A POSSIBLE EVOLUTIONARY FEATURE IN THE SPECTRA OF RADIO GALAXIES

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1. INTRODUCTION

A recent analysis (Slee, 1981) of the spectra of extragalactic sources derived by Slee et al. (1981) has revealed a relationship between spectral index and redshift in the sense that the spectra of identified radio galaxies steepen with increasing redshift; this behaviour is consistent with an effect first reported by Kellermann et al. (1969) that the average spectral index of identified radio galaxies is lower than that of sources in empty optical fields, which are now generally regarded as distant radio galaxies (rather than QSOs). However, because of the selection effects present in the sample, Slee was not able to decide whether the basic correlation is between spectral index and redshift (implying an evolutionary origin), between spectral index and radio power, or between spectral index and linear dimension.

This paper draws attention to another characteristic of the radio galaxy spectra evident in the analysis of Slee et al. (1981), namely that third-degree polynomials fitted to the log s-log ν data of identified radio galaxies possess in many cases a minimum in slope at ~500 MHz; the effect is absent (or much less evident) in the spectra of the unidentified (blank field) sources. If, as seems likely, the unidentified sources are predominantly radio galaxies which formed at approximately the same epoch as the identified radio galaxies, the spectral differences between the two classes probably arise because of evolutionary processes. It seems probable that the correlation between spectral index (slope of the best-fitting first-degree polynomial) and redshift identified by Slee (1981) may be partly due to the presence of redshift-dependent structure in the spectra of radio galaxies.

2. THE AVERAGED BEST-FITTING THIRD-DEGREE POLYNOMIALS

Figure 1 shows the result of fitting third-degree polynomials to the log s-log ν data of Slee et al. (1981), to which the reader is referred for a full discussion of the properties of the radio source

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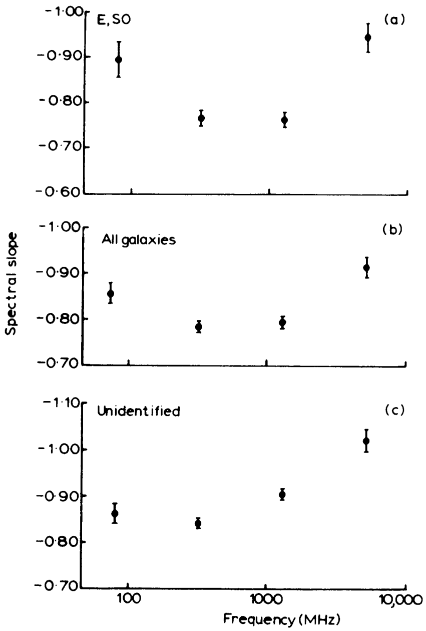

Figure 1. Average slopes of the best-fitting third-degree polynomials to the log s-log ν data of Slee et al. (1981). The slopes have been averaged at frequencies of 80, 320, 1280 and 5120 MHz; the vertical line about each mean has a half-length equal to its standard error. (a) refers to the results from 169 E, S0 radio galaxies, (b) to 404 sources identified with N, D, cD, E, S0, db and G galaxies, and (c) to 850 unidentified sources in blank optical fields.

sample, origins of the flux densities used in constructing the spectra and corrections to flux scales used by various observers. The points plotted are spectral slopes at four frequencies averaged over all sources in the identification class, together with the standard error of each average. It is clear that a minimum in the spectral slope occurs at ~500 MHz for the identified radio galaxies. The minimum is especially clear for the E, S0 class but is also very significant when all identified radio galaxies (N, E, S0, D, cD, db and G) are grouped. On the other hand, the Class III sources (blank optical fields), show no clear minimum in spectral slope; the average spectrum of an unidentified source tends to be straight at low frequencies but steepens progressively as frequency increases.

In order to investigate in more detail this apparent redshift-dependent trend in spectral shape, the identified radio galaxies have been subdivided into four intervals of redshift with approximately equal numbers of sources (~22) in each interval. Figure 2 shows the averaged spectral slopes at four frequencies in each redshift range resulting from fitting third-degree polynomials to E, S0 galaxies; a similar set of figures is obtained for the 'all galaxies' classification. It is clear that the averaged spectrum of the E, S0 radio galaxies in the two lower intervals of redshift show deep minima in spectral slope at ~500 MHz. The third redshift interval (Fig. 2c) shows a much less pronounced minimum while the highest redshift interval (Fig. 2d) yields an averaged spectrum with no evidence for a minimum; Figure 2(d) is in fact similar to 1(c), which applies to the unidentified sources.

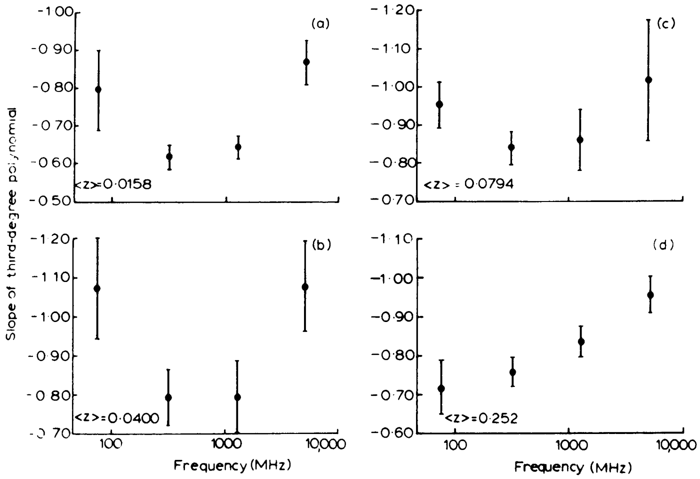

Figure 2. Average slopes of the best-fitting third-degree polynomials to the subset of 87 sources with measured redshifts drawn from the E, S0 identification class of Slee et al. (1981). (a) to (d) refer to sources grouped in successively higher ranges of redshift, whose average values are given in the lower left-hand corners. Each redshift interval contains ~22 sources.

It can be shown (see e.g. Slee et al., 1981) that the spectral minima in Figures 1(a) and 1(b) and Figures 2(a) and 2(b) are statistically significant. The effect is unlikely to be a spurious one, introduced by systematic differences in flux scales used by various observers; if this were the case then Figures 1(c) and 2(d), which are derived from the same sources of flux data, should also show significant minima.

3. DISCUSSION

The presence of minima in the spectral slopes of many of the closer radio galaxies is probably responsible for the correlation between spectral index (first-degree fit) and redshift (Slee, 1981). Slee pointed out that as redshift increases existing samples preferentially select increasingly more powerful radio galaxies; in addition, the subsets of resolved radio galaxies preferentially select those with increasingly larger linear dimensions as redshift increases. If the minima of Figure 2 are in fact properties of the less powerful and/or smaller radio galaxies and are not due to general evolutionary effects, then perhaps such sources have components with different spectra which combine to give a complex spectrum in the total flux density. Alternatively, evolutionary effects such as synchrotron losses, inverse Compton losses, bremsstrahlung losses, expansion losses and the injection, escape and acceleration of relativistic electrons may be more or less effective in the weaker/smaller sources than they are in the powerful/larger sources.

It is simpler (possibly simplistic) to interpret Figure 2 in terms of the general evolution of a radio galaxy irrespective of its power output or linear dimensions. If we can assume that all these radio galaxies were first formed within say 10^7 years, so that evolutionary processes within them can be considered to have started almost simultaneously, then significant changes have occurred in the time interval of 4.1×10^9 years ($H_0 = 50$ km s^{-1} Mpc^{-1}) represented by the averaged redshifts of the galaxies in Figures 2(d) and 2(b).

It is difficult to propose an explicit evolutionary model that could reproduce the observed spectral features; the theory of source evolution is still in rather a primitive state and treats only the simplest source geometries (Melrose, 1980) incorporating only one or two of the several possible evolutionary processes. According to the idealized model of Kellermann (1966) with recurring injections of flat-spectrum particles into a magnetic field and the subsequent influence on the spectrum of synchrotron losses (ignoring other evolutionary influences), the low-frequency spectrum reflects the flatter initial electron energy distribution in the particle injections. The intermediate frequency spectrum is steeper and reflects the presence of an electron energy range in which the synchrotron losses are balanced by the injection of fresh electrons; at higher frequencies the radio spectrum steepens further owing to the full effects of synchrotron losses.

The only spectra which approximate the predictions of Kellermann's (1966) model are those of Figures 1(c) and 2(d). If, as seems probable, this model applies to the most distant detectable radio galaxies, then there have been repeated injections of fresh electrons during the time interval of $\sim 5 \times 10^9$ years following the formation of these galaxies. A further $\sim 4 \times 10^9$ years corresponding to the spectra of Figures 2(a) and 2(b) is sufficient to show the effects of other evolutionary influences which have yet to be evaluated in a quantitative manner.

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