Frequency selection, spectral-index distributions and source counts
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FREQUENCY SELECTION, SPECTRAL-INDEX DISTRIBUTIONS AND SOURCE COUNTS*

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A notation for relating source samples complete at different frequencies, to different depths, their spectral-index distributions and their number counts is introduced and such relations are discussed.

Spectral data show that over a survey frequency range of a factor ~50, with a geometric mean near 178 MHz, the frequency of the extensive Cambridge surveys, only one source population contributes significantly to a complete sample. Surveys at frequencies outside this range detect additional populations: at low frequencies old low-brightness sources possibly associated with clusters, at high frequencies young compact and opaque sources of the quasar type.

In the last section the Cambridge 408-MHz and the Parkes 2700-MHz counts are compared and conditions necessary for their reconciliation are given. The spectral evidence now available exhibits trends in conflict with these conditions. There seems no way to avoid the conclusion that the Parkes 2.7-GHz counts are too high at those levels where the number of sources per steradian is less than one hundred.

1. Introduction

Important surveys of extragalactic radio sources were until recently carried out at or near meter wavelengths (38, 178 and 408 MHz). High-frequency surveys (1420, 2700 and 5000 MHz) are now under way or were recently published. The relation of their results to earlier work and the comparability of low-and high-frequency source samples are therefore of direct interest.

Study of the statistical distribution of properties of a radio-source population requires knowledge of the selection effects which, for a given sample population, determine inclusion or exclusion of sources. Astrophysically the interest may for example be in the sources which occupy a given region of space, but observationally a source sample is invariably composed of members spread over a large volume and selected from that volume through a complex discriminating "filter".

Generally speaking it is desirable to select groups of sources for the purpose of statistical studies from *complete samples*. This is usually a necessary, though not sufficient condition for relating sample-property distributions to intrinsic source relations. A sample is complete if it consists of all sources in a given area of sky (away from obscuring regions such as the galactic plane and spurs) whose flux densities at the survey frequency exceed the sample's limit. Thus a complete sample is characterized by its frequency and its flux limit and is here denoted by $\Sigma(\nu, S)$. In practice the sample's flux limit depends on the survey instrument (system noise temperature, angular resolution) and the observing technique (c.q. scanning rate, beam switching or not, etc.), in relation to background irregularities and number of sources per unit solid angle. In this paper some relations between complete samples $\Sigma(\nu_i, S_m)$ are the subject of discussion**.

2. Frequency selection

Whether or not a source in sample $\Sigma(\nu_i, S_m)$ is also a member of $\Sigma(\nu_j, S_n)$ depends not only on the ratio S_m/S_n but also on the relative flux at ν_i and ν_j, i.e. on the source spectrum.

After the first extensive radio spectral studies, a source was usually assigned a spectral index, generally minus one times the value of the slope of its log S_ν, log ν curve. This was possible since over a limited frequency range (about two decades) this curve is in many cases well represented by a straight line. Deeper and

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** Unless indicated otherwise, frequencies are in MHz, flux densities in flux units (1 f.u. $=10^{-26}\mathrm{W{\cdot}m^{-2}{\cdot}Hz^{-1}}$).

more extensive surveys have revealed more spectral structure and for many sources it is now ambiguous to speak of "the spectral index". It is desirable to specify the frequency limits of all spectral-index designations. Often the use of "two-point spectral indices" is preferable:

$$\alpha(\nu_1, \nu_2) = \log (S_{\nu_1}/S_{\nu_2})/\log (\nu_2/\nu_1). \qquad (1)$$

This is well defined regardless of complex spectral structure. When comparing $\Sigma(\nu_i, S_m)$ and $\Sigma(\nu_j, S_n)$ the spectral details are in any case quite secondary and the distribution of $\alpha(\nu_i, \nu_j)$ in each sample is of direct interest.

The general manner in which two samples selected at very different frequencies differ, can be seen directly from figure 1, where for purposes of illustration the limits of the 4C survey and the Parkes 2.7-GHz survey (SHIMMINS, BOLTON and WALL, 1968) are drawn on the log S_{178}-log S_{2700} plane. The position of a source in this plane determines whether that source appears in either, both or neither of the two samples. It is obvious from the figure that irrespective of the distribution details, the sample complete at a high frequency favours sources with small spectral indices.

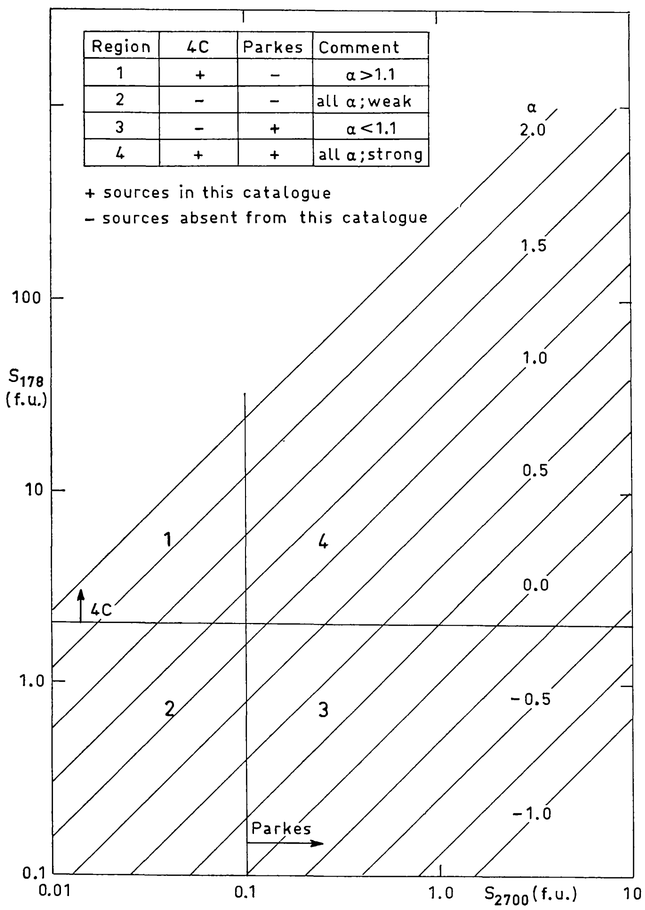

Figure 1. The log S_{178} -log S_{2700} diagram. Given a distribution of sources in this diagram, counts of points above successive horizontal lines yield the log N-log S_{178} relation; similarly the log N-log S_{2700} relation is given by counts of such points to the right of successive vertical lines. The distributions $g_2{}^{178}$ $[\alpha(178, 2700)]$ and $g_{0.1}{}^{2700}$ $[\alpha(178, 2700)]$ are obtained by counting above the appropriate flux limits throughout the various spectral-index intervals.

3. Spectral distributions

A great deal of work in radio astronomy is devoted to the determination of source spectra. One aim is to present the distribution $g_{S_m}^{\nu_k}[\alpha(\nu_i, \nu_j)]$ of the spectral index $\alpha(\nu_i, \nu_j)$ among the sources of a complete sample $\Sigma(\nu_k, S_m)$. There are two features to be looked for:

a) the difference in spectral distributions for samples complete at *the same frequency* but *to different depths*; i.e. compare

$$g_{S_m}^{\nu_k}[\alpha(\nu_i, \nu_j)] \quad \text{and} \quad g_{S_n}^{\nu_k}[\alpha(\nu_i, \nu_j)], \qquad (2)$$

and

b) the difference in distribution for samples complete *at different frequencies* but *at comparable depths*; i.e. compare

$$g_{S_m}^{\nu_k}[\alpha(\nu_i, \nu_j)] \quad \text{and} \quad g_{S_0}^{\nu_l}[\alpha(\nu_i, \nu_j)]. \qquad (3)$$

For feature a the observers claim no definite evidence for a dependence of $g(\alpha)$ on S. Differences between various samples are apparently not statistically significant (cf. LONG *et al.*, 1966; STEWART and LONG, 1967). As pointed out by the Parkes observers, evidence for the independence of $g(\alpha)$ from S is not convincing and this important question remains uncertain with respect to finer details, although present evidence is sufficient to conclude that the dependence, if any, is rather weak. Flux densities at several frequencies for large samples complete to low flux levels are required.

As for b, the Gaussian form of $g_{\sim 5}^{178}[\alpha(38, 1400)]$ allows the median spectral index $\bar{\alpha}(38, 1400)$ for samples complete at other frequencies to be calculated, provided *no other spectral classes enter the sample population.* In that case, as has been frequently shown,

$$\bar{\alpha}_{\nu_j}(\nu_1, \nu_2) = \bar{\alpha}_{\nu_i}(\nu_1, \nu_2) - \beta\sigma^2 \ln (\nu_j/\nu_i), \qquad (4)$$

where the subscript of $\bar{\alpha}$ denotes the sample's frequency of selection, β is the slope of the log N-log S_{ν_i} curve

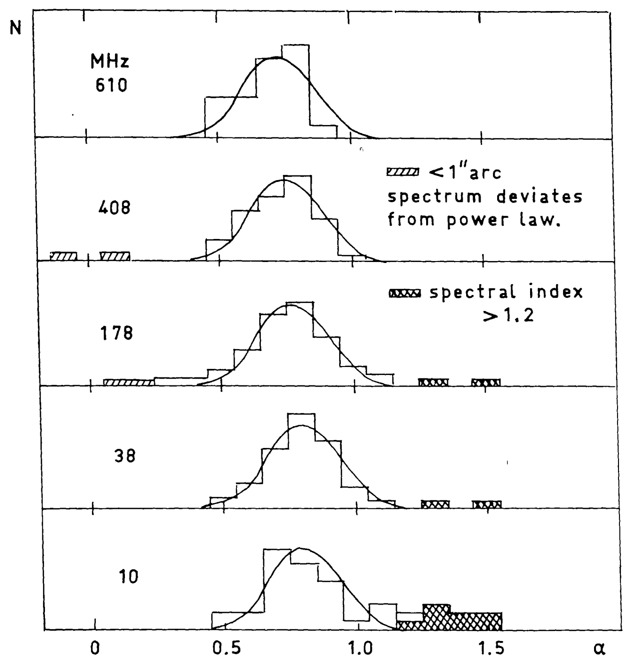

Figure 2. From WILLIAMS and BRIDLE (1967): histograms of the distributions of spectral indices in complete samples of sources selected at several frequencies. The Gaussian distribution predicted for the main population at each frequency is also shown.

and σ is the standard deviation of the distribution $g_S^{\nu_i}$ [$\alpha(\nu_1, \nu_2)$]. Figure 2, taken from WILLIAMS and BRIDLE (1967), shows the observed distributions (histograms) and the ones predicted relative to g_5^{178} [α(38, 1400)] (smooth Gaussians). As long as the survey frequency does not differ from that of the 3C and 4C 178 MHz by a factor greater than five, the spectral content of the samples $\Sigma(\nu_j, S)$ is related in a simple manner to that of Σ(178, 5) when we use $\alpha(178, \nu_j)$ as spectral index and require $S \gtrsim 5\,(178/\nu_j)^{\bar{\alpha}_{178}}$. For much deeper surveys the situation is not known at this time.

$\nu_j/178 \lesssim 0.1$

For $\nu_j = 10$ MHz there are more sources with $\alpha(10, 1400) \gtrsim 1.0$ than expected from 178-MHz catalogue samples. Many of these sources have been tentatively identified with clusters of galaxies (Bridle, private communication). These sources belong to a new spectral component which does not contribute significantly to $\Sigma(178\,p, S)$ where $p \gtrsim 0.2$. Its presence was not *a priori* predictable, but its detection at 10 MHz and the identification of some of its members with clusters suggest possible explanations.

Synchrotron losses steepen an initial spectrum of a transparent source with index α, to $\alpha + 1/2$. Spectral data show that the frequency at which this steepening occurs lies, for most radio galaxies, at $\nu_{\rm S.L.} \gtrsim 3000$ MHz. For a steady source $\nu_{\rm S.L.} \simeq 10^3\, H^{-3} t^{-2}$. For $H \simeq 10^{-5}$ Gauss and $t \simeq 10^7$ years this gives $\nu_{\rm S.L.} \simeq 10^4$ MHz. Since a sample such as Σ(178, 9) has few sources with steep spectra [$\alpha(178, 1400) \geq 1.25$] it may be concluded that radio galaxies fade to a luminosity level far below their peak power before the synchrotron steepening affects the range $\nu < 3$ GHz. This is presumably due to adiabatic expansion of the source's magnetic field and relativistic gas and the subsequent escape of particles into the intergalactic medium.

Assuming that clusters have typical ages $\sim 10^9$ years, while radio-galaxy lifetimes are one to two orders of magnitude shorter, a cluster may be a region where a relativistic gas, representing the contributions of several radio-galaxy and quasar generations, has accumulated. The radio spectrum would be similar to that of the radio galaxies (and transparent quasars), but shifted to lower frequencies. The *particle energy* has decreased due to adiabatic losses (this loss rate is proportional to the energy and hence does not alter the spectral shape) while the *cluster magnetic field strength* may be an order of magnitude below that of radio galaxies. A particle which radiates mainly at frequency ν_0 in the original source will then radiate mostly near the frequency ν_1, where $\nu_1/\nu_0 = (H_1/H_0)\,(E_1/E_0)^2$. This factor has to have an entirely plausible value $\sim 10^{-3}$ in order to explain the steep spectral component in the sample complete at 10 MHz.

$\nu_j/178 \gtrsim 10$

There are at present only a few publications reporting high-frequency survey results. A recent one is that of GALT and KENNEDY (1968) at 1420 MHz (the DA catalogue), which contains 615 sources and, to 2 f.u., is thought to be complete. The sample Σ(1420, 2) contains sources most of which are in the 4C catalogue. Only when $\alpha(178, 1420) \leq 0$ and S_{178} is nearly 2 f.u. would the source be present in Σ(1420, 2) but absent from Σ(178, 2). Figure 3 shows the spectral distribution of the 226-source sample *common* to DA and 4C with $S_{1420} \geq 2$ f.u. and lying well outside the galactic plane and spurs. The data are from the Galt and Kennedy paper, but here the α(178, 1420) distribution is

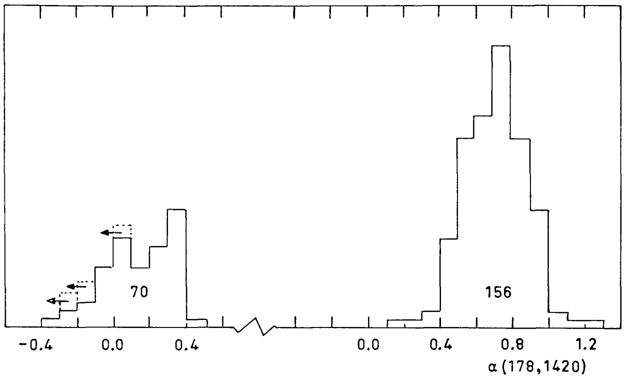

Figure 3. The distribution $g_2^{1420}[\alpha(178, 1420)]$; data from GALT and KENNEDY (1968). The histogram to the right represents the $\alpha(178, 1420)$ distribution for a sample complete to two flux units at 1420 MHz, expected from the normal population seen in figure 2. From eq. (4), $\bar{\alpha} = 0.72$. The left histogram is made up of the sources then remaining and represents a different population, virtually absent in the histograms of figure 2. The stippled blocks are sources for which $S_{178} < 2$ f.u., so that of their spectral index only an upper limit is known.

shown split into two components: one approximately symmetrical with an $\bar{\alpha} = 0.72$ as expected at this frequency for the normal population referred to above, and a component consisting of the sources then remaining. It should be noted that this sample is not quite complete for at least two reasons: a) for all the sources both S_{178} and S_{1420} exceed 2 f.u.; sources with $\alpha \leq 0$ are discriminated against; and b) the DA catalogue may not be altogether complete to two flux units, since a "marginal" source was included in the list if it appeared in 4C, while excluded if it was not. This also causes sources with $\alpha(178, 1420) \leq 0$ to be missed*.

The marked asymmetry of this distribution, which remains in spite of the two effects just mentioned, contrasts with the distributions in figure 2. The tentative conclusion seems justified that already at 1420 MHz a source population, differing from the radio galaxies and transparent quasars with inverse power-law spectra, makes a noticeable contribution to a complete sample. *Deeper* surveys at this frequency are likely *to increase* this fraction somewhat, because redshift corrections for sources with positively sloped spectra are favourable: e.g. two sources a and b at the same distance and emitting the same monochromatic power at their effective frequency of emission, one with a spectral index 0.75 and the other with $\alpha = -1.25$ over a range which includes the emitting and the observing frequencies, have flux densities in the ratio $S_b/S_a = (1+z)^2$. The result of the 5C2 survey (POOLEY and KENDERDINE, 1968) shows a pronounced secondary maximum in $g^{1420}_{>0\cdot01}$ [$\alpha(408, 1420)$], consistent with this expectation, although this is only a 16-source sample, so that the statistics need to be greatly improved.

The data therefore indicate that $g_S^{\nu}(\alpha)$ is comparable over a range $\nu_{max}/\nu_{min} \simeq 50$, where it shows only simple shifts, but at lower and higher frequencies other source populations make contributions which are the cause of asymmetric features in the spectral-index distributions. The survey frequency *par excellence*, 178 MHz of the third and fourth Cambridge catalogues, is fortuitously close to the geometric mean of this range.

High-frequency surveys

At least two limited surveys have been made at frequencies exceeding 1420 MHz, viz. the 2.7-GHz survey at Parkes (SHIMMINS *et al.*, 1968) and a 5-GHz survey at N.R.A.O. by BLUM and DAVIS (1968), The latter covered only a very small area of sky and resulted in a 27-source sample, $\Sigma(5000, 0.1)$. But this sample contains nine sources with $\alpha(1400, 5000) \leq 0.4$, compared with an expectation of three from the population seen at lower frequencies. The Parkes 2.7-GHz results, although not yet published in detail, show the same trend.

These spectral distributions, while again not quantitatively predictable *a priori*, can be understood in the light of our current understanding of active-quasar spectral evolution (see PAULINY-TOTH and KELLERMANN, 1967; KELLERMANN and PAULINY-TOTH, 1968; and VAN DER LAAN, 1966, for details of such spectral changes).

The steep positive slope of opaque-component spectra *and* the fact that these spectra evolve, by shifting to lower fluxes with increasing age, *along a line with slope* $\sim +1.3$ *in the log* S_ν*-log* ν *plane*, ensure the rapid increase in the probability of detecting such sources with increasing survey frequency. This state of affairs, combined with the evidence that at $\nu \geq 3$ GHz sources with dominant opaque components constitute a significant fraction of a complete sample, serves to em-

* It is possible, however, that *these* effects are partly balanced or even outweighed by underestimates of 178-MHz flux densities due to partial resolution by the 4C interferometer. But an improbably drastic revision of many 4C fluxes would be required if a significant fraction of the flat-spectrum component of figure 3 were attributable to this effect.

phasize the importance of extensive high-frequency surveys and subsequent studies of structural details (cf. DAVIS *et al.*, 1968).

4. Source counts at widely different frequencies

The 2.7-GHz survey at Parkes has also made possible the counting of radio sources to a depth of $S_{2700} = 0.1$ f.u., where the surface density is about 3000 sources per steradian. The log N-log S_{2700} relation has a slope of -1.4 over the entire range from 5.5 to 0.1 f.u., corresponding to approximately $N = 10$ to 3000 sterad^{-1}, according to these counts. This contrasts with the Cambridge counts, made independently at 178 and 408 MHz, based on rather extensive surveys (GOWER, 1966; POOLEY and RYLE, 1968). Since the latter, below $S_{408} = 4$ f.u. made with the one-mile telescope, are the deepest (to $S_{408} = 0.01$ f.u. and $N = 10^5$ sterad^{-1}), the Parkes results will here be compared with them. The slope of the log N-log S_{408} curve is about -1.85 for $S_{408} > 4$ f.u. or $N < 100$ sterad^{-1}. It smoothly changes to -1.4 for $0.4 < S_{408} < 2$ f.u. (or approximately $3000 > N > 300$) and the curve further flattens to a slope of -0.8 for $S_{408} \simeq 0.02$ f.u. (POOLEY and RYLE, 1968).

Source counts at different frequencies are related by the spectral distributions of complete samples. In this section that relation and the discrepancy between Cambridge and Parkes counts are discussed.

The formal expression which relates counts at one frequency to those at another is easily derived and can be written as

$$N_{\nu_i}(S) = \int_{-\infty}^{+\infty} N_{\nu_j}[S(\nu_j/\nu_i)^{-\alpha}]\, g^{\nu_j}_{S(\nu_j/\nu_i)^{-\alpha}}[\alpha(\nu_i, \nu_j)]\, \mathrm{d}\alpha\,, \tag{5}$$

where $g^{\nu_j}_{S(\nu_j/\nu_i)^{-\alpha}}[\alpha(\nu_i, \nu_j)]$ is the distribution of spectral indices $\alpha(\nu_i, \nu_j)$ of a sample selected at frequency ν_j and complete to a flux-density limit $S(\nu_j/\nu_i)^{-\alpha}$, and $N_{\nu_i}(S)$ is the number of sources per steradian whose flux density at frequency ν_i exceeds S.

Equation (5) can, for this particular comparison, be written as follows:

$$N_{2700}(S) = \int_{-2.5}^{\infty} N_{408}[S(6.6)^{\alpha}]\, g^{408}_{S(6.6)^{\alpha}}[\alpha(408, 2700)]\, \mathrm{d}\alpha \tag{6}$$

and

$$N_{408}(S) = \int_{-2.5}^{\infty} N_{2700}[S(6.6)^{-\alpha}]\, g^{2700}_{S(6.6)^{-\alpha}}[\alpha(408, 2700)]\, \mathrm{d}\alpha\,, \tag{7}$$

where the lower integration limit has become -2.5, since all available evidence indicates extragalactic sources to be either thermal or synchrotron radiators, so that $\alpha \geq -2.5$. It is obvious from eq. (6) that *rigorous* deduction of 2700-MHz counts to a flux limit S from counts at 408 MHz requires knowledge of the latter to a flux limit ~ 0.01 S *and* of the distributions of $\alpha(408, 2700)$ for all samples $\Sigma(408, S_0)$ where $S_0 \geq 0.01$ S, at present an impracticable procedure even at modest levels of S_{2700}, since 2.7-GHz fluxes of the $\Sigma(408, 0.01\,S)$ sources are not available.

The alternative approach is to take the counts N_{408} and N_{2700} and to find the conditions the spectral-index distributions must meet if these counts are to be compatible.

Define an "effective spectral index" α_e such that

$$N_{2700}(S) = N_{408}[S(6.6)^{\alpha_e}]. \tag{8}$$

This is equivalent to replacing $g(\alpha)$ by a delta function $\delta(\alpha - \alpha_e)$. The dependence of α_e on S_{2700} can be calculated from eq. (8) and the published counts*. For $N = 300$, $S_{408} \simeq 2.0$ and $S_{2700} \simeq 0.5$ f.u. For lower flux densities the log N-log S slope is the same in both cases; the counts *above* these flux densities are satisfactorily represented by

$$N_{2700}(S) = 300(S/0.5)^{-1.4}$$

and

$$N_{408}(S) = 300(S/2.0)^{-1.8}. \tag{9}$$

Combining eqs. (8) and (9) gives

$$\alpha_e = 0.65 - 0.27 \log S_{2700} \tag{10}$$

for

$$S_{2700} \geq 0.5 \text{ f.u.}$$

For $S_{2700} < 0.5$ f.u., $\alpha_e \simeq 0.73$ and the counts at the two frequencies are quite compatible. According to WILLIAMS and BRIDLE (1967) the median of $g^{408}_{5.6}$ [$\alpha(178, 1400)$] is $\bar{\alpha} = 0.73$ and its dispersion is small. The distribution g^{408}_{S} [$\alpha(408, 2700)$] cannot be very differ-

* With the advent of source counts at various frequencies it is desirable that results be given in tabular as well as graphical form. It is awkward and inaccurate to read numerical values from the published logarithmic plots.

ent in the range $0.4 \leq S \leq 2.0$ f.u. if the source counts from $N = 300$ to 3000 are correct at both frequencies and the relative flux-density calibration is right.

Compatibility at higher flux densities requires *a decreasing* α_e *with increasing flux density*. This could be achieved in several ways:

a) An asymmetric g_S^{408} [α(408, 2700)] with a secondary maximum near $\alpha \simeq 0$; this second component is zero for $S < 4$ f.u., but becomes increasingly prominent as S increases to ~ 13 f.u.

b) A fixed distribution $g(\alpha)$ for $0.4 \leq S \leq 4$, shifting to lower values of α as S increases from 4 to 13 f.u.

c) A constant dispersion for $0.4 \leq S \leq 4$, but an increasing dispersion with S increasing beyond 4 f.u.

d) Some combination of the above.

As is evident from eq. (7) and the requirement of compatible counts, analogous statements can be made for g_S^{2700} [α(408, 2700)].

No data known to the author support any of the possibilities just mentioned. Current spectral information points to a surprising degree of independence of spectral distributions from the sample's flux limit. According to the results of WILLIAMS *et al.* (1968) there seems to be a tendency for the median value of α(408, 2700) to increase as the flux increases from $S_{408} = 4.0$ to 8.3 f.u. and greater, this in contrast to requirements a and/or b. But this result is provisional and of little statistical significance, especially when an average correction of 8 per cent is applied to the Parkes fluxes used by Williams et al., a correction indicated by the measurements of KELLERMANN *et al.* (1968). The possible change in dispersion with sample depth mentioned in section 3 is in a direction opposite to requirement c*.

In conclusion, there is no independent supporting evidence in the literature for the conditions which must be met if the Parkes 2.7-GHz counts are to be reconciled with the Cambridge counts. Since the latter are more extensive and the independent sets at 178 and 408 MHz are mutually consistent within the errors (RYLE, 1968), it seems that the Parkes counts at high fluxes, where $N < 100$ sterad^{-1}, are probably overestimates, possibly due to statistical uncertainty (POOLEY, 1968) or to a non-linear flux calibration discrepancy. It will be valuable to extend 2.7-GHz survey areas and to improve our knowledge of α(408, 2700) distributions for samples complete at either of these frequencies.

* This dispersion, if real, is not conclusive in this context, however, for it concerns the indices α (38, 1420).

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Note added in proof

After submission of this paper an article appeared which deals with frequency selection in a similar vein and contains new 5-GHz observational data: K. I. KELLERMANN, I. I. K. PAULINY-TOTH and M. M. DAVIS, 1968, *Ap. Letters* **2** 105.