Spectra of Radio Sources in Rich Clusters of Galaxies

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At the Waterloo meeting of the Canadian IAU in 1968, one of us (A.H.B.) reported 10 MHz observations of radio sources which indicated that some sources located in rich clusters of galaxies had unusually high spectral indices compared with those of the general extragalactic population at low frequencies. This prompted us to investigate the distribution of the radio spectral index among sources in rich clusters over a wider frequency range and among a larger sample of sources. We have now derived radio spectra in the frequency range 10 to 5000 MHz for ninety radio sources satisfying Wills' criterion for identification with a rich cluster in Abell's catalog, and find that the association with systematically high spectral indices is more general than was realised at the time of the first report. Samples of radio sources in rich clusters of galaxies have higher spectral indices than extragalactic sources in general throughout the frequency range 30 to 1400 MHz, as shown in Table 1.

Table 1

MEAN SPECTRAL INDICES OF EXTRAGALACTIC SOURCES IN GENERAL AND OF SOURCES IN RICH CLUSTERS OF GALAXIES

FREQUENCY (MHz)	GENERAL	CLUSTERS
30	0.85 ± 0.05	1.42 ± 0.20
178	0.753 ± 0.013	0.926 ± 0.032
1400	0.64 ± 0.03	0.83 ± 0.04

The distribution of the spectral indices has been studied in detail at 178 MHz, using statistically unbiassed samples of radio galaxies and of sources in rich clusters of galaxies provided by the 3C and 4C surveys. Optical identifications of 4C radio sources with rich clusters of galaxies have been made by Wills, and we have derived spectra for all such sources to a limiting flux density of 3 f.u. at 178 MHz. Table 2 compares the distribution of the spectral index among the 41 such sources with that derived by Kellermann, Pauliny-Toth and Williams for radio galaxies in the 3C Revised Catalog (normalised to 41 sources).

Table 2

SPECTRAL INDEX RANGE	NUMBERS OF SOURCES 3CR GALAXIES	SOURCES IN CLUSTERS
0.2 - 0.3	0.31	0
0.3 - 0.4	0.31	0
0.4 - 0.5	0.31	1
0.5 - 0.6	4.69	1
0.6 - 0.7	7.51	2
0.7 - 0.8	13.46	5
0.8 - 0.9	7.51	9
0.9 - 1.0	4.07	13
1.0 - 1.1	2.50	5
1.1 - 1.2	0.00	0
1.2 - 1.3	0.31	2
1.3 - 1.4	0.00	0
1.4 - 1.5	0.00	0
1.5 - 1.6	0.00	1
1.6 - 1.7	0.00	2

A χ^2 test shows that there is a probability of less than 1 in 1000 of obtaining the distribution observed for sources in rich clusters of galaxies by random sampling among the distribution observed for galaxies in general. In particular, there is a marked excess of sources in clusters with spectral indices greater than 0.9, relative to the general population of galaxies.

The nature of the sources in the rich clusters is therefore of some interest. They are sources of low intrinsic luminosity; none is of power greater than 5×10^{25} W Hz^{-1} at 178 MHz. It is interesting to note that they therefore violate the correlation between 178 MHz radio luminosity and spectral index found for radio galaxies in general by Kellermann, Pauliny-Toth and Williams. Table 3 illustrates this correlation.

CORRELATION BETWEEN RADIO LUMINOSITY AND SPECTRAL INDEX FOR RADIO GALAXIES IN GENERAL

(from Kellermann, Pauliny-Toth and Williams 1969)

P_{178} ($W.Hz^{-1}$)	MEAN SPECTRAL INDEX
$< 10^{24}$	0.52 ± 0.03
$10^{24} - 10^{25}$	0.77 ± 0.06
$10^{25} - 10^{26}$	0.77 ± 0.06
$10^{26} - 10^{27}$	0.89 ± 0.05
$10^{27} - 10^{28}$	0.90 ± 0.04
$10^{28} - 10^{29}$	0.98 ± 0.08

This suggests that the evolution (or origin) of these sources may be different from that of radio galaxies in general.

Estimates of the angular sizes of the sources, together with Abell's distances to the clusters, show that the linear sizes of most of the sources are much less than those of the clusters, and comparable with the typical sizes of individual radio galaxies. Exceptions to this are three sources with anomalous low-frequency components which have scales comparable with those of the clusters themselves. In these sources the spectra show both a 'normal' high frequency component and an extended component of low luminosity at 178 MHz which dominates the low-frequency emission. There may therefore be two types of source contributing to the observed phenomenon.

The small-scale sources with high spectral indices might be radio galaxies whose evolution has been affected by location of the source in a cluster environment. A well recognised mechanism which will steepen a radio spectrum with increasing age of the source is the combination of synchrotron losses and adiabatic expansion. A difficulty of explaining the observed spectra simply as those of 'old' radio galaxies is that the time-scale for steepening the spectrum at 178 MHz is rather long compared with that for quenching the luminosity by adiabatic expansion. An interesting possibility is that the sources in rich clusters may not expand adiabatically quite so freely as sources elsewhere if they have to expand into a tenuous intra-cluster medium. If the typical cluster contained an intergalactic medium some 10 to 50 times as dense as that around a non-cluster source, the time-scale for the adiabatic expansion might be lengthened sufficiently for the steepening of the spectrum to occur while the source was still at about 10^{-2} to 10^{-3} of its initial luminosity, while sources outside clusters with similarly steepened spectra would be too faint to be detected.

The larger-scale sources might be produced by very energetic electrons with an intrinsically steep energy spectrum escaping from one or more radio galaxies in the cluster into a large-scale region containing a weak magnetic field (perhaps ~ 10^{-8} gauss).