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The Spectral Index–Luminosity Relation for Radio Galaxies and Quasi-Stellar Sources

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Data on the spectra of radio galaxies and quasi-stellar sources between 100 MHz and 7 GHz are used to examine the spectral index–luminosity relation. There is a statistically significant relation when only radio galaxies with power-law spectra are considered. The quasi-stellar sources with power-law spectra may continue the relation to luminosities greater than those of the galaxies.

INTRODUCTION

Studies of the continuum spectra of powerful extragalactic radio sources have provided few strong constraints on theories of their energy production. The salient phenomenon—the inverse power-law spectra of many sources—is only a weak indicator of physical conditions within the emitting regions (van der Laan 1969). It is therefore important to establish relationships between the spectral properties of sources and their other observable features. In this paper we examine the spectral index–luminosity relation proposed by earlier workers (Heeschen 1960, Pskovskii 1962, Conway *et al.* 1963, Kellermann 1966, Kellermann *et al.* 1969), using new spectral data on radio galaxies and quasi-stellar sources (QSS) in a 1.4-GHz source catalogue. We define the spectral index α by the relation $S(\nu)\propto\nu^{-\alpha}$ where S is the flux density and ν the frequency.

THE SPECTRAL INDEX–LUMINOSITY RELATION

The relation was discussed most recently by Kellermann *et al.* (1969), using spectral indices between 750 MHz and 5 GHz for a statistically complete sample of radio sources selected at 178 MHz. They found that (i) the spectral indices of radio galaxies correlated positively with their 178-MHz monochromatic powers, (ii) there was considerable dispersion about the mean relation, (iii) no similar relation appeared to exist for the QSS. They concluded that the emitting regions of the powerful radio galaxies are deficient in high-energy electrons relative to those of the intrinsically weaker galaxies.

It would be of interest for theories of particle acceleration within the sources if the relation could be described as a correlation of the index γ of a power-law electron energy spectrum with the luminosity of the source. This description could not be justified unless the spectral index–luminosity relation holds for the sources with power-law radio spectra over a wide frequency range (van der Laan 1969). We have therefore considered the following questions.

Firstly, can the relation be ascribed to luminosity dependence of the spectral indices of the radio galaxies with *power-law* spectra, or does it depend on the presence within the sample of sources with non-power-law spectra, such as those produced by E^2 losses (Kardashev 1962)? Secondly, although the QSS as a whole do not exhibit a spectral index–luminosity relation, do those with power-law spectra continue the relation shown by the galaxies? This could be consistent with the observation of Niell and Jauncey (1971) that the spectral indices of QSS with power-law spectra below 1.4 GHz tend to exceed those of the galaxies, if the redshifts of the QSS are cosmological.

DATA

We have determined the radio spectra of all sources in the area of sky defined by $-5° < \delta < +70°$, $|b| > 5°$, whose flux densities are greater than 2.0 fu in the statistically complete 1.4-GHz catalogue of Bridle *et al.* (1972). The spectra are defined by our own (unpublished) observations at 3.24, 6.63 and 10.6 GHz with the 150-ft telescope of the Algonquin Radio Observatory and those of other workers listed in Table 1. We have adopted the flux density scale of Roger *et al.* (1972) below

TABLE 1

Frequency (MHz)	Correction applied to published flux densities	Reference
38	×1.18	Williams *et al.* (1966)
85	×0.94	Artyukh *et al.* (1969)
178	×1.09	Caswell and Crowther (1969)
	×1.09	Gower *et al.* (1967)
	×1.09	Pilkington and Scott (1965)
	×1.18	Bennett (1962)
318	×1.00	Condon (private communication)
430	×1.00	Niell (private communication)
750	×0.955	Pauliny-Toth *et al.* (1966)
1400	×1.00	Bridle *et al.* (1972)
2695	×1.00	Kellermann *et al.* (1968) Witzel *et al.* (1971)
5000	×1.00	Pauliny-Toth and Kellermann (1968)
	×1.00	Witzel *et al.* (1971)
5009	×1.00	Shimmins *et al.* (1969)
10630	×1.00	Doherty *et al.* (1969)

300 MHz and that of Kellermann *et al.* (1969) at higher frequencies.

We have restricted our analysis to sources whose spectra do not deviate significantly from a power law between 100 MHz and 7 GHz, the widest frequency range over which reliable data are available for most of the sources. Such sources comprise about one-third of the catalogue. As distance estimates are available for the sources whose spectra can be used to define the spectral index–luminosity relation, we have considered these spectra in the rest-frames of the sources. Data from frequencies below 100 MHz and above 7 GHz were used to assess the reality of departures from power-law spectra which were only marginally significant within this frequency range. Spectral indices were computed by fitting power laws to the data by least squares.

Fifty-five radio galaxies in the catalogue have power-law spectra in this frequency range. Redshifts were available for thirty-two; for the remainder, distances and redshifts were estimated from their photographic and photovisual apparent magnitudes. There is disagreement in the literature about the validity of some of the identifications with galaxies of unknown redshift, and for others there are discrepancies among the magnitudes estimated by different workers. We have adopted only those identifications whose optical positions are consistent with the radio positions and structures listed by Bridle *et al.* (1972) and have determined a separate magnitude–redshift relation for each published list of galaxy magnitudes. Distances estimated from different magnitude lists have been averaged; residual uncertainties in the adopted galaxy distances are usually less than a factor of two. The catalogue also contains fourteen QSS with power-law spectra and known redshifts. We have assumed their redshifts to be cosmological.

The monochromatic power emitted by each source at 1.4 GHz in its rest-frame was calculated with a Hubble constant of 100 km sec^{-1} Mpc^{-1} and an Einstein–de Sitter cosmology ($\lambda = 0$, $q_0 = 0.5$). Figure 1 shows the spectral indices plotted against the logarithms of the monochromatic powers for all sixty-nine sources.

DISCUSSION

The data are very scattered in the α–log$P$ plane, as noted by earlier workers. We have carried out

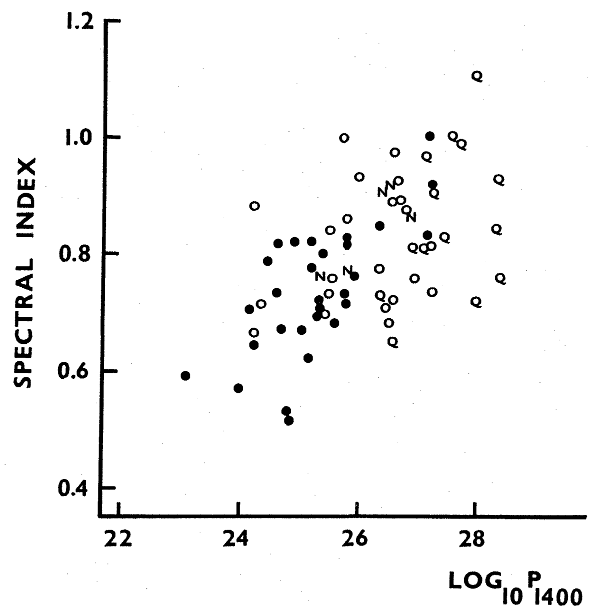

FIG. 1. Plot of spectral index α against $\log_{10} P_{1400}$ for 69 sources with power-law spectra. α and P_{1400} (units of W Hz^{-1}) are evaluated in the rest-frame of the source. Symbols: Q = QSS, N = N galaxy, ● = galaxy with redshift, ○ = galaxy without redshift.

a linear correlation analysis to determine whether these data indicate a statistically significant relation. The results are shown in Table 2.

There is a significant correlation between α and $\log P$ for the galaxy sample as a whole. The standard deviation of an individual data point from the mean relation is equivalent to 0.1 in the spectral index. The correlation is most significant for the galaxies of known redshift, for which the luminosities are the most reliable. It is unlikely to be due to a selection effect. A spurious relation between the spectral index and luminosity could be introduced by the spectral dependence of the radio K-correction. This would, however, favour the inclusion of sources with low spectral indices at high redshifts, and thus at high luminosities, thereby tending to diminish the correlation actually observed. The five N galaxies are not distinguishable from the remainder of the galaxy sample (see Figure 1).

TABLE 2

Source group	Population correlation coefficient (95 per cent confidence limits)	Probability of observed correlation arising randomly
32 galaxies of known redshift	$0.67^{+0.16}_{-0.24}$	<0.1 per cent
23 galaxies of unknown redshift	$0.26^{+0.37}_{-0.43}$	12
14 QSS	$0.33^{+0.40}_{-0.60}$	12
55 galaxies	$0.57^{+0.15}_{-0.20}$	<0.1
All 69 sources	$0.57^{+0.14}_{-0.19}$	<0.1

The relation proposed by earlier workers is therefore not due wholly to departures from power-law spectra, such as those produced by E^2 losses. Preliminary analysis of the galaxies with non-power-law spectra suggests further that there is no spectrum–luminosity correlation for these objects; particularly large departures from the relation found for power-law spectra are seen in the spectra of the galaxies 0053−01, 1502+26, 1514+07 and 1626+39, which have spectral indices $\alpha \gtrsim 1.4$ at frequencies above 1.4 GHz but have $\log_{10} P_{1400} < 26$.

There may be a real correlation between the electron energy spectral indices γ and the luminosities of the radio galaxies. The correlation between the radio spectral indices and their luminosities does not ensure this, however, for a power-law radio spectrum does not *necessarily* imply the existence of a single power-law electron spectrum throughout the source (van der Laan 1969, Bridle 1969).

The data do not permit an independent spectral index–luminosity relation to be established for the QSS. Twelve of the fourteen, however, have spectral indices within two standard deviations of those predicted by the linear α–$\log P$ relation best fitting the galaxy data, if this relation is continued to higher luminosities. The spectral indices of the two remaining QSS fall 2.1 and 2.3 standard deviations below this relation. There is therefore little evidence that the QSS with power-law spectra do not form a continuum with the galaxies on the spectral index–luminosity relation. This suggestion of continuity would be weaker in cosmologies with $q_0 < 0.5$ and stronger in cosmologies with $q_0 > 0.5$. As was found for the galaxies, some QSS with non-power-law spectra exhibit large departures from the spectrum–luminosity relation. Examples are 1116+12, 1328+30, 2221+21, 2230+11 and 2251+15, which have $\log_{10} P_{1400} > 28$ and complex or self-absorbed spectra which would be assigned mean indices $\alpha < 0.5$ in an analysis using all spectra.

In samples of sources drawn from the relatively small ranges of flux density available in the 3C survey and in the 1.4-GHz catalogue used here, the distribution of luminosities is determined almost entirely by the distribution of redshifts. The spectral index–luminosity relation could therefore also be interpreted as a spectral index-redshift relation. Our results suggest however that some importance should be attached to mechanisms of particle acceleration in radio sources which would predict a positive correlation between the electron energy index γ and the radio luminosity.

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