1415, and 2650 MHz with the Ohio State University 260- by 70-foot telescope and at 3.2, 6.6, and 10.6 GHz with the 150-foot telescope of the Algonquin Radio Observatory. The remaining nine sources are listed in Table 2; the high-frequency data for several of them are from Bridle (1969), who used the identical equipment at the Algonquin Radio Observatory to measure their flux densities.

The spectra of the sources are presented in Figure 1. In drawing a spectral curve the criterion adopted was that the curve should be the simplest one consistent with the accuracy of the observations. Where no error bars are shown in Figure 1, the accuracy of the measurement is such that the error bars have approximately the same dimensions as the plotted points.

Many sources with flat spectra are variable at high frequencies, so that measurements made at different epochs can give a false impression of the overall spectrum of a source. The sources DA 55 and DA 393 are known to be variable at 6.6 and 10.6 GHz from the program of variable-source observations in progress at the Algonquin Radio Observatory. Figure 1 shows clearly the different spectra obtained for DA 393 at high frequencies, depending on whether we used the flux densities reported here (*open circles*) or the flux densities of Bridle (1969) and Pauliny-Toth and Kellermann (1968) (*filled circles*). The sources OI 363 and OQ 208 are also included in the ARO variable-source program, but for these two sources there is only slight evidence of variability. The epoch of the ARO measurements is nearly the same at all frequencies for any individual source in Table 1, though the epoch may differ from source to source.

II. DISCUSSION

It is clear from Figure 1 that for the majority of sources a straight line gives a good fit to the data over much of the observed range of frequency. The flux density often

TABLE 1

RADIO SOURCES DISCOVERED IN THE OHIO SURVEY

Source	α	Source	α	Source	α
OA 33	−0.1	OL 318	0.0	OV −213	0.0
OB 338	+0.4	OL 333	+0.5	OV −148	+1.0
OB 343	+0.2	OM 133	−0.1	OV −262	+0.9
OC−022	+0.1	OM−037	(+0.9)	OV 080	0.0
OD 003	+0.8	OM 344	+0.9	OW −015	+0.7
OD 148	+0.2	ON 343	+1.0	OW 154.9	+0.3
OD 058	+0.6	OP 114	+0.9	OX 131	+0.5
OD 062	0.0	OP −192	−0.4	OX 036	+0.6
OD 094.7	−0.1	OQ 208	...	OX −145	+0.4
OF 036	...	OQ 323	+0.3	OX 161	+0.1
OF 097	+0.5	OQ 172	+0.6	OX 074	0.0
OG 003	+0.4	OR 103	−0.4	OX −192	−0.3
OG 050	+0.1	OR 186	0.0	OY −211	+0.6
OI 318	+0.5	OS −268	+0.4	OY 077	+0.3
OI −039	+0.3	OS −191	+0.8		
OI 255	+0.7	OS 092	−0.1		
OI −060	+0.3	OT −229	+0.8		
OI 363	+0.2	OT 081	−0.2		
OI 380	+0.4	OU −033	+0.6		
OK 290	−0.3	OU 134	+0.7		

TABLE 2

MEASURED FLUX DENSITIES

Source	3.2 GHz	6.6 GHz	10.6 GHz	α	Remarks
DA 55	3.10	4.35	6.00	...	Variable
DW 0400+25	...	...	...	0.2	1
DW 0742+10	3.50	3.25	2.50	...	
DW 1108+20	...	...	...	0.5	1
DA 393	1.90	2.35	2.60	...	DW 1555+00. Variable.
CTD 93	...	...	...	1.0	2
DA 406	...	...	...	0.1	1
DW 1616+06	...	...	...	0.2	1
DW 1656+05	...	...	...	...	1

Remarks: (1) Bridle (1969); (2) Kraus *et al.* (1968).

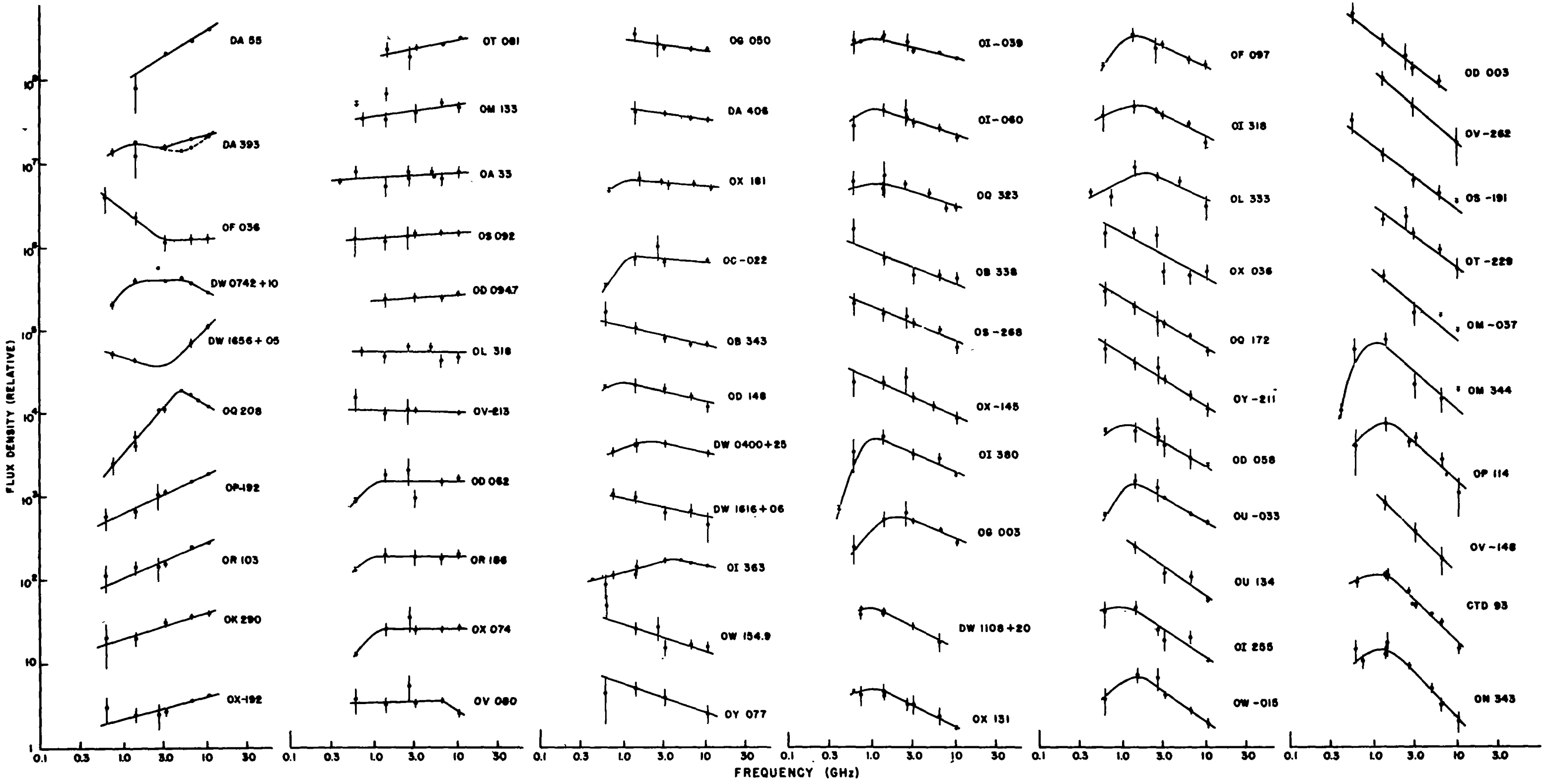

FIG. 1.—Spectra of the sources

decreases at the low-frequency end, which is probably indicative of synchrotron self-absorption in the sources and implies angular diameters $\sim 5 \times 10^{-4}$ seconds of arc, since most of the cutoff frequencies are in the range 1000–2000 MHz.

Of the sixty-three sources in Tables 1 and 2, only OF 036, DW 1656+05, and possibly DW 0742+10 have spectra which require the existence of more than one component in order to explain their shape. (It is assumed that the radiation arises from synchrotron emission from electrons with an energy spectrum $N(E)dE \propto E^{-\gamma}dE$, giving rise to a radiation spectrum $S \propto \nu^{-\alpha}$, where $\alpha = \frac{1}{2}[\gamma - 1]$.) While it must be emphasized that the fitted spectra may be biased in favor of straight lines by insufficient and inaccurate data, it seems, nevertheless, that there is a remarkably small percentage of sources in the sample which clearly have more than a single spectral component.

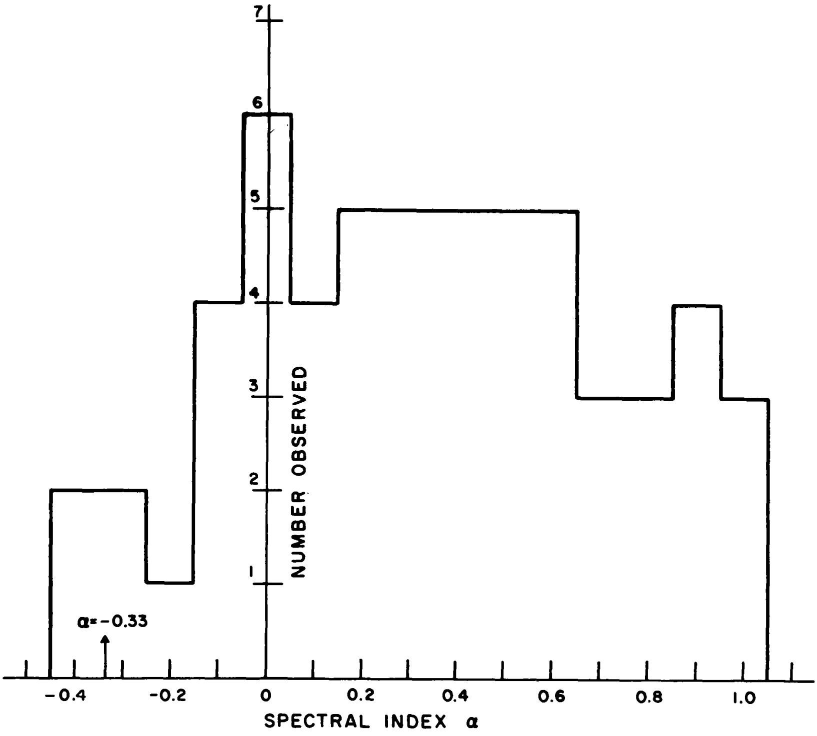

FIG. 2.—Distribution of spectral indices of the sources

One source, OQ 208, has a spectrum characterized by two straight lines meeting in a sharp peak. This spectrum is well documented, and it is difficult to explain on any of the usual assumptions. Allen (1968) has suggested that OQ 208 may contain a thermal X-ray–emitting plasma.

We show in Figure 2 the distribution of spectral indices for all the sources other than the six (DA 55, DA 393, OF 036, DW 1656+05, DW 0742+10, and OQ 208) mentioned above. The spectral index is that of the dominant straight portion of the spectral curve of each source and is in each case the spectral index at 5000 MHz. The dearth of spectra with $\alpha \sim 0.7$ in Figure 2 is of course due to the adopted selection criterion.

One conclusion which can be drawn from Figure 2 is that the distribution of spectral indices is continuous. Hence any detailed classification of radio sources based on spectral index alone would appear to be arbitrary.

It is generally held that sources with normal spectra are optically thin and characterized by $\gamma \simeq 2.5$, while it is often suggested (e.g., Kellermann and Pauliny-Toth 1969) that flat spectra can be explained by the superposition of a number of spectral components, each of which is optically thick at some wavelength. This suggestion is supported by the evidence from long-baseline interferometry that some quasi-stellar sources, which tend to have flat spectra, are composed of a number of small optically thick components. Additional evidence is provided by the observations of variable sources which indicate the existence of small components with flat spectra which are optically thick at high frequencies (Kellermann and Pauliny-Toth 1968).

However, there seems to be no a priori reason that the distribution of spectral indices α cannot simply reflect the distribution of the electron-energy index γ in optically thin sources. Previous evidence indicating the existence of a population of sources with flat spectra has been frequently based on observations at only two frequencies, one low and one high. Although two points were sufficient to indicate the average spectral index between the two frequencies, they gave no indication of the possible complexity of the spectrum. However, in Figure 2 we now have many sources whose spectra have been quite well defined over a wide frequency range, from 0.6 to 10.6 GHz, and which appear to be simple curves rather than the resultant of distinct components. Further, recent observations of variable sources (Locke, Andrew, and Medd 1969) have indicated that at least some variations arise in components which remain optically thin at all times and have electron populations which are characterized by $\gamma \sim 1$ or may even be monoenergetic.

The radiation spectrum of a single electron has an index $\alpha = -0.33$. Thus $\alpha = -0.33$ is the limiting spectral index of any population of optically thin sources, and any source with $\alpha < -0.33$ must be optically thick. The histograms of other workers (e.g., Kellermann, Pauliny-Toth, and Davis 1968; Pooley and Kenderdine 1968) showed very few sources with spectral indices more negative than -0.33. The present work confirms this effect and in addition suggests that it is not merely due to complex spectra being averaged by making observations at only two wavelengths.

There are undoubtedly a number of spectra resulting from multiple components which are optically thick at high frequencies (e.g., Kellermann and Pauliny-Toth 1969). However, we suggest that a sizable fraction of the population of sources with flat spectra at high frequencies are optically thin sources with low values of γ.

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