

THE SPECTRA OF RADIO SOURCES

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I have already reported on the spectra of 31 radio sources [1], but since then, new observations have become available, and, in addition, I have corrected my own 38-Mc/s measurements for a nonlinearity in the response of my receiver. The qualitative picture remains the same, but from the more recent information I have found values for the spectral indices of 85 sources, and have revised some of those given previously. From the larger sample of sources now available, it is possible to suggest some relationships of sufficient interest to warrant further investigation.

The approach to the problem is determined by the well-known difficulty of making absolute measurements of flux densities, which is well illustrated by the spread of values obtained for four of the most intense sources by different observers (Figs. 1 and 2). The two principal uncertainties in such measurements are the absolute gain of the aerial system and the calibration of receiver sensitivity.

It is difficult to measure the gain of a large aerial system since small side-lobes occupying a large solid angle contribute significantly to the total radiation; methods of calculating the gain of such a system are also unreliable. The gains of horn aerials and small arrays of dipoles can be calculated; such aerials have been used for absolute measurements at low [2, 3, 4, 5] and high [6] frequencies respectively. Owing to their low resolving power, such aerials are suitable for observing a few intense sources only.

Early measurements of the absolute sensitivity of receivers were based on the shot noise in a saturated diode. Experiments have shown that even at low frequencies serious errors can arise from impedance transformations in the electrode structure, unless special coaxial diodes are used [3]. Recent observations [2, 4, 5, 6] have used the thermal noise from a resistance as a standard source, and these measurements are believed to be considerably more accurate.

Although absolute measurements are difficult to make, it is relatively easy to compare the flux densities of two sources, provided that the aerial can be directed at each in turn without the disturbing effects of ground reflections, and that the linearity of the receiver response can be established. If the spectrum of one intense source is established by accurate absolute measurements, it then becomes possible to use the observations of relative intensities made with uncalibrated (or less reliably calibrated) systems to derive the spectra of a large number of sources.

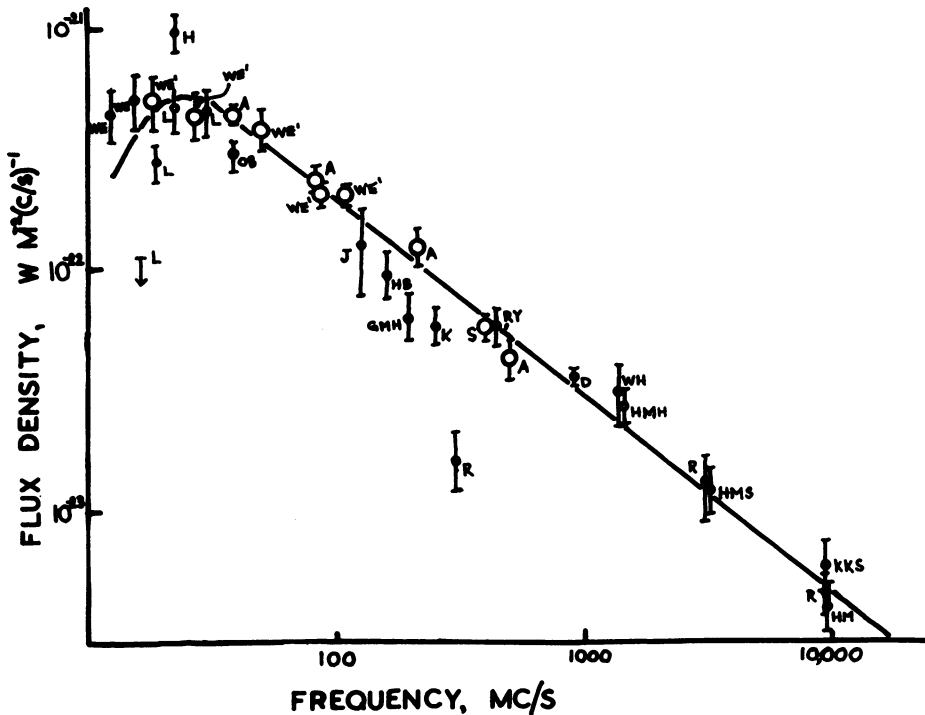


FIG. 1. The spectrum of Cassiopeia A, 23N5A, from absolute measurements of flux density reported by various observers. Sources of information are represented by the same letters as in Whitfield [1].

All known observations (with the exception of a few early measurements) of the flux density of 23N5A (Cassiopeia A) are plotted on a logarithmic scale in Fig. 1. (Fig. 1 is substantially the same as its 1957 counterpart, but it contains some additional points, notably those marked WE' due to Wells [5].) The large circles denote measurements in which special attention was paid to accurate thermal calibration and calculation of aerial gain. There is a decrease in flux density at the lowest frequencies, generally attributed to absorption in H II regions, but in the 30- to 10,000-Mc/s range the most accurate observations show no significant deviations from a straight line, which can be represented by

$$\text{flux density} \propto (\text{frequency})^x,$$

in which the spectral index, x , has a value of -0.80 .

In 1955 it was suggested [7, 8] that the relatively small values of flux density found in the 400- to 500-Mc/s region represented a true departure from this simple relationship, and that further measurements in this region are needed. More recent observations, however, do not support this suggestion. The adoption of a linear relationship for 23N5A also leads to simple spectral curves for 19N4A (Cygnus A), 05N2A (Taurus A), and 12N1A (Virgo A) (Fig. 3);

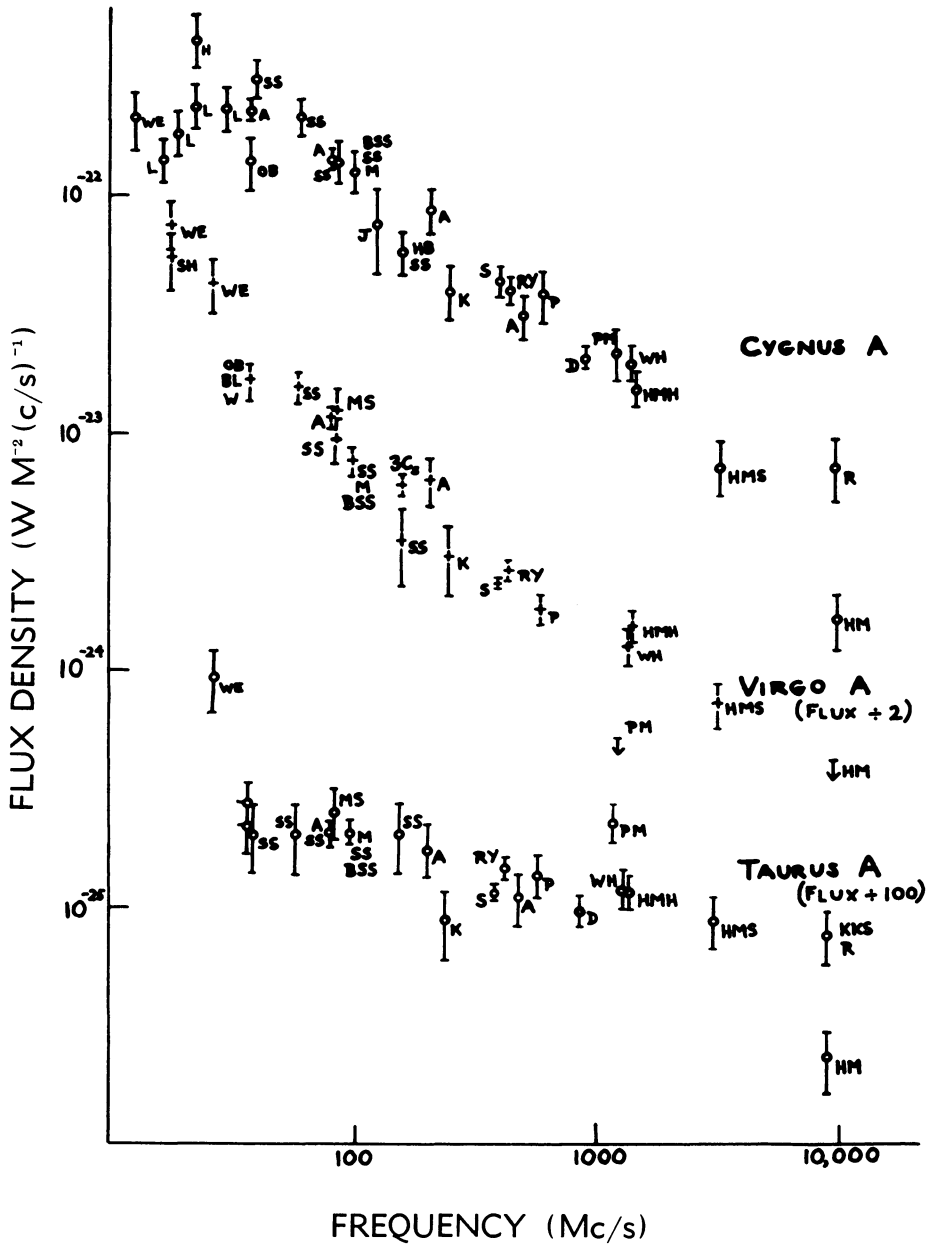


FIG. 2. The spectra of three intense sources, from absolute measurements of flux density.

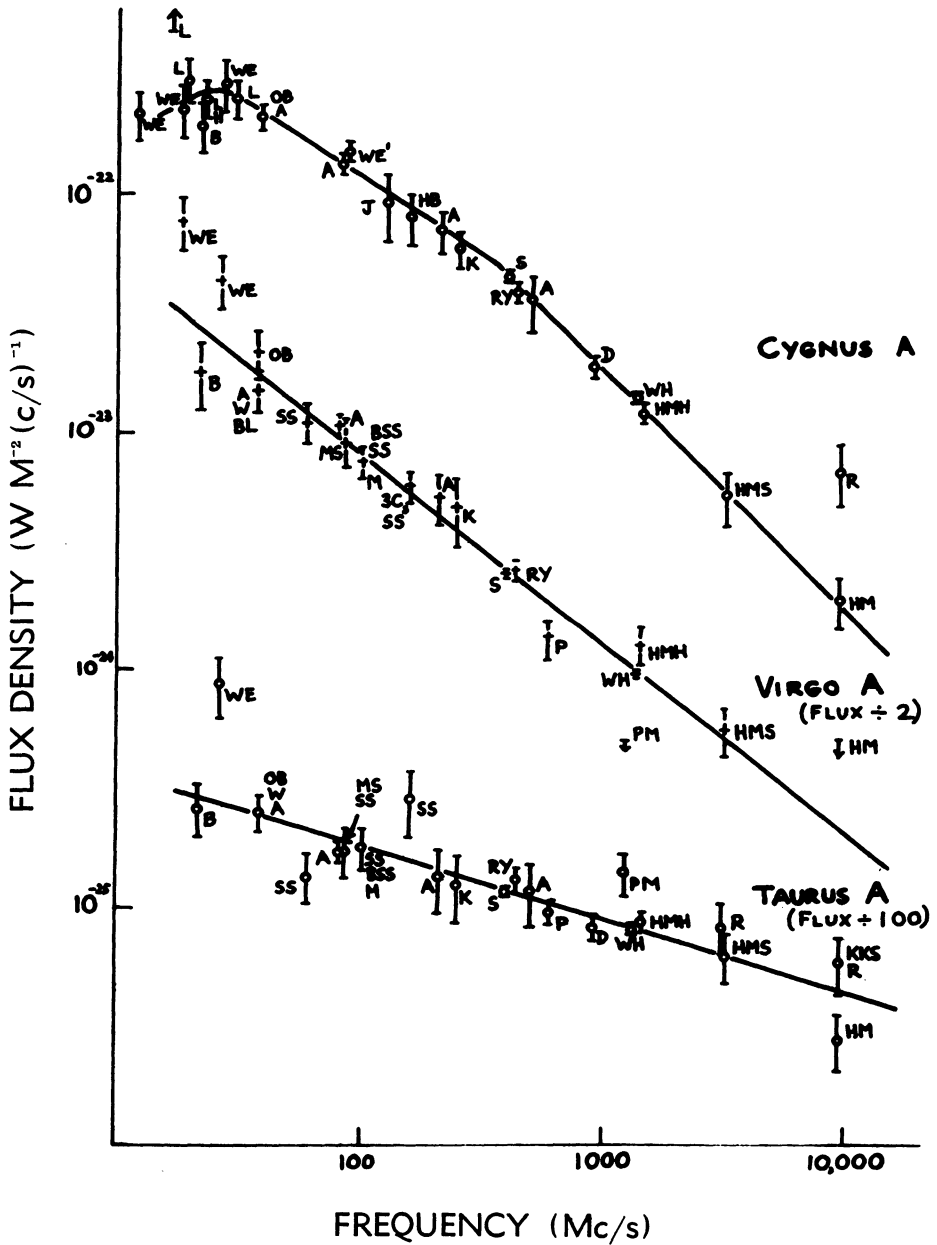


FIG. 3. The spectra of the same three sources, derived from flux densities relative to Cassiopeia A.

if there were a reduction in the 400- to 500-Mc/s region, it would imply that a similar irregularity also occurred at these frequencies in the spectra of these and other sources.

Ryle has suggested that the spectrum of 23N5A becomes steeper at frequencies above 1000 Mc/s; for, of the observations in this region, three [9, 10, 11] were made in the same laboratory with the same paraboloid and using similar techniques, and would be expected to be internally consistent. The spectral index derived from these points, -1.0 , is supported by three of the other four observations in this region. I do not regard the present evidence on this point as strong enough to justify the additional complication, and I tentatively retain my assumption of a linear spectrum for 23N5A. If the spectrum of 23N5A were steeper above 1000 Mc/s, the spectra of all the other sources would be similarly affected, but for most of the 85 sources considered, the data do not extend up to 1000 Mc/s; therefore, the present results would not be affected. The high-frequency spectra of sources might, however, be important if, as Ryle has suggested [12], many of the fainter sources are so distant that their radiation suffers a large red-shift.

Scheuer suggests using an H II region rather than 23N5A as a standard source at high frequencies since the flux density of an optically thin thermal source varies with frequency very slowly and in a predictable manner. However, the spectra that I derived for four thermal sources show a deplorably wide scatter of observed relative fluxes; perhaps this is partly because thermal sources occur in complicated regions of the Milky Way.

Lack of space prevents the reproduction of all 85 spectra; this information will be published elsewhere. Many of the spectra depend chiefly on the Cambridge surveys of radio sources on 81.5 and 159 Mc/s and on Blythe's and my observations on 38 Mc/s, but confirmation from other observations is available for the intense sources. In most cases the spectra are linear, or the 3 or 4 points available do not permit a more elaborate interpretation; in five cases (besides 19N4A) there are indications of a change in spectral index at high frequencies, similar to that found in the spectrum of 19N4A.

In 1957 I pointed out [1] the correlation between spectral index and type of sources, which is confirmed by using the present more extensive data (Fig. 4). The mean spectral index of known galactic sources is approximately -0.6 ; that of identified extragalactic sources about -0.9 ; while that of unidentified sources that are further than 10° from the galactic equator and that may not unreasonably be presumed to be, with few exceptions, abnormal external galaxies, about -1.2 . Unidentified sources near the galactic equator should represent a mixture of galactic sources and other "unidentified" sources, and the total absence of spectral indices less than -1.2 in this group might be regarded as puzzling, since absorption effects due to the Galaxy should be negligible; however, the sample is too small to make this absence significant.

The spectral indices of the unidentified sources with $|b| > 10^\circ$, together with those of sources known to be extragalactic, have been plotted against

flux density (Fig. 5). There is a large scatter, but there appears to be a gradual diminution of the mean spectral index, from about -0.8 for the brightest sources to -1.3 for the faintest. This result is not independent of the results in Fig. 4, since the six sources brighter than 10^{-23} watts $\text{m}^{-2}(\text{c/s})^{-1}$ on 38 Mc/s are all optically identified with external galaxies.

Instrumental errors that might lead to a spurious variation of spectral index with flux density have been examined. There can be little doubt about the spectra of the brighter sources, which are derived from numerous observations made in different laboratories. Many spectra of fainter sources, however, depend on the observations at 38 and 159 Mc/s; the 81.5-Mc/s point contributes little to the value of the spectral index. A systematic and intensity-dependent error amounting to a factor of two would be required to

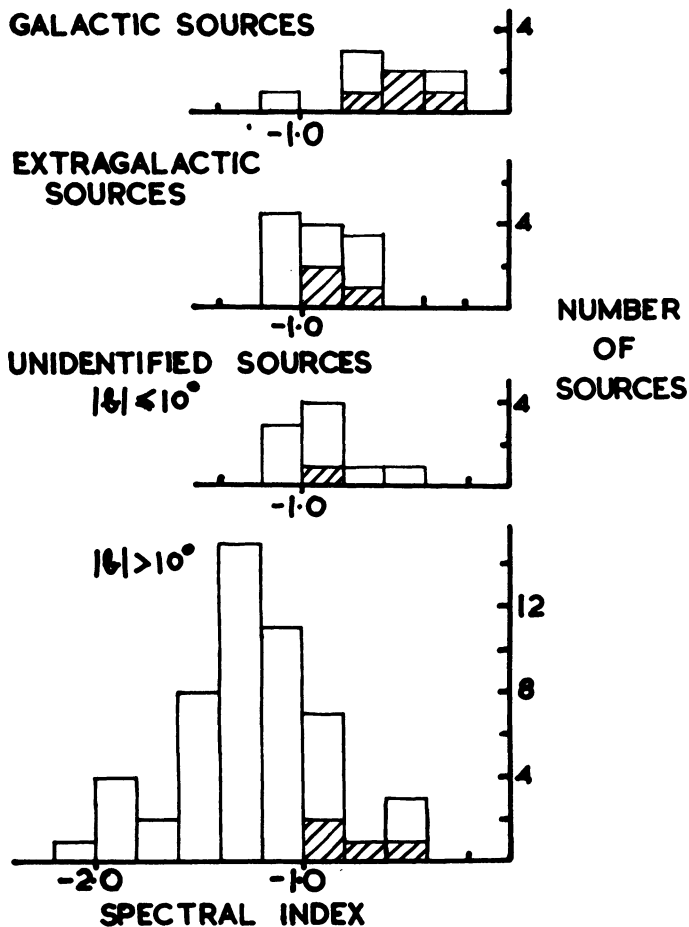


FIG. 4. The spectral indices of various classes of sources. Shaded areas represent sources with angular diameters > 20 minutes of arc.

account for the observed effect. Since the 81.5 and the 159-Mc/s surveys are far more extensive, the inclusion of sources in the list of 85 spectra was generally limited by the existence of a 38-Mc/s observation; this procedure favors sources with steep spectra, and introduces a selection effect in the direction of the observed effect if the spectral indices are plotted against flux density on 81.5 or 159 Mc/s. This selection effect has been eliminated by plotting against flux density on 38 Mc/s. The effects of confusion are also more severe on 38 Mc/s, which could introduce a systematic tendency toward exaggerated flux densities for the fainter sources. This source of error has been examined and found inadequate to account for the observed effect. If a large proportion of the fainter sources had angular diameters of the order of 5 minutes of arc, the flux density measured on 159 Mc/s would be too

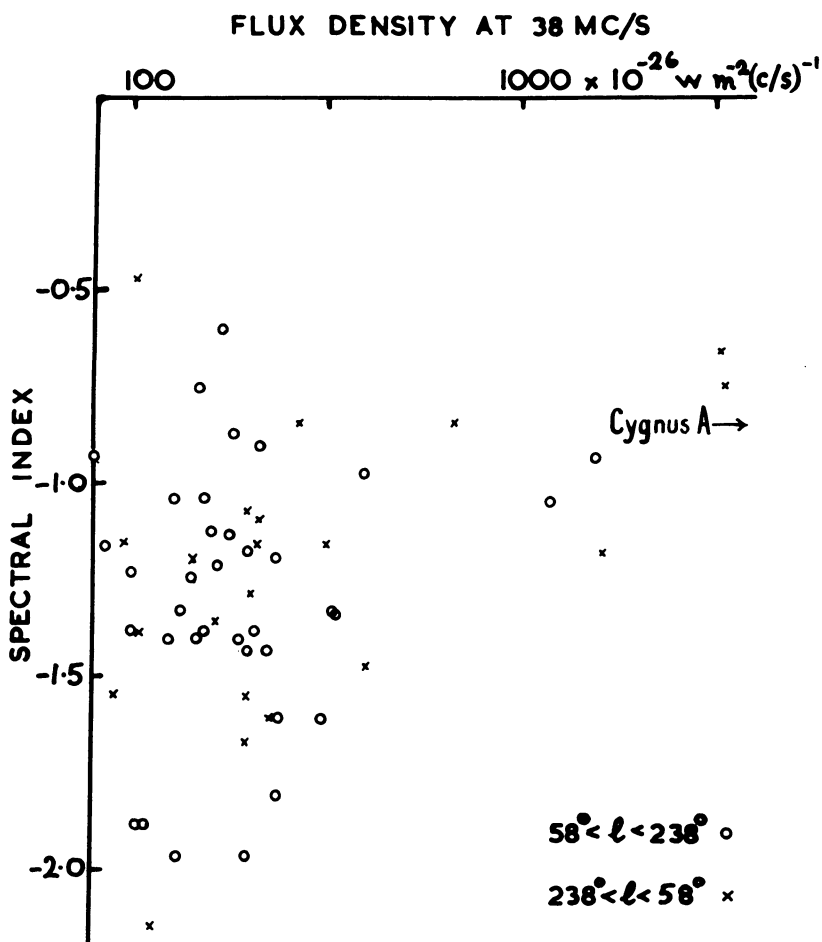


FIG. 5. The spectral indices of extragalactic sources, and unidentified sources with $|b| > 10$ degrees, plotted against flux density at 38 Mc/s.

low, since this measurement was made with a 307λ interferometer. In view of the scarcity of large angular diameters among the brighter sources, this explanation is not altogether plausible, but it cannot be excluded completely on the present evidence. Simple instrumental faults, such as nonlinearity of receiver response, would have to be excessive to account for the observations, and have almost certainly been measured with sufficient accuracy.

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Discussion

Mills: It may be that the angular size-selection effect is more important than suggested. We find many sources of apparently large size, and in several instances I know of sources in our catalogue that appear in 3C with *very* much less intensity and at a slightly different position, suggesting either small-scale clusters or large angular size.

Scheuer: Evidence tending to show that there is something resembling small-scale clustering of sources seems to be accumulating. So far as the spectra are concerned, one must examine the individual sources used by Whitfield, and find out what evidence there is concerning the angular diameter or doubling of the source in each case.

Westerhout: In Whitfield's published paper one sees that in his figures for the brighter sources, where he draws a line through the many observations, a line taking into account only the 2C and 3C observations is steeper in at least 75 per cent of the cases. The spectra of the weaker sources are mainly determined by the 2C and 3C surveys. I should also like to know the reason why the 38-Mc/s flux densities are now the basic data, while in the published paper they fell generally below the spectra.

Scheuer: Since the publication of his paper, Whitfield has found a non-linearity in the response of his receiver; he has now corrected his 38-Mc/s flux densities, and the corrected 38-Mc/s points generally fall on the same straight line as the 81.5- and 159-Mc/s points.