1988A&A...192...37G

Astron. Astrophys. 192, 37–41 (1988)

ASTRONOMY
AND
ASTROPHYSICS

An investigation of the redshift-dependence of the radio spectral index among powerful double radio sources

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Received July 28, accepted August 10, 1987

Summary. Using two flux-limited, metre-wavelength samples of extragalactic sources, for which multifrequency measurements of flux density as well as an essentially complete redshift information are now available, we present an analysis of the spectral properties, based on spectral indices $\alpha_{1\mathrm{e}}$ and $\alpha_{2\mathrm{e}}$ determined at 1 and 2 GHz in the rest-frame of the source. Both our samples are selected at 408 MHz and represent sources observed at high ($\geqq 10$ Jy) and intermediate (~ 1 Jy) flux densities, for which median values of redshift (z) are about 0.2 and 1.4, respectively. Despite the large difference between their median redshifts, the median radio luminosities of the two samples are quite comparable ($\sim 10^{28}$ WHz^{-1} at 408 MHz). The median values of $\alpha_{1\mathrm{e}}$ and $\alpha_{2\mathrm{e}}$ adjusted to the flux scale defined by Baars et al. (1977) are found to be close to -0.81 and -0.86 respectively, for both the 10-Jy and the 1-Jy sample. The near constancy of the intrinsic spectral index over the flux density range from ~ 25 Jy to 1 Jy at 408 MHz, suggests that the steepening of α with z reported in the literature, if real, probably does not continue to early cosmological epochs ($z > 1$).

Key words: extragalactic radio sources – spectral indices of radio sources – radio sources and cosmology

1. Introduction

Various analyses of strong source samples, notably the 3 CR sample, with well measured radio spectra have shown that the decimetre-wave spectral index (α) of extended, powerful radio sources is statistically correlated with radio luminosity (P) and/or with cosmological redshift (z) (e.g. Laing and Peacock, 1980). A major cause for the ambiguity is that in flux density limited samples, such as the 3 CR sample, a strong correlation always exists between P and z. Applying the Spearman partial rank correlation test to a well defined set of 93 3 CR sources, Macklin (1982) suggested that α is fundamentally related to z (or cosmological epoch). We attempt to investigate the question of α–z correlation for metre-wavelength samples by comparing the spectral properties of a complete sample of strong radio sources (median $z = 0.2$) with those of another complete sample comprising of fainter radio sources, for which typical redshift is much higher ($z \sim 1.4$), although the median radio luminosity is quite similar ($P_{408} \simeq 10^{28}$ WHz^{-1})[1]. A unique advantage of this intermediate flux-density sample (the 1-Jy sample; Allington-Smith, 1982) is that either precise or fairly reliable estimates of z are available for most of the sources in the sample, as described below. Moreover, flux densities of each source have been accurately measured at $\geqq 4$ well-spaced frequencies between 0.15 and 5 GHz. The availability of the good database for this as well as for the strong source sample enables us to estimate the spectral index of each source at some fixed frequencies, say 1 and 2 GHz, defined in the rest-frame of the source. Such "radio *K*-corrected" spectral indices are particularly relevant in the case of the 1-Jy sample, since the typical redshifts of the sources are large, as mentioned above, and the radio spectra of powerful sources are known to be often appreciably curved (Laing and Peacock, 1980). In some recent studies it has been shown that for samples selected at 408 MHz, the median spectral index, α, measured between 0.4 and 2.7 or 5 GHz, steepens significantly from -0.8 to -0.9 as the flux density limit of the sample decreases from ~ 25 Jy to ~ 1 Jy (Steppe and Gopal-Krishna, 1984; Kapahi and Kulkarni, 1986). The present analysis shows that the steepening may largely be an artefact arising from the inability of these earlier workers to define α in the rest-frame of the source.

2. The samples

We first summarise the selection procedure for our samples of strong and intermediate strength sources together with a description of the redshifts and the radio spectral data.

2.1. *The strong source sample (SSS)*

This sample consisting of 102 sources is derived from the "All-Sky Catalogue" of extragalactic sources stronger than 10 Jy at 408 MHz (Robertson, 1973), by excluding sources lying south of declination-20° and ensuring, thereby, the availability of spectroscopic redshifts for at least 90% of the sources. The redshifts are available for 83 sources from Spinrad et al. (1985), for an additional 12 sources from Parkes Master Catalogue (CSIRO, private communication), or from Kühr et al. (1981). Of the 7 sources for which spectroscopic redshifts are lacking, 4 are known to lie in obscured or confused optical fields and we have assumed for them a redshift of 0.2 which is the median redshift for the sample (since the number of these sources is small and, moreover, their spectra are fairly straight, the uncertainty about redshift poses no serious difficulty for the present study). For the remaining 3 sources, all of which are galaxies, redshifts were

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[1] Taking $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0$

estimated from the visual magnitudes published by Kühr et al. (1981), using the relation given by Wall and Peacock (1985).

The next step was to compute spectral indices α_{1e} and α_{2e} of each source at the *emission* frequencies of 1 and 2 GHz. As seen below, the choice of these frequencies which were also adopted in case of our intermediate strength sample (Sect. 2.2), ensure that (i) the corresponding frequencies in the observer's frame are adequately covered by the available measurements for each source, and (ii) the contribution from the compact central component is generally expected to remain minor. The latter is important because only for extended radio components the observed spectral slope is a direct indicator of the electron energy distribution. For 70 of the 102 sources in the SSS, straightline or functional fits to the radio spectrum have been given by Kühr et al. (1981), adjusted to the flux scale defined by Baars et al. (1977) (hereafter referred to as BGPW flux scale). For the remaining 32 sources, spectral curves were determined by fitting a 2nd order polynomial in the logarithmic plane to the measured flux densities at frequencies between 178 and 2700 MHz (always numbering 4 or more), weighing the square of deviation of each measurement by the inverse of the quoted fractional error. The required flux densities together with the errors were available for 28 of the 32 sources from Kühr et al. (1981, 1979), all adjusted to the BGPW flux scale. For the remaining 4 sources we took the flux density data from Kellermann et al. (1969) and adjusted them to the BGPW scale using the factors given by Kühr et al. (1981).

2.2. *The sample of intermediate-strength sources*

This sample, also known as 1-Jy sample, consists of 59 sources selected from the Bologna B2 catalogue to have flux densities, S_{408}, between 1 and 2 Jy at 408 MHz (Allington-Smith, 1982; see also Eales, 1985, for a discussion on the completeness). By combining the high-resolution radio maps with deep CCD photography, Allington-Smith et al. (1982) have been able to identify about 75% of the sources in the 1-Jy sample with objects brighter than $m_r \sim 23$. For 21 of the sources, including 5 quasars, spectroscopic redshifts are known (Allington-Smith et al., 1982, 1985). For another 17 sources, identified either with galaxies or empty fields (which are likely to be galaxies at $z > 1$; see Lilly et al., 1985), we have estimated redshifts from their K-magnitudes measured by Lilly et al. (1985) at more than a 3σ level of significance. For this, we made use of the K–z relation given by them for powerful radio galaxies; we preferred using K-magnitudes instead of optical magnitudes, since the K-z diagram has smaller scatter. Redshifts for the remaining 21 sources in the 1-Jy sample were obtained as follows:

(i) In 12 cases, including 8 quasars ($Q/Q?$) and 4 galaxies ($G/G?$), redshifts estimated from optical magnitudes were adopted from Allington-Smith (1984) and Eales (1985b).

(ii) For the remaining 9 sources identified with empty fields and assumed here to be radio galaxies (see above), we have assigned a typical value of $z = 2$, guided by the interpretation of the K-band measurements by Lilly et al. (1985). The plausible uncertainty in this assigned value is unlikely to bias the present analysis seriously, firstly, because the number of sources involved is small and, secondly, because their radio spectra happen to be, by and large, fairly straight. We note parenthetically that the median values of α_{1e} and α_{2e} for just these 9 sources are in good agreement with the corresponding values for the entire 1-Jy sample.

The spectral indices were computed using the published flux densities at 0.151, 0.408, 1.4, and 4.9 GHz, all measured with beams of size $\gtrsim 1'$. At the lowest frequency, the sources were observed as a part of the 6C survey with a $4'(\alpha) \times 6'(\delta)$ beam and their integrated flux densities on BGPW scale are given by Eales (1985a) to 10% accuracy. At 408 MHz, we have used the flux densities reported in the Bologna catalogues B3.1 (Ficarra et al., 1985) and B2.3 (Colla et al., 1973). B3.1 gives integrated flux densities for 23 of the total 59 sources, measured with a $2\overset{'}{.}6(\alpha) \times 5'(\delta)$ beam. For the remaining 36 sources, flux densities are taken from B2.3 and these refer to peak flux densities measured with a $3'(\alpha) \times 10'(\delta)$ beam. To compensate for the "resolution", small (a few percent) corrections were applied, as estimated from Fig. 1 of the B2.3 catalogue, in cases of 3 sources having prominent east-west structure of size $> 30''$. Also, the values of B2.3 and B3.1 flux densities were adjusted to the BGPW scale by multiplying with 1.03 and 1.07, respectively. It may be further noted that the estimated errors in B2.3 flux densities are 8% of the flux density, while the B3.1 flux densities have smaller quoted errors (see Ficarra et al., 1985) which are adopted after imposing a lower limit of 5% which we consider a reasonable limit considering the uncertainty about flux scale at the low frequencies. At the higher frequencies of 1.4 and 4.9 GHz, flux densities for the 1-Jy sample were taken from Allington-Smith (1982) and from Grueff and Vigotti (1979), respectively. The measurements at 1.4 GHz were made using the Cambridge one-mile telescope with a synthesized beam of $0\overset{'}{.}4(\alpha) \times 0\overset{'}{.}7(\delta)$ and the integrated flux densities to a typical accuracy of 5% are given on the BGPW scale. The flux densities at 4.9 GHz were measured using the Effelsberg radio telescope having a beamwidth of $2\overset{'}{.}4$ and the published values refer to the KPW flux scale which is practically indistinguishable from the BGPW scale at the frequency. The quoted values of error for these measurements are those associated with fitting the beam profile to the observed scans and are found to be the quadratic sum of 4 mJy and 0.7% of the flux density. To these errors we have imposed a plausible lower limit of 3% of the flux density. Since the published values refer to the peak flux density, we have, moreover, enhanced them, in cases of sources larger than 30″, using factors estimated from Fig. 1a of Grueff and Vigotti (1979), taking into account the source structure reported by Allington-Smith (1982). The quoted flux

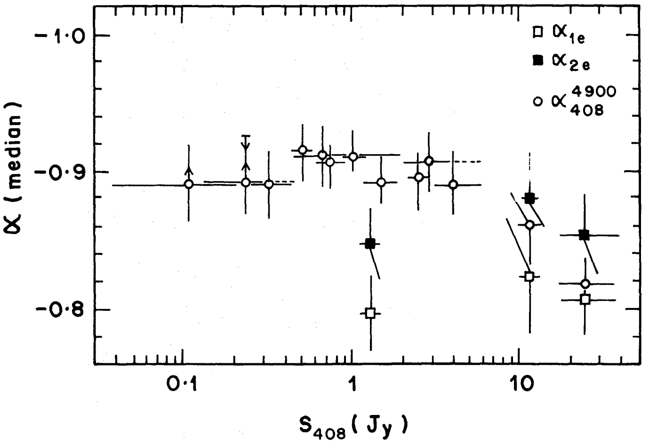

Fig. 1. The derived median values of spectral indices α_{1e} and α_{2e} computed at the emission frequencies of 1 and 2 GHz are plotted against the flux density, S_{408}, for 3 complete samples, namely, SSS 1, SSS 2 and the 1-Jy sample, all selected at 408 MHz (Sect. 2). These values are superposed on the α (median) – S_{408} plot (open circles) published recently by Kapahi and Kulkarni (1986) for samples selected at 408 MHz, where α is the two-point spectral index computed between 408 MHz and 5 GHz

Table 1. The median spectral indices for strong and intermediate-strength radio sources selected at 408 MHz[a]

Name of the sample	No. of sources	z_{med}	S_{408} (Jy)	$\alpha_{1\mathrm{e}}$ (med)[c]	$\alpha_{2\mathrm{e}}$ (med)[c]	α_{408}^{4900} (med)
SSS 1	50 (46, 48)[b]	0.15	>14	-0.808 ± 0.028 (-0.825 ± 0.028)	-0.853 ± 0.03 (-0.855 ± 0.03)	-0.816 ± 0.025[d]
SSS 2	52 (50, 51)[b]	0.25	10–14	-0.823 ± 0.042 (-0.825 ± 0.04)	-0.880 ± 0.034 (-0.880 ± 0.034)	-0.860 ± 0.028[d]
1-Jy	59 (51, 54)[b]	1.4	1–2	-0.796 ± 0.028 (-0.826 ± 0.026)	-0.847 ± 0.025 (-0.857 ± 0.026)	-0.885 ± 0.03

[a] The flux scale defined by Baars et al. (1977) has been used. α is defined as flux density α (frequency)$^{\alpha}$

[b] The two numbers refer to the steep spectrum sources, classified according to $\alpha_{1\mathrm{e}} < -0.5$ and $\alpha_{2\mathrm{e}} < -0.5$, respectively

[c] The values given inside brackets refer to just the steep-spectrum population

[d] These two values taken from Kapahi and Kulkarni (1986) are actually estimated for the whole of the "All-Sky Catalogue" (total 160 sources) out of which our strong source samples SSS 1 and SSS 2 have been derived by excluding sources located south of declination -20^{0} (see Sect. 2.1)

density errors were correspondingly enhanced by percentages which are twice as large. The values of $\alpha_{1\mathrm{e}}$ and $\alpha_{2\mathrm{e}}$ were determined finally by fitting a 2nd order polynomial to the above mentioned measurements at 0.151, 0.408, 1.4, and 4.9 GHz, following the procedure outlined for the subset of 32 strong sources (Sect. 2.1).

3. Results and discussion

Whereas median redshifts for the strong source sample ($z\sim0.2$) and the 1-Jy sample ($z\sim1.4$) are clearly very different (Sect. 2), their median radio luminosities fall within a narrow range ($10^{28\pm0.5}$ WHz^{-1} at 408 MHz). Since such luminosities lie well above the break in radio luminosity function known to occur near $P_{408}\sim10^{25}$ WHz^{-1}, both our samples must be dominated by powerful radio sources. In Table 1, we have given the values of median spectral indices, $\alpha_{1\mathrm{e}}$(med) and $\alpha_{2\mathrm{e}}$(med), computed for *emission* frequencies of 1 and 2 GHz, as well as the median values of α computed between two fixed frequencies of 408 MHz and 4.9 GHz (Sect. 2). Note that the strong source sample, SSS, has been divided into two almost equal subsets by flux density. We also tabulate inside brackets the median spectral indices for just the steep-spectrum population ($\alpha < -0.5$) of SSS 1, SSS 2 and the 1-Jy sample. A general trend seen from Table 1 is that for all the 3 samples $\alpha_{1\mathrm{e}}$(med) is flatter than $\alpha_{2\mathrm{e}}$(med), though the difference is statistically not very significant for any single sample. This pattern is consistent with the finding of Laing and Peacock (1980) for powerful 3 CR sources according to which the radio spectra, more often than not, steepen towards higher frequencies (see also Allington-Smith, 1982). Further, it is seen for SSS 1 and SSS 2 that α_{408}^{4900}(med) lies close to both $\alpha_{1\mathrm{e}}$(med) and $\alpha_{2\mathrm{e}}$(med). This, too, is expected in view of the generally small redshifts of the strong sources, due to which the effect of "radio K-correction" on α is marginal. The situation is different for the 1-Jy sample where half of the sources lie beyond $z\sim1.4$ (Lilly et al., 1985). For this sample, we find α_{408}^{4900}(med) to be significantly steeper than $\alpha_{1\mathrm{e}}$(med), underlining the relevance of the radio K-correction.

In Fig. 1 we have superposed the median values of $\alpha_{1\mathrm{e}}$, and $\alpha_{2\mathrm{e}}$ derived for our 3 samples on the α_{408}^{4900}(med) – S_{408} plot recently published by Kapahi and Kulkarni (1986) for samples selected at 408 MHz. Our 3 samples are, in fact, subsets of the large database used by them. The median values of α_{408}^{4900} for our samples are found to agree well with the general trend (Fig. 1; Table 1) reassuring us that no statistical anomaly is present within any of our samples. In the context of the α-S correlation (Fig. 1) it may be recalled that the possibility of a 3-sigma steepening of α between $S_{408}\sim15$ Jy and $S_{408}\sim1$ Jy was first pointed out by Murdoch (1976) who observed a sample of 133 sources having $S_{408}\geqq0.97$ Jy, selected from the Molonglo surveys MC 2 and MC 3. The values of S_{408} used by him were substantially revised in the Molonglo Reference Catalogue (Large et al., 1981) and, as noted by Steppe and Gopal-Krishna (1984), the amount of revision could account for roughly half of the steepening of α found by Murdoch, thus reducing his original result to a barely significant level. Nevertheless, the steepening of median spectral index between flux densities $S_{408}\sim15$ Jy and $S_{408}\sim1$ Jy is now established, based on observations of substantially larger samples derived from Molonglo and Bologna surveys at 408 MHz (Gopal-Krishna and Steppe, 1982; Steppe and Gopal-Krishna, 1984; Kapahi and Kulkarni, 1986; Fig. 1). The inconsistency of the observed change in α (med) above $S_{408}\sim1$ Jy with the prediction of most published models of the epoch dependence of radio luminosity function has been discussed by Kapahi and Kulkarni, who have attributed it to a basic deficiency of the models in treating spectral indices to be independent of frequency, which results in the contribution of compact steep-spectrum sources of high radio luminosity to be incorrectly estimated as a function of frequency and flux density. While this shortcoming of the models needs to be tackled, we believe that it is even more important to first determine the α-S correlation by computing α in the frame of reference of the source. Until then, any physical interpretation of the α-S correlation would remain unrealistic. While the present analysis is a beginning in this direction, it is clearly important to employ larger samples with limiting flux density $S_{408}\lesssim1$ Jy and having essentially complete redshift information. It will then also be possible to discard from the analysis all compact sources, i.e., not only of flat spectrum but also steep spectrum type, as the correlation of α with P or z has been found mainly for extended powerful sources (e.g., Laing and Peacock, 1980; also Peacock, 1985). It may, however, be noted that among metre-wavelength

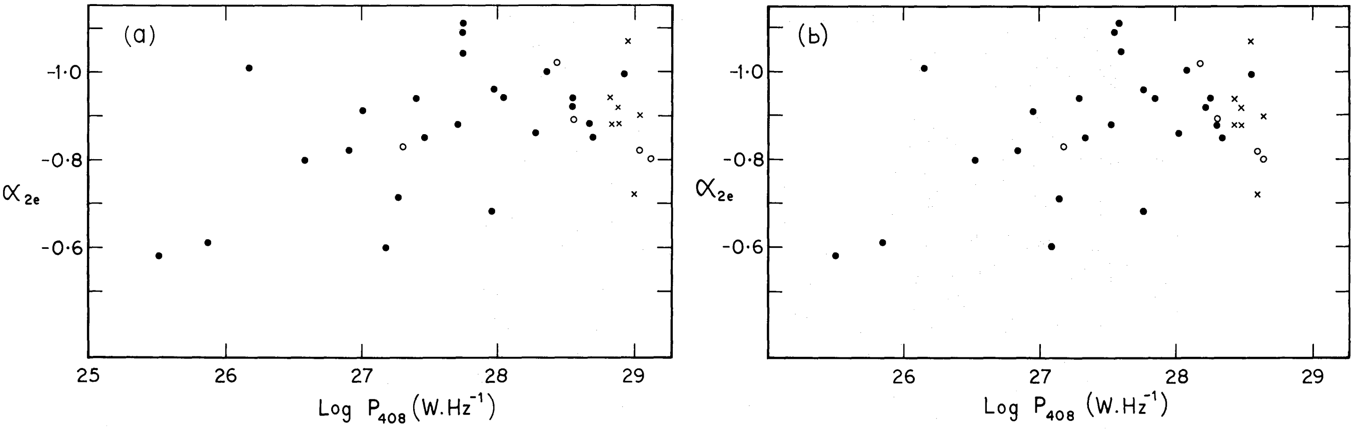

Fig. 2. **a** The spectral index-radio luminosity plot showing α_{2e} *versus* $\log P_{408}$ for the subset of 36 sources, derived from the 1-Jy sample (Sect. 3). The deceleration parameter, q_0, is assumed to be equal to 0. The different symbols refer to galaxies (filled circles), quasars (open circles) and empty-field sources (crosses) which are assumed to lie at $z=2$ (Sect. 2.2). **b** the same as a but computed for $q_0=0.5$

samples with limiting flux densities $S_{408}^{\min} \gtrsim 1$ Jy, the fractions of flat spectrum ($\alpha > -0.5$) and compact steep-spectrum sources (size $<3''$, $\alpha < -0.5$) are not large, being $<10\%$ and $\sim 15\%$, respectively (Steppe and Gopal-Krishna, 1984; Gopal-Krishna et al., 1986). Hence, the proposed exclusion of compact sources is not likely to alter the main trend noticed in the present work, i.e., the *intrinsic* radio spectrum of powerful radio sources does not undergo a significant change along with the large increase in median redshift from ~ 0.15 at $S_{408} \simeq 25$ Jy to ~ 1.4 at $S_{408} \approx 1$ Jy. Hence, either the α-z correlation inferred from the 3 CR sample (Macklin, 1982) does not extend to large redshifts ($z>1$), or, the intrinsic correlation in the 3 CR sample is between P and α (see Sect. 1). Recently, a similar inference has been made by Eales (1985b) on the basis of metre-wavelength samples comparable to those used in the present study. However, the interpretation of that result is complicated due to the fact that the effect of radio K-correction on α has been ignored, although, as discussed above, it is quite significant for intermediate-strength sources. It is noteworthy that the statistical steepening of the *apparent* spectral index between $S_{408} \approx 25$ Jy and $S_{408} \approx 1$ Jy, found in the studies of large samples mentioned above (Steppe and Gopal-Krishna, 1984; Kapahi and Kulkarni, 1986) has not been detected in the analysis reported by Eales (1985b).

The small range in the median radio luminosities of our samples precludes an investigation of the $P-\alpha$ correlation by inter-comparing their spectral properties. Hence we shall presently try to discern any $P-\alpha$ correlation that may be present within the 1-Jy sample alone. Figure 2 shows plots of α_{2e} versus P_{408} for a subset of 36 sources derived from the 1-Jy sample, which includes all sources [2] having a clearly resolved radio structure (size $\geqq 2''$) and displaying a Fanaroff-Riley class II morphology, or, at least, a steep spectrum showing a negative curvature which is a signature of the absence of a prominent self-absorbed central radio component [such spectra have been classified as $E(3)$ by Allington-Smith (1982)]. The selected subset typifies sources to which the $P-\alpha$ correlation observed in the 3 CR sample is mainly attributed, as discussed by Laing and Peacock (1980). It is seen from Fig. 2 that compared to the 3 CR sample, evidence for a $P-\alpha$ correlation in the 1-Jy sample is modest, giving the following regression lines of α_{2e} on P_{408}:

$$\alpha_{2e} = -0.053 \log(P_{408}/\mathrm{WHz}^{-1}) + 0.58 \quad (q_0=0)$$
$$\alpha_{2e} = -0.063 \log(P_{408}/\mathrm{WHz}^{-1}) + 0.88 \quad (q_0=0.5).$$

Note that instead of correlating with P, α could as well be correlated with z, since P and z are tightly correlated within the 1-Jy sample. However, in view of the above discussion, this possibility will not be explored further in this paper. While we stress that the significance of the $P_{408}-\alpha_{2e}$ correlation (Fig. 2) is marginal, this could just be due to the small size of the sample, which is less than a quarter of the 3 CR sample used by Laing and Peacock. For that sample they found an $\alpha - \log P$ correlation for which the fitted regression line is in rough agreement with the expressions derived above for the 1-Jy sample. It seems, thus, that the same $P-\alpha$ correlation might continue from low to high redshifts. It would be desirable to carry out this analysis after subtracting from the spectra of 1-Jy sources the flux densities due to the self-absorbed central components, as done by Laing and Peacock (1980) for the 3 CR sample.

Finally, we note that although the median luminosity of the strong source sample (P_{408}(med) $\sim 3\ 10^{27}$ WHz^{-1}) is somewhat (~ 5 times) lower than the value for the 1-Jy sample, the median values of α_{1e} or α_{2e} are found to be practically the same for the two samples (Table 1). This is not inconsistent, since from the well-studied 3 CR sample, the evidence for $P-\alpha$ correlation is not known to be strong for $P_{408} \gtrsim 3\ 10^{27}$ WHz^{-1} (Laing and Peacock, 1980).

4. Conclusions

For two complete samples of radio sources, selected at 408 MHz and representing strong ($S_{408} \geqq 10$ Jy) and intermediate-strength ($S_{408} \sim 1$ Jy) sources, it has been possible to determine spectral indices of individual sources at emission frequencies of 1 GHz and

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[2] The selection does not discriminate against quasars, except for the quasar 1129+351 for which a very high redshift of 3.3 has been given by Allington-Smith (1984), estimated from its apparent visual magnitude. The redshift is probably grossly overestimated, considering its large angular size (13''; see Barthel, 1986) and anomolously flat K-corrected spectral indices ($\alpha_{1e}=-0.5$, $\alpha_{2e}=-0.6$) despite an undetected radio core (<1 mJy at 1.4 GHz) in the middle of the two prominent hot spots (see Machalski and Condon, 1983)

2 GHz. Using these intrinsic spectral indices, α_{1e} and α_{2e}, it is shown that:

(i) The median values of these "radio K-corrected" spectral indices are practically the same for the strong and intermediate-strength source samples.

(ii) Since the median redshifts of the two samples mentioned above are very different ($z \sim 0.2$ and ~ 1.4, respectively) and their median radio luminosities quite similar ($P_{408} \simeq 10^{28}$ WHz^{-1}), a fairly plausible interpretation of the above result could be that the correlation of α with z, reported in the literature for strong extended radio sources, if real, does not continue to high redshifts ($z > 1$). Alternatively, α is probably correlated primarily with radio luminosity.

(iii) A marginal correlation between P and α is noticed for the intermediate-strength source sample, whose statistical significance may be limited by the small size of the sample. This $P-\alpha$ correlation appears to be of a similar type as the one observed for strong, extended sources located at small redshifts.

Acknowledgements. It is a pleasure to thank Drs. V.K. Kapahi, C.R. Subrahmanya, and P.J. Wiita for the fruitful discussions.

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Note added in proof: The difference between the median redshifts of the strong-source-sample and the 1-Jy sample implies that their effective selection frequencies are also different. This, however, is not found to significantly affect the present result about the spectral behaviour of extended, powerful radio sources (Gopal-Krishna and H. Steppe, in preparation).