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THE SPECTRA OF RADIO GALAXIES AND QUASI-STELLAR OBJECTS

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This paper discusses the differences in radio spectra of two samples of sources which have been identified with either QSO's or radio galaxies. Small but significant differences are found to exist, particularly for frequencies above 1000 MHz. In general, the spectra of radio galaxies are found to steepen at frequencies above 1000 MHz whereas QSO's have spectra which are either straight to at least 5000 MHz (approximately 55 per cent of QSO's) or show enhancement at high frequencies.

INTRODUCTION

With the identification of large numbers of radio sources as either galaxies or quasi-stellar objects, the radio spectra of many sources have been examined for significant differences between the spectra of the two classes. It would clearly be advantageous to be able to classify radio sources on the basis of their spectra alone.

Bolton (1966) first pointed out that there was a significant statistical difference in the spectral indices, measured between 1400 MHz and 2650 MHz, of his identified QSO's and radio galaxies; many of the QSO's had spectral indices flatter than 0.75 whereas most of the galaxies were steeper than 0.75 ($S_{1410}/S_{2650} = 1.6$). Williams and Collins (1967) have, however, disputed this, finding that between 38 and 1410 MHz the spectra of 233 radio galaxies and 108 QSO's from the Cambridge 3C R and 4C catalogues show no differences in either their mean spectral index or in the curvature of the spectra at high frequencies. Their results, however, are somewhat affected by the inclusion of a number of suggested QSO's whose identification has been subsequently revoked (Bolton, private communication).

This paper presents conclusive evidence for differences in the radio spectra of QSO's and radio galaxies. It is shown that while the differences in spectra below 1400 MHz are small, as found by Williams and Collins, there are significant differences in the spectra between 1400 and 5000 MHz.

THE SPECTRA OF RADIO SOURCES

Conway, Kellermann, and Long (1963), hereafter referred to as CKL, have shown that below 1420 MHz the spectra of most radio sources can be represented by a simple power law. The flux density S_ν is given by:

$$S_\nu = k\nu^{-\alpha}$$

where ν is the frequency and α is the spectral index.

The value of α is approximately 0.75 for most extra-galactic radio sources. CKL found that, on the limited information then available on flux densities above 1420 MHz, the spectra of at least 50 per cent of radio sources showed deviations from a straight line, the spectrum generally becoming steeper at the higher frequencies. Since then a number of flux density measurements at frequencies above 1400 MHz have become available, which include measurements at 2650 MHz and 5000 MHz at Parkes (Parkes catalogues 1964, 1966; Kellermann 1966; and unpublished measurements), at 5000 MHz (Maxwell and Rinehart 1966), at 8000 MHz (Dent and Haddock 1966) and at 10 600 MHz (Medd *et al.* private communication, 1968).

Many of the sources for which more extensive spectral data are available have been identified with optical counterparts. Before considering these spectra, it is convenient to define two parameters concerned with the curvature of spectra. Following CKL and Dent and Haddock, we define the curvature index K as the difference between the spectral indices at 3000 and 300 MHz. It is also possible to define a quantity ρ_ν as:

$$\rho_\nu = \frac{S_\nu \text{ (extrapolated from low frequency data)}}{S_\nu \text{ (measured)}}$$

This is an alternative measure of the curvature of a spectrum. For the simple case of a spectrum consisting of two straight lines which meet at a 'break' frequency ν_B, the curvature index K and ρ_ν are related by the break frequency ν_B:

$$\rho_\nu = \left(\frac{\nu}{\nu_B}\right)^{-K} \quad (\nu > \nu_B)$$

SPECTRA SHOWING ABSORPTION

A small fraction of radio sources—possibly less than 5 per cent of sources found in low frequency surveys, such as the 3C, 4C and Parkes catalogues—have maxima in their spectra with a decrease in flux density at lower frequencies, probably due to synchrotron self-absorption. Examples of such sources are given in Table I. There is no way of distinguishing between QSO's and radio galaxies on the basis of the frequency of the maximum ν_{max} and no clear distinction is found between the spectral indices at frequencies higher than ν_{max} within the range of present observations. The numbers of galaxies and QSO's amongst the present sample of such sources are about equal. However, from the sample survey at 2700 MHz made by Shimmins, Bolton, and Wall (1968) the fraction of objects showing synchrotron cut-off is considerably higher than 5 per cent and the fraction of identifications with QSO's is also substantially higher.

If sources with absorption are not considered separately in a sample, they produce an apparent relationship between curvature index and spectral index as obtained by Dent and Haddock. Such sources have a high value for ρ_{2650}, and their inclusion in a given sample dilutes the statistical distinction between QSO's and radio galaxies, which is normally given by this parameter. It is therefore essential to consider all spectra exhibiting synchrotron self-absorption separately.

These sources will not be discussed further except to note that we have found no evidence of secular variability in them such as occurs in the QSO's.

SPECTRA OF RADIO GALAXIES

The majority of radio galaxies have spectra which can be closely approximated by two straight lines which meet at a 'break' frequency which is usually between 400 and 1000 MHz. The spectral index may increase rapidly near the break frequency and then remain constant to at least 10 000 MHz. The spectra of 3C 295 and 3C 405 (Cygnus A) are notable examples where the change in slope is rather pronounced. However, for the majority of radio galaxies the increase in slope is small and can only be detected where precise measurements of flux density exist over the frequency range.

We have examined a sample of 82 radio galaxies for which the identifications are well established and for which reasonable spectral information exists. We have calculated for each source the spectral index α_{300} between 38 MHz and 408 MHz and α_{3000} between 1400 and 2650 MHz or higher

TABLE I

Examples of Radio Sources showing Synchrotron Self-Absorption

Source (PKS)	Other Catalogue Number	S_{max} flux units	ν_{max} MHz	Identification	Remarks
0106 +01	—	4.2	260	QSO	
—	3C 48	70.0	80	QSO	Scintillates
0237 −23	—	7.2	1400	QSO	
0320 +05	4C 5.15	7.0	300	Galaxy	Scintillates
0440 −00	NRAO 190	5.0	4000	QSO	
0518 +16	3C 138	21.6	200	QSO	Scintillates
—	3C 147	65.0	180	QSO	Scintillates
0736 +01	—	3.4	800	QSO	
0818 +17	4C 17.44	6.0	250	Galaxy	Scintillates
1340 +05	4C 05.57	5.6	300	Galaxy	
1345 +12	4C 12.50	8.5	400	Galaxy	Scintillates
1518 +04.7	4C 04.51	4.8	1000	Galaxy	
1934 −63	—	16.3	1400	Galaxy	
2128 −12	—	2.1	4000	QSO	
2134 +004	—	13.0	6000	QSO	Scintillates
2230 +11	CTA 102	7.5	500	QSO	Scintillates

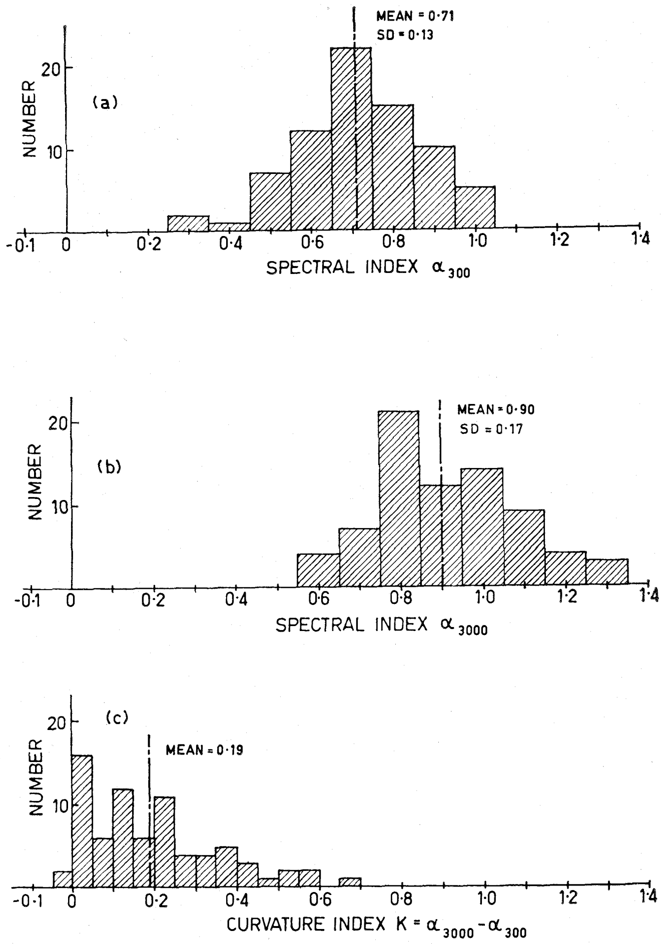

FIG. 1. Distribution of spectral indices and curvature index for radio galaxies.

frequencies where available, and have estimated the 'break' frequency for each source, assuming the spectrum to be two straight lines. Figure 1(a) and (b) shows the histogram of these spectral indices. The mean spectral indices are 0.71 for α_{300} and 0.90 for α_{3000}. The distributions are approximately Gaussian and the dispersions about the means are 0.13 and 0.17 respectively. Figure 1(c) shows a histogram of the curvature index *K*. It is interesting to note that for 22 per cent of radio galaxies the spectrum has a curvature index less than 0.05, i.e. the spectrum is essentially straight, whereas for 78 per cent of radio galaxies there is a significant steepening of the spectrum. In only two cases in the present sample is there a slight flattening of the spectrum at higher frequencies.

Figure 3(a) shows the index ρ_{2650} for radio galaxies and also indicates a steepening of the spectra. The mean value of ρ_{2650} is 1.40 and only two values are less than 1.00.

Thus for radio galaxies the spectrum is either straight or increases in slope at some frequency near 1000 MHz. The mean increase in slope is 0.19.

There are two known exceptions, which are the Seyfert galaxies 3C 84 and 0430 + 05 (3C 120); these show high frequency enhancements with secular variations similar to those of some QSO's.

SPECTRA OF QSO's

For those QSO's found in low-frequency surveys, the spectra consist of a straight line at the low frequencies with an enhancement at high frequencies in about 30 per cent of known cases. These spectra can be considered as consisting of two components—the basic straight line (component A)

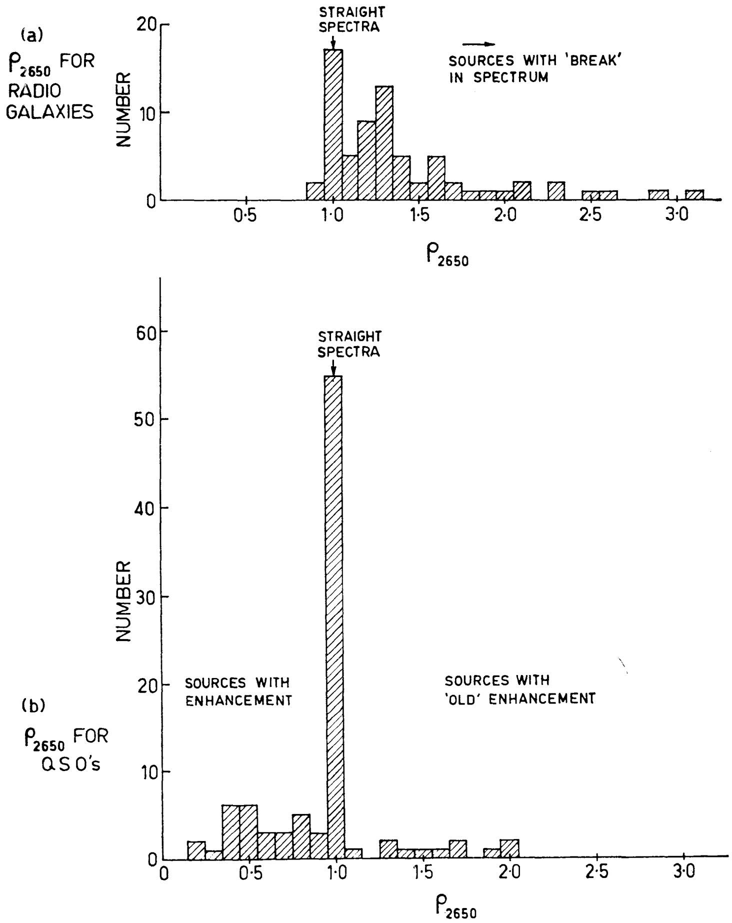

FIG. 3. Distribution of ρ_{2650} for radio galaxies and QSO's.

with a high frequency enhancement component (component E) superimposed. Component A, which is seen alone in 60 per cent of sources, shows no sign of the increase in slope at a 'break' frequency, which is characteristic of radio galaxies. In this respect they resemble the spectra of supernova remnants.

The enhancement component E, if present, is generally noticeable only at frequencies higher than 1000 MHz and appears to be due to a small-diameter source which exhibits synchrotron self-absorption. In many objects this source may be expanding rapidly, as in models suggested by Shklovsky (1963) and giving rise to the secular variations. Component E is relatively short-lived but is obviously recurrent in some objects. Approximately 10 per cent of QSO's show signs of 'old' enhancements, which show up as a slight 'bump' at intermediate frequencies on what would otherwise be a straight spectrum. Examples are PKS 0207 − 17, 0340 + 04 (3C 93), 0347 + 13, 0349 − 14 (3C 95), 0350 − 07 (3C 94), 0947 + 14 (3C 228) and 3C 196. Over a limited frequency range such spectra are similar in appearance to those of radio galaxies with high curvature index.

As component E ages it decreases rapidly in amplitude and at the same time the frequency of the peak decreases. It is possible that all QSO's show enhancement at some time. When first discovered in 1963 the source PKS 0106 + 01 showed a straight spectrum extending to at least 2650 MHz. A strong enhanced component started to appear in 1966 and is still active (March 1968) at 2650 MHz.

We have examined the spectra of 98 QSO's selected because their identification is well established (in many cases a red shift is available) and reasonable spectral information is available. In all cases the spectral index α_{300} of the basic component A was estimated in the vicinity of 300 MHz together with the spectral index between 1400 and 2650

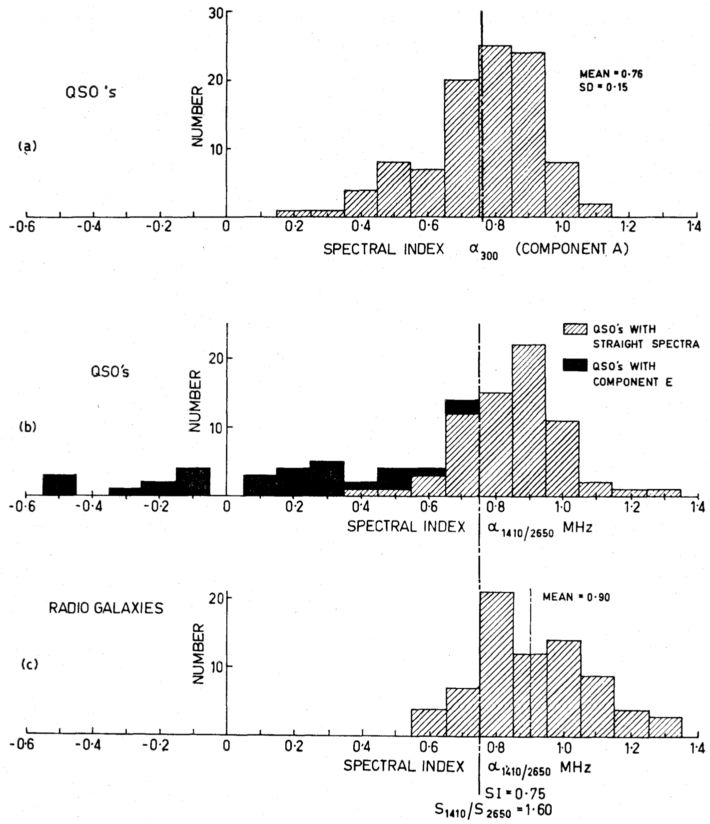

FIG. 2. Distribution of spectral indices for QSO's and radio galaxies.

MHz ($\alpha_{1400-2650}$). The factors K and ρ_{2650} were also calculated for each QSO.

Figure 2(a) shows the histrogram of the spectral indices α_{300} of the basic component A of QSO's. The mean spectral index is 0.76 and the dispersion is 0.15. Note, however, that the distribution is skewed to lower spectral indices. This could be due to the incomplete separation of the enhancement component for some sources or, in some cases, to synchrotron self-absorption at very low frequencies.

Figure 2(b) shows the distribution of spectral indices for the range 1410 to 2650 MHz. Different shading distinguishes those QSO's which have straight spectra and those with enhancement. The diagram shows the close relationship between a low value of $\alpha_{1400-2650}$ and an enhancement component. Comparison of this diagram and the distribution of $\alpha_{1400-2650}$ for radio galaxies (Figure 2(c)) clearly shows Bolton's point that there is statistically a difference in this index for the two classes of identified radio sources. The similarity between the distributions of α_{300} for galaxies in Figure 1(a) and for QSO's in Figure 2(a) is in essential agreement with the findings of Williams and Collins.

Figure 3(b) shows ρ_{2650} for the QSO's. In general this index is equal to or less than unity. Comparison with Figure 3(a) for radio galaxies shows that ρ_{2650} less than 1.0 is an almost exclusive indicator of a QSO while sources with ρ_{2650} greater than 1.0 are predominantly galaxies.

Including the synchrotron cut-off objects of Figure 3, the full sample of QSO's has the following spectral distribution:

- 53 % have spectra which are straight to at least 5000 MHz
- 38 % show enhancement at the high frequencies, 29 % above 1400 MHz, and 9 % some sign of 'old' enhancement below 1400 MHz
- 9 % have synchrotron self-absorption above 100 MHz.

CONCLUSION

Whilst the distribution of spectra of galaxies is likely to be relatively independent of the frequency of the source survey from which they were selected, the same will not be so for quasi-stellar objects. As shown in the limited survey by Shimmins, Bolton, and Wall (1968) at 2700 MHz, the proportion of quasi-stellar objects with enhancement spectra or spectra with synchrotron absorption at the high frequencies may increase dramatically. Objects of the latter type could continue to increase in ν_{max} with the frequency of the survey to form the link between the quasi-stellar objects with appreciable emission and the 'radio quiet' quasi-stellar galaxies.

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