SPECTRAL INDEX STUDIES OF EXTRAGALACTIC RADIO SOURCES

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1. INTRODUCTION

Spectral index distributions can be indicated conveniently by $g_S^{\nu_1}(\alpha_{\nu_1,\nu_2})$, i.e. the distribution of the two-point spectral index between frequencies ν_1 and ν_2 for a sample of radio sources complete to flux density S at the selection frequency ν_1 (flux densities will be expressed in Jy and frequencies in GHz). Such a detailed specification is necessary because $g(\alpha)$ has been found to depend on all three parameters. The effect of varying ν_1 is well-known: the fraction of flat-spectrum sources increases with selection frequency. Variations of $g(\alpha)$ with S have also been found: both the fraction of flat-spectrum sources and the mean spectral index of the steep-spectrum sources depend on S, at least at high frequencies. The magnitude of this dependence on S as well as $g(\alpha)$ itself appear to depend on the choice of ν_2, or rather on the relation between ν_2 and ν_1. This complex behaviour of $g(\alpha)$ is not unexpected if one considers that the redshift and luminosity distributions of a source sample vary with selection frequency and flux density limit. Intrinsic or induced correlations between spectral index and redshift or luminosity, or different redshift distributions of flat- and steep-spectrum sources may cause variations of $g(\alpha)$ with ν and S. An understanding of the behaviour of $g(\alpha)$ requires observations over large ranges of frequency and flux density. Even then, it will be difficult to interpret these data without information about the composition of the various samples, which can be obtained only through optical work. Here we describe recent spectral index information for weak sources selected at 1.4 GHz, as well as work on spectral index/optical identification correlations in 5 GHz samples.

2. SPECTRAL INDICES OF WEAK SOURCES SELECTED AT 1.4 GHz

Spectral index work with the Westerbork Synthesis Radio Telescope has concentrated so far on reobservation at 0.6 GHz of source samples defined earlier at 1.4 GHz. The first result of this work, an estimate of $g_{0.007}^{1.4}(\alpha_{1.4,0.6})$ from a sample of 36 sources (Katgert and Spinrad, 1974) was rather unexpected. About half of the sources appeared to have flat

D. L. Jauncey (ed.), Radio Astronomy and Cosmology, 99-106. *All Rights Reserved.*

spectra (i.e. $\alpha < 0.5$) resulting in an unusually low mean spectral index of about 0.5. At present, 0.6 GHz observations are available also for parts of the other 1.4 GHz Westerbork surveys, viz. the 1st survey (Katgert et al. 1973), the 3rd survey (Katgert, 1975) and the survey of background sources (Willis et al. 1976). The main questions to be answered by these new observations are whether the above-mentioned result of the second survey is representative for this selection frequency and flux density level, and whether there is real evidence for variations of $g_S^{1.4}(\alpha)$ with S.

From the 1.4 GHz samples - which are all complete to at least 0.01 Jy - we selected a complete sample of 183 sources with $S > 0.02$ Jy, for 174 of which a 0.6 GHz flux density is known at present. The choice of this rather high completeness limit should ensure that corrections for flux density dependent selection against flat-spectrum sources (among other things due to the primary beam attenuation) are small. In fact, we found that such corrections are negligible for these samples and therefore did not apply any. In Table 1 we give the parameters of the distribution $g_{0.02}^{1.4}(\alpha_{1.4,0.6})$ for the total sample and for the various subsamples. There appear to be rather large differences between the four surveys, and especially the 2nd survey is anything but representative. The sample of background sources probably comes nearest to being representative because of its size and distribution on the sky. Because of the observed differences between surveys it is not clear to what extent the total sample is representative, but it may be noticed that it is not very different from the sample of background sources.

A comparison with Gillespie's (1975) result based on 1.4 GHz surveys of the 5C regions (made with the Half-Mile Telescope) is interesting because the 3rd Westerbork survey and Gillespie's survey of the 5C2 region do have some overlap. The mean spectral index of the two subsamples is found to differ by 0.21±0.08, a result which can be explained completely by differences between the zero-points of the two spectral index scales. For 17 sources from the original 5C2 survey (with a 0.4 GHz attenuation between 2.0 and 5.0) and detected also at 0.6 and 1.4 GHz in our observa-

Table 1

Parameters of Spectral Index Distributions $g_S^{1.4}(\alpha_{1.4},\nu_2)$

Sample	S	ν_2	n	$\langle\alpha\rangle$	σ_α	%($\alpha < 0.5$)
BDFL/B2	2.00	0.4	50	0.61±0.05	0.37	0.24±0.07
All Wbk	0.02	0.6	174	0.64±0.03	0.34	0.25±0.04
1st Wbk	0.02	0.6	46	0.73±0.04	0.27	0.22±0.07
2nd Wbk	0.02	0.6	19	0.44±0.09	0.38	0.47±0.16
3rd Wbk	0.02	0.6	45	0.59±0.05	0.34	0.31±0.09
BGS Wbk	0.02	0.6	64	0.66±0.04	0.34	0.17±0.05
All 5C	0.01	0.4	140	0.71±0.03	0.36	0.21±0.04
5C2	0.01	0.4	31	0.80±0.06	0.33	0.19±0.08

tions, we find $\langle\alpha_{1.4,0.4}-\alpha_{1.4,0.6}\rangle = 0.16\pm0.03$. The difference between the two 1.4 GHz flux density scales (Katgert, 1976) accounts for an additional spectral index difference of about 0.08. Although the discrepancy can be explained empirically, its origin remains to be investigated.

Also shown are the parameters of the spectral index distribution of a strong source sample taken from the 1.4 GHz BDFL catalogue. For the spectral indices we used 0.4 GHz flux densities from the Bologna catalogue, hence the sample only covers declinations between 24° and 40°. The 0.4 GHz flux densities have been corrected for the effects of partial resolution using the structure information of the BDFL catalogue. Before comparing the strong and weak source samples, it is again necessary to establish the relation between the two spectral index scales. In the Westerbork samples there are nine unresolved sources for which we have flux densities at 0.4 (Bologna), 0.6 and 1.4 GHz (Westerbork). For these sources we find $\langle\alpha_{1.4,0.4}-\alpha_{1.4,0.6}\rangle = -0.02\pm0.05$. Since the Westerbork and BDFL 1.4 GHz flux density scales are identical to within the errors (Fomalont et al. 1974) we find a formal difference of 0.01±0.09 between the mean spectral indices of the weak and strong source samples. Note that the uncertainty in this result is only partly due to limited statistics. The fraction of flat-spectrum sources is also practically the same for both samples.

Given the rather large uncertainty of this result we will discuss only very briefly some of its possible implications. It is clear that the two samples differ markedly with respect to average luminosity and redshift. Because direct redshift information is not available, we have computed redshift and luminosity distributions of both samples (see Table 2) on the basis of a conventional evolutionary model which reproduces the observed 1.4 GHz source count satisfactorily. Of course, these distributions are approximate, if only because the luminosity function (and its dependence on redshift) may be different for e.g. flat- and steep-spectrum sources. In view of the reported correlation between spectral index and luminosity for extended radio sources identified with elliptical galaxies (see e.g. Véron et al. 1972), the change in the luminosity distribution might produce variations of $g(\alpha)$, because the intrinsically strong sources (presumably with steep spectra) are almost absent from the weak sample. In order to account for the apparent absence of a change in the spectral index distribution it may appear necessary to postulate, e.g. a redshift dependent ratio of flat- and steep-spectrum sources as a function of luminosity.

Table 2

Hypothetical Redshift and Luminosity Distributions of 1.4 GHz Samples

Sample	z										log $P_{1.4}$						
	0.0	0.5		1.0		1.5		2.0		2.5	21		23		25		27
S > 2.00	46	11	8	7	6	6	5	4	4	3	1	3	11	18	19	27	21
S > 0.02	12	10	8	8	8	8	9	11	14	12	1	3	10	25	55	6	0

3. SPECTRAL INDEX / IDENTIFICATION CORRELATION FOR 5 GHz SAMPLES

The most convincing evidence for variations of g(α) with S comes from high-frequency samples. In particular, $g_S^{5.0}(\alpha_{5.0},\nu_2)$ has been studied in considerable detail on the basis of the NRAO 5 GHz surveys (see e.g. Condon and Jauncey, 1974 and Pauliny-Toth et al. 1974). The main result appears to be that the mean low-frequency spectral index (i.e. $\nu_2 < 1$ GHz) increases significantly between a sample complete to 0.6 Jy and one complete to 0.067 Jy. However, the high-frequency spectral index (i.e. $\nu_2 > 2$ GHz) remains practically constant. Because the identification percentage of high-frequency samples is rather high, one has a good opportunity to study possible spectral index/identification correlations. The first analyses of this kind made use of identifications based on radio positions of moderate quality (see e.g. Fanti et al. 1974). At present, radio positions of arc-second quality allow much more reliable identifications to be made. For a sample of 135 sources with S > 0.6 Jy, Johnson (1974) obtained accurate identifications using radio positions obtained with the RRE interferometer, while Condon et al. (1975) reidentified part of the weak 5 GHz sample (i.e. S > 0.1 Jy) on the basis of NRAO interferometer positions.

We have made 5 GHz observations with the Westerbork telescope of essentially all sources in the weak 5 GHz sample to obtain accurate radio positions and structures. For a small number of sources, not detected at 5 GHz due to strong resolution effects, additional 1.4 GHz observations were made. About 40 per cent of the sources were found to be appreciably extended (with sizes of up to 4-5 arc minutes). Identifications were carried out on the PSS prints, on the basis of positional coincidence only. The number of spurious identifications is estimated to be less than three. For a comparison with the strong source sample (S > 0.6 Jy), we limit the weak sample to the 91 sources with flux densities between 0.067 and 0.6 Jy. The spectral separation of the weak sample is based on $\alpha_{5.0,0.4} \gtrless 0.50$; for the strong sample (of 118 sources) we used $\alpha_{5.0,0.3}$ (Condon and Jauncey, 1974), increased by 0.05 to account for the difference between the 0.3 and 0.4 GHz flux density scales.

The percentage of flat-spectrum sources changes from 56% in the strong sample to 36% in the weak sample, in good agreement with earlier results. In Table 3 we compare the identification content of the flat- and steep-spectrum subsamples in the strong and weak surveys.

Table 3

sp.	sample	n	QSO	GAL	EF	NI
flat	strong	66	64%	23%	13%	--
	weak	33	55%	21%	24%	--
steep	strong	52	17%	52%	29%	2%
	weak	58	19%	28%	50%	3%

The percentage of identified flat-spectrum sources changes from 86±11 in the strong sample to 76±15 in the weak sample, which is not significant. On the other hand, the percentage of identified steep spectrum sources changes from 69±12 to 47±9. This change is wholly due to the loss of galaxy identifications in the weak sample (from 52±10 to 28±7 per cent).

The fraction of flat-spectrum sources identified with galaxies apparently does not vary with flux density limit. One might think that this indicates a low value for the ratio between radio and optical luminosity of flat-spectrum galaxies. However, in that case, most flat-spectrum galaxies in the strong sample should have optical magnitudes well above the PSS limit, which appears not to be true. The constancy of the fraction of galaxy identifications among flat-spectrum sources is probably a result of the very flat source count for the flat-spectrum subsample (which is determined largely by the quasars). The percentage of quasar identifications is more or less independent of flux density limit for both flat- and steep-spectra quasars, i.e. the counts of flat- and steep-spectra quasars also differ considerably.

It would seem that the optical identification information does not really enable one to choose between possible explanations for the increase of the fraction of steep-spectrum sources with decreasing flux density. For instance, the validity of the model proposed by Fanaroff and Longair (1973) cannot be checked without redshift information. Observations at lower flux densities are needed to see whether the steepening continues (as predicted by the "cosmological" model), or whether the variation in spectral index distributions is due to relatively local irregularities in the density of radio sources.

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DISCUSSION

Wall: If the "flat spectrum" galaxies are weak emitters and hence optically bright, would this not explain the lack of change in identification rate for these objects as flux density decreases?

Katgert: Certainly, but one would then expect to find the flat spectrum galaxies in the strong sample well above the sky survey limit, which is found not to be the case.

Jauncey: How do you distinguish flat spectrum galaxies from QSO's?

Katgert: Basically on their optical appearance and colour, but I admit that near the sky survey limit the classification is rather uncertain.

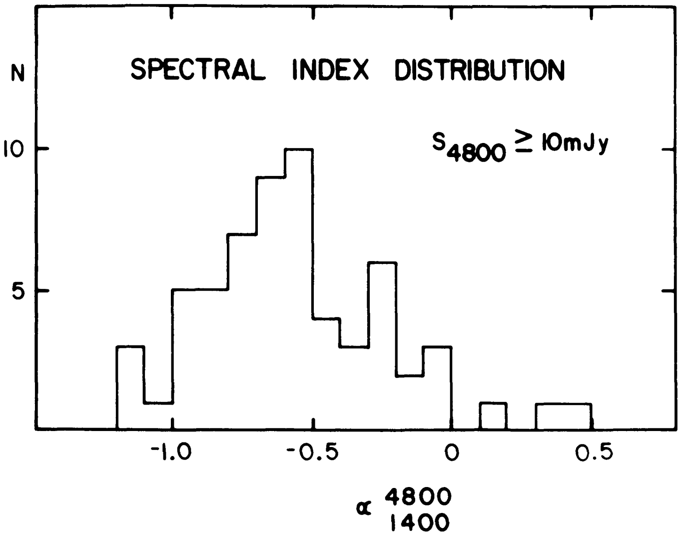
Shaffer: Did you say 40% of the weak survey sources were resolved? At what resolution?

Katgert: Yes, at 6".

THE SPECTRAL INDEX DISTRIBUTION OF A SAMPLE OF VERY FAINT SOURCES FROM A SURVEY AT 4.8 GHz

M.M. Davis

Yesterday Dr. Pauliny-Toth described a survey using the Bonn 100m telescope at 4.8 GHz in selected small areas. This is the faintest sample we are likely to have at the shortest wavelengths for some time to come. It is of particular interest to investigate the spectral content of this sample, as some evolutionary models predict a rapid decrease in the flat spectrum population of radio sources at low flux densities.



The spectral index distribution shown in the figure was determined with the Arecibo telescope using a 3.3 arcminute beam at 1.4 GHz. The sensitivity was sufficient so that only sources with spectral index flatter than +0.5 might be undetectable. For 61 sources > 9 mJy at 4.8 GHz, 34 percent are flat spectrum ($\alpha > -0.5$). The median spectral index is -0.60, with a quartile range of 0.46, from -0.32 to -0.78. For the brighter half of the sample, cutting off at 20 mJy at 4.8 GHz, the fraction of flat spectrum sources is essentially unchanged (36%). Hence the large ratio of steep to flat spectrum population of about 5 to 1 predicted by the Fanaroff and Longair model is found to be too large; the actual decrease is from a ratio of about 1 to 1 at high flux density levels to 2 to 1 at this very faint level.

Ekers: How does your result on the lack of change in $\langle\alpha\rangle$ compare with the change reported yesterday in $\langle\alpha\rangle$ with flux density for the 5 GHz surveys?

Davis: $\langle\alpha\rangle$ does change, down to about 0.5 Jy, but stays constant from there down to about 0.01 Jy at a flat spectrum population of about 35%.

SPECTRA OF RADIO SOURCES SELECTED AT 408 MHz

H.S. Murdoch

A complete set of "normal" spectrum sources selected at 408 MHz to a limit of 0.97 Jy have a mean spectral index steeper by about 0.1 than a comparison set from an all sky catalogue of sources > 10 Jy at 408 MHz, at a significance level > 3σ. The spectral index distribution of QSO's in the sample is remarkably compact but the distribution for galaxies is broader due to a correlation between spectral index and optical apparent magnitude. For further details and references, see Mon. Not. R. Astr. Soc. (1976) 177, 441.

Conway: In calculating spectral index using 178 MHz did you correct the flux densities for finite angular diameter, since the raw 4C flux densities contain a downwards bias from this effect?

Murdoch: 178 MHz pencil beam flux densities, where available, were used and increased by 10%. 4C interferometer values were increased by 15% but I regard the 178 MHz scaling as somewhat uncertain.

Condon: Since most of the sources in a complete sample lie within a factor of 2 of the lower flux-density limit, each sample describes only a small portion of the number-flux density diagram. The mean spectral index can easily be determined from the number counts at different frequencies. See, Fomalont, E.B., Bridle, A.H., Davis, M.M., 1974, Astron. Astrophys., 36, 273.

Longair: There has been considerable discussion about the validity, or otherwise, of the models which Bernard Fanaroff and I developed to account for spectral index distributions at different frequencies and flux densities. I think we should distinguish clearly the two types of variation in spectral index distributions reported today and yesterday. Hugh Murdoch has shown that there is a shift in the mean of the spectral index distribution of the sources observed at low frequencies. This is a small but significant effect. On the other hand at high frequencies there is a very major change in the fraction of flat spectrum sources with flux density. This can be seen very clearly by comparing the results of I. Pauliny-Toth and Mike Davis. At low flux densities the fraction of flat spectrum sources decreases markedly with flux density.

The point of our work was to show that this second type of variation occurs very naturally in evolutionary world models of the types developed to account for the source counts. The point is that if one supposes that the same form of evolution is valid for sources with $\alpha \approx 0$ and $\alpha \simeq 0.75$ and that the spectral index distribution observed at low frequency is applicable to all sources at all epochs, the powerful flat spectrum sources are observed preferentially at high flux densities in high frequency surveys; the steep spectrum sources are observed at relatively smaller redshifts. Therefore, the sources with $\alpha = 0.75$ and $\alpha = 0.0$ observed in high frequency surveys give information about the evolution over different redshift ranges. Because the evolution eventually "saturates" for all classes of source, the flat spectrum sources fall out first whilst the relative proportion of steep spectrum sources continues to increase with decreasing flux density. This is the essence of the models and my comparison of our models with the results shown today suggests that the models are in remarkable agreement with the observations - certainly not as bad as suggested by the speakers In these models one can obtain large changes in the spectral index distribution at high densities at high frequencies - which is not possible in non-evolutionary models. There is plenty of scope for improving the agreement of the models and the observations using all the new information.

SOME EVIDENCE FOR LARGE SCALE CLUSTERING OF RADIOSOURCES

G. Grueff and M. Vigetti

A complete sample of 526 radiosources with $S_{408} > 0.9$ Jy, $24° < \mathrm{DEC} < 34°$, $23^h\ 30^m < \mathrm{R.A.} < 02^h\ 30^m$, and $07^h\ 30^m$, and $07^h\ 30^m < \mathrm{R.A.} < 17^h\ 30^m$ has been optically identified on the Palomar Sky Survey, and all the spectral indices α_{408}^{5000} were also obtained. The distribution of such sources was investigated for possible anisotropies. By dividing the sky strip in intervals half an hour long in R.A. no evidence for anisotropy was found in the density of sources. However when computing the average spectral indices in each box, their distribution was found to be non-random for Quasars, at the significance level of 4%, and for Empty Fields, at the significance level of 0.3%. Any possible systematic error in flux measurement has been excluded by checking that the variations of average spectral index for Quasars and Empty Fields are completely uncorrelated. An attempt to decide whether the steep spectra or the flat ones were producing the anisotropy indicates the latter as more probably responsible.