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IMPROVED SPECTRA OF SOME OHIO RADIO SOURCES WITH UNUSUAL SPECTRA

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ABSTRACT

Accurate flux-density measurements at 318 and 606 MHz are presented for forty-seven Ohio sources with unusual spectra. Many of the sources show a more complex spectral behavior than previously reported, and require several components to describe their spectra. It is argued that even the flat-spectrum sources are probably a superposition of normal-spectrum components that become optically thick at different frequencies.

Flux densities for seventy-one sources with unusual radio spectra have been measured with the Ohio State University (OSU) telescope at 612, 1415, and 2650 MHz and with the Algonquin Radio Observatory (ARO) telescope at 3.2, 6.6, and 10.6 GHz (Kraus and Andrew 1970). On the basis of these measurements Andrew and Kraus (1970) found that only three out of sixty-three such sources had spectra which require the existence of more than one component in order to explain their shapes. Furthermore, since many of these sources had unusually flat spectra, they concluded that these were probably optically thin sources with a low value of the electron energy index, γ.

At low frequencies the spectra of these weak sources are uncertain because of the low angular resolution and large quoted errors of the 612-MHz Ohio measurements. Most of these sources are sufficiently weak that there are only a few published flux-density measurements for them below 612 MHz. Accordingly, the forty-seven Ohio sources investigated by Kraus and Andrew (1970) that are visible at Arecibo were included in a larger program of flux-density measurements at 111.5, 318, and 606 MHz at the Arecibo Observatory (AO). The half-power beamwidth at 111.5 MHz is 45′. New high-efficiency line feeds were used at 318 and 606 MHz (LaLonde and Harris 1970; LaLonde 1970) with the AO 1000-foot spherical reflector to give half-power beamwidths of 16′ and 9′, respectively. At 612 MHz the beam area of the Ohio telescope is 25 times that of the Arecibo telescope at 606 MHz.

For each source the declination was measured with the 606-MHz line feed. The flux densities were then measured from the peak deflection of the drift scan in right ascension made at the measured declination. There was no evidence that any of the sources broadened the beam of the Arecibo reflector at any frequency. The flux-density scale is based on the interpolated flux densities from Kellermann, Pauliny-Toth, and Williams (1969) of the sources 3C 43, 3C 47, 3C 175, and 3C 441. We estimate that the rms proportional errors are 9, 4, and 6 percent at 111.5, 318, and 606 MHz, respectively, with independent random errors due to noise and confusion of 3.0, 0.17, and 0.07 f.u., respectively. Only seven of the sources were detected at 111.5 MHz. The remainder were estimated to be less than about 3 f.u., except for OS 176 where the upper limit is 5 f.u. All of the observations were made between 1969 October and 1970 April. A detailed discussion of the Arecibo program of flux-density measurement is in preparation.

Table 1 presents the results of the Arecibo flux-density measurements, revised spec-

TABLE 1

ARECIBO FLUX-DENSITY MEASUREMENTS FOR THE FORTY-SEVEN OHIO SOURCES

Source	Arecibo Observatory Flux Density			Spectral Type	Comments
	111.5 MHz	318 MHz	606 MHz		
OB 338	3.0	1.48	1.03	Concave	
OB 343	...	1.12	1.45	Convex	
OC 328	...	3.14	2.69	Convex	DW 0116+31, 4C 31.04, B0116+31
OD 003	...	0.98	1.46	Convex	
OD 148	...	1.64	1.53	Complex	P0229+13, 4C 13.14, measurements from Pks and NRAO at 2.7 and 5.0 GHz indicate a complex spectrum and variability
OD 058	...	1.51	1.28	Straight	(4C 08.10), $\alpha=0.5$
OD 062	*	*	0.61	Straight	$\alpha=-0.2$
OD 094.7	...	1.11	1.00	Straight	6′ south of OSU position, $\alpha=0.0$
OE 355	...	2.35	2.86	Complex	4C 32.14, B0333+32, NRAO 140, variable
OF 200	...	1.22	1.42	Convex	DW 0400+25
OF 036	...	*	1.48	Concave	
OF−067	*	1.30	2.06	Convex	5′ south of OSU position, NRAO 190, variable
OF 097	*	*	0.58	Convex	
OG 003	*	*	1.14	Convex	
OG 050	6.6	2.76	2.09	Concave	5′ south of OSU position
OI 318	...	0.67	0.76	Convex	
OI−039	4.0	4.46	3.34	Straight	DW 0723−00, $\alpha=0.2$ (may be complex)
OI 255	*	1.54	1.11	Straight	$\alpha=0.4$
OI 363	...	0.77	1.34	Convex	B0738+31 H0852+20
OJ 287	...	0.72	0.75	Complex	Variable?
OK 118	11.8	4.34	2.54	Straight	7′45″ south of OSU position, P0911+17, 4C 17.48, $\alpha=0.8$
OK 129	5.5	3.20	2.12	Straight	4C 18.29, P0917+18, H0917+18, $\alpha=0.8$
OK 290	...	0.77	0.50	Concave	
OL 318	...	0.74	0.44	Concave	B76
OL 333	...	<0.40	0.55	Convex	B1019+30
OM 133	...	0.74	0.58	Concave	H1119+18
OM 344	...	0.76	0.50	Straight	B1128+30A, 4′ south, 17 sec following OSU position, $\alpha=0.3$
ON 343	...	1.13	1.25	Complex	
OP 114	...	0.38	0.58	Convex	
OQ 208	...	<0.3	0.36	Convex	
OQ 323	3.7	1.87	1.40	Complex	B207
OQ 172	...	1.83	1.90	Convex	
OR 103	3.3	1.65	1.17	Concave	Double, main source 17 sec following OSU position
OR 186	...	1.45	1.07	Concave	
OS 176	...	3.14	2.87	Complex	4C 17.71, NRAO 517, P1645+17
OS 092	...	1.44	1.80	Complex	
OT 081	*	1.43	0.86	Concave	9′ south of OSU position
OU 134	*	*	0.83	Convex	11′ south of OSU position
OV 080	...	1.01	0.91	Complex	
OW 101	*	*	1.53	Straight	4C 14.73, P2001+13, $\alpha=0.7$
OW 154.9	...	1.33	0.97	Concave	
OX 131	...	0.95	0.87	Convex	H2118+18
OX 036	*	*	0.57	Straight	16′ south of OSU position, $\alpha=0.1$
OX 057	*	0.96	1.27	Complex	P2134+004, possible variable
OX 161	...	0.89	0.98	Straight	$\alpha=0.0$
OX 074	...	0.78	1.14	Convex	
OY 077	*	*	0.90	Straight	$\alpha=0.3$

NOTE.—Flux densities are in units of 10^{-26} W m^{-2} Hz^{-1}, and frequencies are in MHz. Other observations listed are 4C from Pilkington and Scott (1965) and Gower *et al.* (1967); B from Grueff and Vigotti (1968) and Colla *et al.* (1970); DW from Davis (1967); H from Höglund (1967); NRAO from Kellermann, Pauliny-Toth, and Tyler (1968), Pauliny-Toth and Kellermann (1968), and Pauliny-Toth, Wade, and Heeschen (1966); and P from Ekers (1969) or Shimmins, Manchester and Harris (1969).

* No measurement made.

tral classifications, and position corrections for the nine sources which were found to be noticeably displaced from the quoted positions. Comparison of the AO positions with the ARO positions (B.H. Andrew, private communication) confirmed that the Arecibo sources are indeed the same sources measured at the higher frequencies. Some previous observations of the Ohio sources have also been noted. Comparison of the OSU flux densities at 1415 MHz with those from NRAO (Pauliny-Toth, Wade, and Heeschen 1966; Davis 1967; Höglund 1967) and Parkes (Day *et al.* 1966) shows that the OSU flux densities appear systematically high in the range 1–3 f.u. Figure 1 shows spectra of fifteen of the Ohio sources, plotted by using the Arecibo flux densities and the OSU and ARO flux densities above 1 GHz (Kraus and Andrew 1970).

The increase in complexity of the spectra of the Ohio sources that results from the addition of the accurate flux-density measurements at 318 and 606 MHz is quite striking.

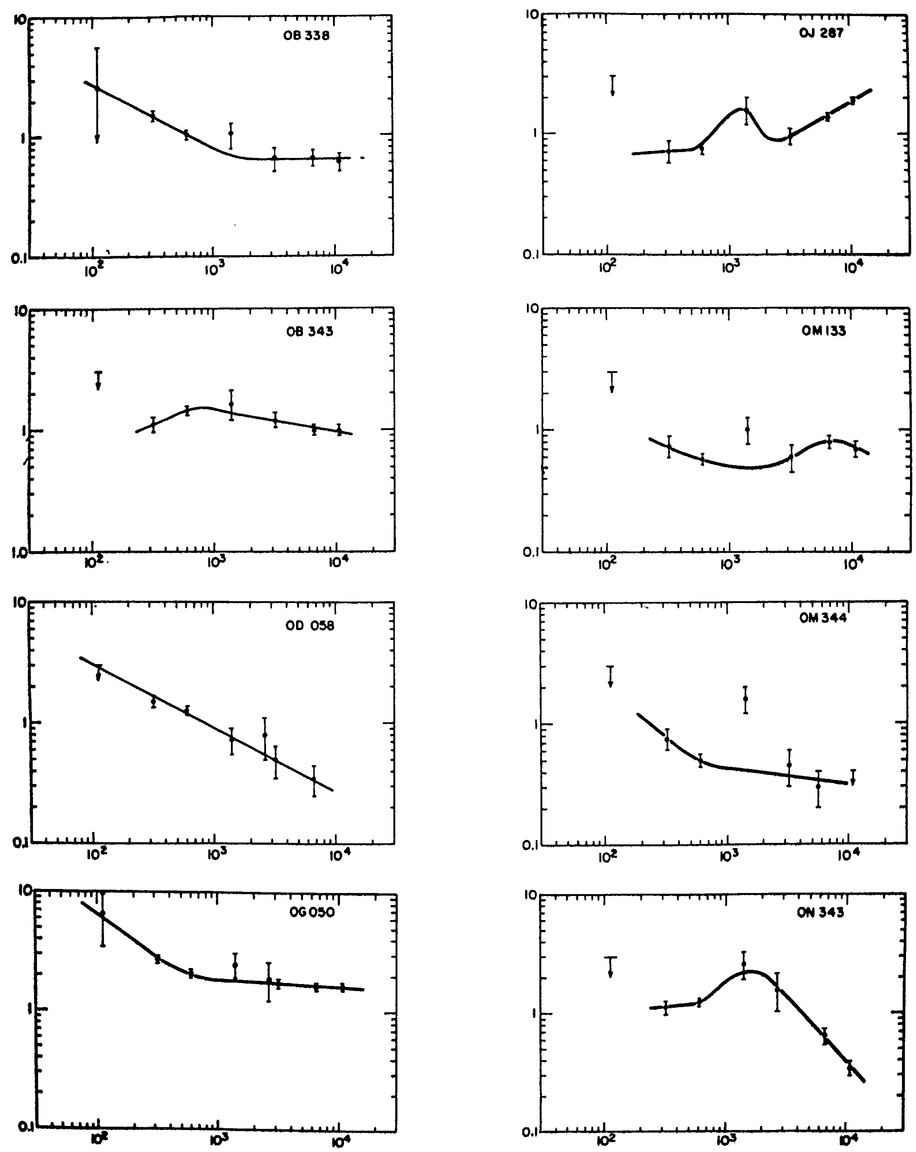

Fig. 1.—Plotted spectra for fifteen of the Ohio sources, together with the spectrum of the source 4C 05.64.

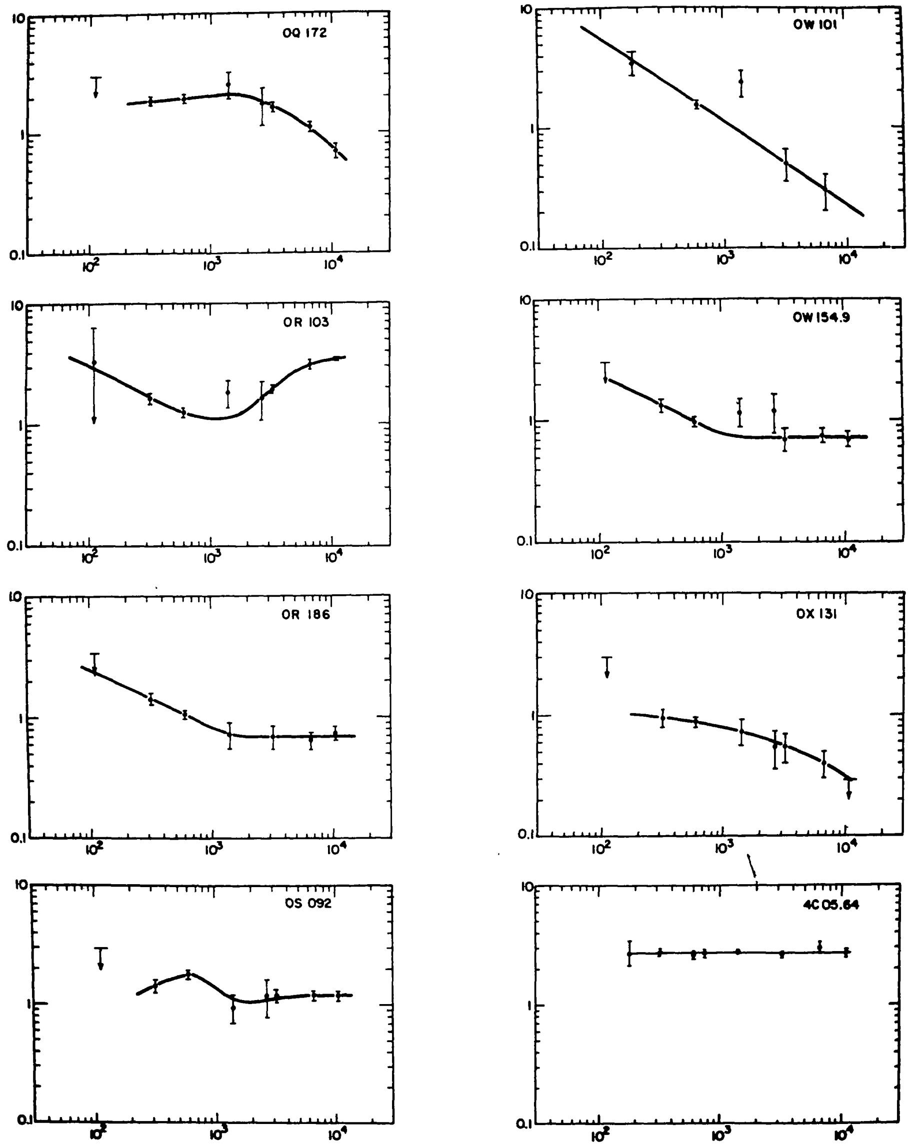

FIG. 1.—*Continued*

In particular, it points out the importance of accurate low-frequency measurements in revealing the presence of low-frequency components or of self-absorption.

Of the eighteen sources originally listed as having straight spectra, only five (OD 094.7, OI 255, OK 118, OX 036, and OY 077) can still be fitted by a single spectral index over the frequency range 318 MHz–10.6 GHz. It is noticeable that while OX 036 is still listed as a straight spectrum source, its spectral index is now 0.1, not 0.6 as listed previously (Andrew and Kraus 1970). We have reclassified a further seven sources (OD 058, OD 062, OI−039, OK 129, OM 344, OW 101, and OX 161) as having straight spectra. That ten of the sources were found to have concave spectra indicates the presence of a low-frequency spectral component similar to that found in normal-spectrum sources in addition to the component responsible for the high-frequency enhancement. An additional nine sources have complex spectra which cannot be fitted by a straight line or a simple peaked curve, a fact which shows clearly the presence of two or more spectral components.

Thirty-seven of the present sources are included in the list of those examined by Andrew and Kraus (1970). Of these, nine are now classified as having straight spectra, ten have concave spectra, five have complex spectra, and thirteen have a spectrum with a single peak. For both the concave and the complex source spectra, two or more components are required in order to explain their shapes. Where previously only one of the thirty-seven sources had been classified as having more than one spectral component, the improved spectra show that at least fifteen of the thirty-seven must now be classified as multicomponent. Thus the conclusion (Andrew and Kraus 1970) that remarkably few of the sources have more than one spectral component is no longer supported by the data. Moreover, we suggest that future improvements in the spectral data will increase this number even further. As an example we recall the case of 3C 273, one of the better known multicomponent sources, which was initially classified as having an accurately straight (S1) spectrum (Conway, Kellermann, and Long 1963).

Of the remaining twenty-two sources with a single spectral component, there are only twelve that have a flat ($\alpha < 0.5$) spectrum, or a flat spectrum above the peak. Such spectra can be explained by a superposition of normal-spectrum components that become optically thick at different frequencies (cf. Kellermann and Pauliny-Toth 1969), or by a single component with a low value of the electron energy-distribution index, γ, as suggested by Andrew and Kraus. The larger proportion of spectrally complex sources now favors the multiple-component interpretation, as do long-baseline-interferometer data. For example, the source 4C 05.64, shown in Figure 1, has an extraordinarily accurately flat spectrum from 178 MHz to 10.6 GHz (Gower, Scott, and Wills 1967; Davis 1967; Bridle 1969*a*), yet recent long-baseline-interferometer measurements at 80 million wavelengths (Kellermann *et al.* 1970) show that this cannot be a single-component optically thin source unless the magnetic field is less than 10^{-8} gauss, an unreasonably low value. It should be noted that the spectrum resulting from the superposition of a few normal-spectrum components that are optically thick at different frequencies often appears to result in quite a smooth curve (cf. Bridle 1969*b*).

Finally, several of the Ohio sources deserve individual comment. The close pair OB 338 and OB 343 have quite different low-frequency spectra and are unlikely to be related, contrary to the suggestion by Kraus *et al.* (1968). There is no longer any evidence for a low-frequency component in OJ 287 such as exists for 3C 273, although many of the other sources do exhibit such a low-frequency component. The source OQ 208 is most probably a synchrotron self-absorbed source, since long-baseline-interferometer measurements indicate that it has an angular diameter of $0''.0018 \pm 0''.0003$ at 2.3 GHz (Kellermann *et al.* 1970).

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REFERENCES

Andrew, B. H., and Kraus, J. D. 1970, *Ap. J.* (*Letters*), **159**, L45.
Bridle, A. H. 1969*a*, *Nature*, **221**, 348.
———, 1969*b*, *ibid.*, **224**, 889.
Colla, G., Fanti, C., Fanti, R., Ficarra, A., Formiggini, L., Gandolfi, E., Grueff, G., Lari, C., Padrielli, L., Roffi, G., Tomasi, P., and Vigotti, M. 1970, *Astr. and Ap. Suppl.*, **1**, 281.
Conway, R. G., Kellermann, K. I., and Long, R. J. 1963, *M.N.R.A.S.*, **125**, 261.
Davis, M. M. 1967, *Bull. Astr. Inst. Netherlands*, **19**, 201.
Day, G. A., Shimmins, A. J., Ekers, R. D., and Cole, D. J. 1966, *Australian J. Phys.*, **19**, 35.
Ekers, J. A. 1969, *Australian J. Phys. Suppl.*, No. 7.

Gower, J. F. R., Scott, P. F., and Wills, D. 1967, *Mem. R.A.S.*, **71**, 49.
Grueff, G., and Vigotti, M. 1968, *Ap. Letters*, **2**, 113.
Höglund, B. 1967, *Ap. J. Suppl.*, No. 135, **15**, 61.
Kellermann, K. I., Clark, B. G., Jauncey, D. L., Cohen, M. H., Shaffer, D. B., Moffet, A. T., and Gulkis, S. 1970, *Ap. J.* (in press).
Kellermann, K. I., and Pauliny-Toth, I. I. K. 1969, *Ap. J.* (*Letters*), **155**, L71.
Kellermann, K. I., Pauliny-Toth, I. I. K., and Tyler, W. C. 1968, *A.J.*, **73**, 298.
Kellermann, K. I., Pauliny-Toth, I. I. K., and Williams, P. J. S. 1969, *Ap. J.*, **157**, 1.
Kraus, J. D., and Andrew, B. H. 1970, *Ap. J.* (*Letters*), **159**, L41.
Kraus, J. D., Scheer, D. J., Dixon, R. S., Fitch, L. T., and Andrew, B. H. 1968, *Ap. J.* (*Letters*), **152**, L35.
LaLonde, M. 1970 (in preparation).
LaLonde, M., and Harris, D. 1970, *I.E.E.E. Trans. Antennas Prop. AP-18*, p. 41.
Pauliny-Toth, I. I. K., and Kellermann, K. I. 1968, *A.J.*, **73**, 953.
Pauliny-Toth, I. I. K., Wade, C. M., and Heeschen, D. S. 1966, *Ap. J. Suppl.*, No. 116, **13**, 65.
Pilkington, J. D. H., and Scott, P. F. 1965, *Mem. R.A.S.*, **69**, 183.
Shimmins, A. J., Manchester, R. N., and Harris, Beverley J. 1969, *Australian J. Phys.*, *Ap. Suppl.*, No. 8.