DEPENDENCE OF LINEAR SIZES AND SPECTRAL INDICES OF EXTENDED RADIO GALAXIES ON REDSHIFT AND RADIO LUMINOSITY

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1. INTRODUCTION

Apart from the well known evolution in the space density of powerful radio sources, the maximum linear sizes and the spectral indices of extended radio sources could also evolve with epoch and it is important to investigate their epoch-dependence in order to understand the cosmological evolution of radio sources. Evidence for size evolution (in the sense that sources were smaller at earlier epochs) has been presented both from the angular size - redshift relation (θ - z) for quasars and from the angular size - flux density relation (θ - S) for all radio sources. Doubts have sometimes been expressed, however, mainly because it has been difficult to investigate the epoch dependence independent of a possible dependence on radio luminosity. Reasonably reliable estimates of the distances of radio sources have generally been limited to a relatively small range in flux density (S), so that high redshift sources are also of high luminosity. An inverse correlation between linear size (ℓ) and radio luminosity (P) is therefore hard to distinguish from a genuine evolution with epoch. A similar situation appears to hold for the spectral indices (α) of extended radio sources, which have generally been assumed to get steeper at higher radio luminosities (eg. Laing and Peacock 1980) but a dependence on epoch cannot at present be ruled out (Katgert-Merkelijn et al. 1980).

Recent availability of deep optical identifications and magnitudes together with high resolution mapping of weak radio sources now makes it possible to disentangle the two effects at least in the case of the linear sizes of extended radio galaxies. First attempts in this direction, which confirm the need for size evolution and suggest a direct relation between ℓ and P, are presented in Sections 2 and 3. Future observations should soon enable this to be done also in the case of the spectral indices. The observed spectral index - flux density relation for sources selected from 408 MHz samples is discussed in Section 4 where we also remark on how the relation can constrain existing models for the evolution of the radio luminosity function which incorporate a correlation between α and P, or between α and z.

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2. EPOCH DEPENDENCE OF LINEAR SIZES

The θ-z relation for radio galaxies in a relatively small range of P, and selected from 3 complete samples at 1.4 GHz has recently been shown (Kapahi 1985) to require evolution in source sizes. An updated version of the relation, based on the 4 samples listed in Table 1, is shown in Fig.1. Note that spectroscopic redshifts are available only for the brightest BDFL sample. The intermediate flux samples are taken from the GB/GB2 samples of radio galaxies defined by Machalski and Condon (1985), who have also estimated the redshifts from photometric data. The weakest flux sample is derived from the Leiden-Berkeley Deep Survey (LBDS; Windhorst 1984) and consists of sources that are either identified with galaxies with an F mag > 22 or have no optical counterpart (F $\gtrsim 22.75$). Most such sources are expected to be radio galaxies at $z \gtrsim 0.8$. All the samples should cover a fairly small range of $P_{1.4\ GHz}$ between $\sim 10^{24.6}$ and 10^{26} WHz^{-1} ster^{-1} which also places the sources in FR luminosity Class II (fanaroff and Riley 1974).

It is clear from Fig. 1 that the linear sizes of radio galaxies of a constant luminosity depend on epoch. For simplicity, if the evolution is characterised by the relation $\ell \propto (1+z)^{-n}$, the parameter n appears to have a value between 1.5 and 2 depending on the value of q_o between 0 and 0.5

Evidence for size evolution is provided also by the observed θ -S

Table 1. Radio galaxy samples at 1.4 GHz

Sample	$S_{1.4}$(Jy)	range of z	z_{median}	no. of sources
BDFL	≥ 2	0.075 - 0.20	0.11	36
GB/GB2	≥ 0.55	0.15 - 0.40	~ 0.28	25
GB/GB2	≥ 0.2	0.25 - 0.60	~ 0.45	35
LBDS	≥ 0.01	0.8	~ 1 to 2	43

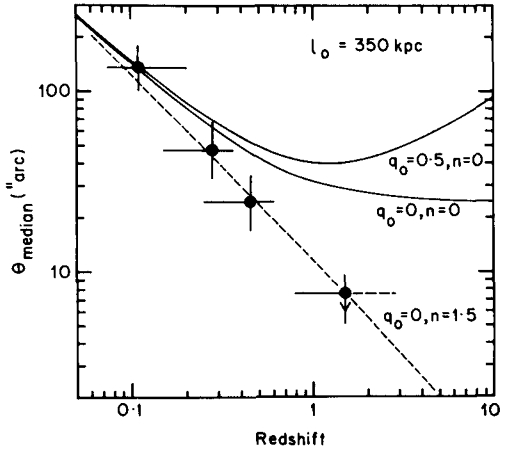

Fig.1. The θ-z relation for radio galaxies of constant radio luminosity

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relation at 408 MHz covering a wide range in S (eg. Kapahi and Subrahmanya 1982). It has been argued however (eg. Downes 1982) that steep-spectrum compact (SSC) sources seen at high redshifts could make a large contribution at low flux levels in the 408 MHz samples, which can obviate the need for size evolution. Expected θ-S relations are generally obtained by considering individual sources in a well observed parent sample of bright sources and calculating the contribution made by such sources in different bins of θ and S by a V/V_m type analysis which includes the effects of evolution in the space density of radio sources according to the prescriptions of a successful evolutionary model for the radio luminosity function (RLF). Because SSC sources are better represented in high frequency samples (due to low frequency turn overs in their spectra) it has been argued that a parent sample selected at 2.7 GHz is more appropriate in predicting the θ-S relation at low frequencies. Such a procedure leads, however, to overestimating the contribution of SSC sources at all flux levels because it does not take into account the marked curvature in the spectra of SSC sources at low frequencies. When approximate corrections are made for this effect (by using spectral indices observed near 1.4 GHz rather than those between 2.7 & 5 GHz) and for the fact that the 2.7 GHz strong source sample (Peacock and Wall 1981) does not include several large radio galaxies now known to have $S_{2.7}$ above the flux limit of the survey, the θ-S relation can no longer be explained without invoking size evolution (Kapahi,

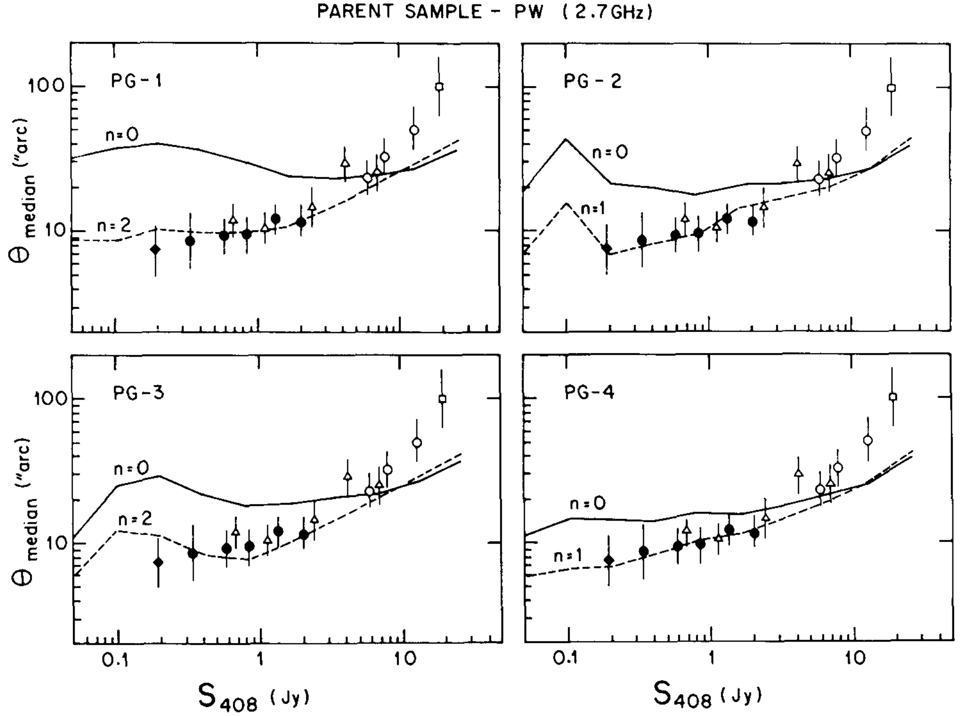

Fig.2. Observed and predicted θ-S relations for the 4 RLF models of Peacock & Gull (1981) with and without size evolution

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Kulkarni & Subrahmanya, in preparation). The predicted θ-S relations from the 2.7 GHz parent sample for the 4 models of Peacock and Gull (1981) are shown in Fig. 2. We have also considered other parent samples (BDFL 1.4 GHz survey & 3CR) and evolutionary models (Condon 1984; Subrahmanya and Kapahi 1983). Size evolution was found to be necessary in every case.

3. LUMINOSITY DEPENDENCE OF LINEAR SIZES

By comparing the sizes of sources in the samples of Table 1 with those of radio galaxies in the same z interval in a bright source sample we can also investigate any dependence of ℓ on P. The BDFL sample (S > 2 Jy) would have been ideal for this purpose but for the fact that deep optical identifications and radio structures are still not available for many sources. We have therefore used the 3CR-LRL sample (Laing et al. 1983). The lower defining frequency of 3CR is unlikely to be serious for our purpose of investigating the sizes of steep-spectrum extended radio galaxies. The possible deficit of SSC and flat-spectrum compact sources (both are predominantly identified with quasars) in the 3CR compared to 1.4 GHz sample can be dealt with by excluding all sources with $\ell \lesssim 30$ kpc from all the samples. The distribution of ℓ in the LBDS (estimated $z \gtrsim 0.8$) and the 3CR-LRL (measured or estimated $z > 0.8$) radio galaxies are shown in Fig 3. It is clear that the 3CR sources, which are likely to be about 2 orders of magnitude more luminous than the LBDS sources but in approximately the same redshift range, have considerably larger sizes suggesting a direct relation between ℓ and P, contrary to an inverse relationship which is required to explain the angular size data without invoking size evolution.

The ratio of ℓ_{med} (3CR) in the different z ranges to the corresponding

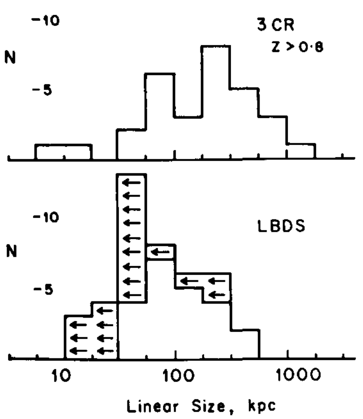

Fig.3. Distributions of ℓ for sources at $z \gtrsim 0.8$. $q_o = 0.5$; H_o=50 $kms^{-1}Mpc^{-1}$

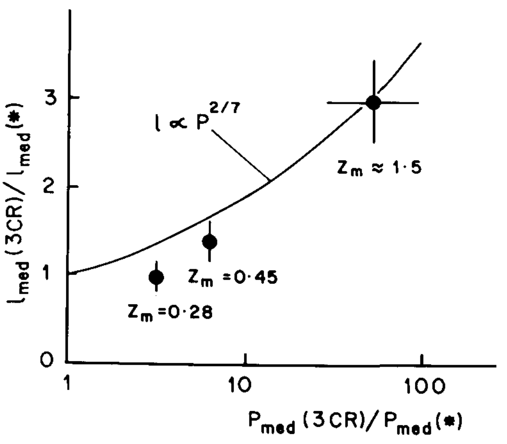

Fig.4. Ratio of ℓ_{med} in the 3CR and 1.4 GHz samples (at constant z) against the ratio of corresponding values of P_{med}

values of ℓ_{med} (*) in the 1.4 GHz samples of Table 1 is shown plotted against the ratios of the corresponding luminosities P_{med} (3CR)/P_{med} (*) in Fig 4. It is interesting to note that the data are consistent with the simplest explanation for linear size evolution in terms of a denser intergalactic medium at earlier epochs. If the density of the IGM surrounding the radio galaxies varies as $(1+z)^3$, it is easily shown (to first approximation) by balancing the internal pressure in the hot spots ($\propto P^{4/7}\ V^{-4/7}$, where V is the Volume) with the ram pressure of the IGM $\{\propto (1+z)^3\ v^2\}$ that the average speed of advancement of the hot spot (v) is proportional to $P^{2/7}\ V^{-2/7}\ (1+z)^{-1.5}$. Since ℓ is likely to be proportional to v and the size of the hot spots is probably not strongly dependent on P or z, one may expect $\ell \propto P^{2/7}\ (1+z)^{-1.5}$. This appears to be consistent with the observed ℓ-z relation (at constant P) and the ℓ-P relation at constant z. Although the above treatment is oversimplified the point is that ℓ is indeed expected to be larger for higher luminosity sources.

4. THE SPECTRAL INDEX - FLUX DENSITY RELATION

Because of the statistical correlation between α and P (or z) the observed distributions of α at different S can be useful in constraining evolutionary models of the RLF. This is particularly important at low S where little redshift information exists. The α_{med}(S) relation for complete samples selected at 408 MHz, derived recently by Kapahi and Kulkarni (1986), is shown in Fig 5. The value of α_{med} is seen to rise considerably from high to intermediate S. But between about 1 and 0.1 Jy there appears to be little change in α_{med} ($\sim$0.9) contrary to the earlier results of Steppe and Gopalkrishna (1984) who found a significant flattening of α_{med} with decreasing S. Their results at low S

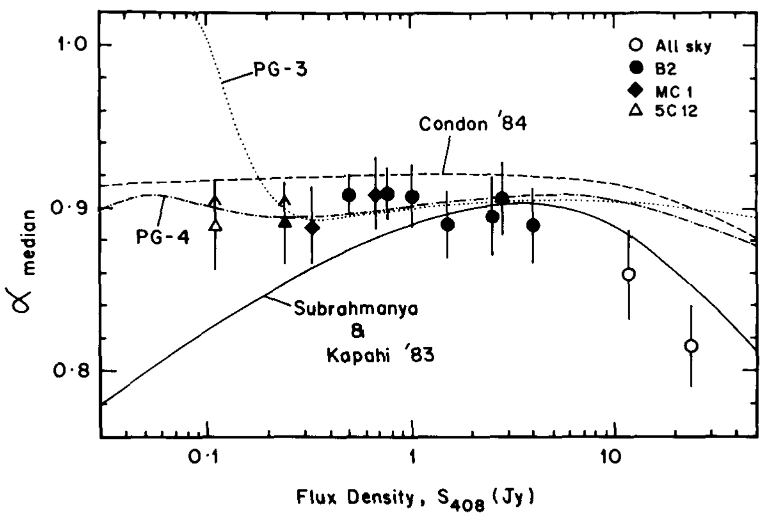

Fig.5. The observed α-S relation and predictions of evolutionary models of the RLF.

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are likely to be affected by selection effects and scaling factors.

The predicted $\alpha_{med}(S)$ relations for several models of the evolving RLF are also shown in Fig 5. Surprisingly none of the models (only 2 shown in Fig 5) of Peacock and Gull (1981) or of Condon (1984) fit the observed α_{med} at high S where the models should be tightly constrained by the good redshift information already available. The discrepancy can be traced (Kapahi and Kulkarni 1986) to the low frequency turnover in the spectra of SSC sources which are assumed in the evolutionary models to have α independent of frequency. This assumption leads to an over-estimate in the number of high-luminosity SSC sources in strong source samples at low frequencies, the same effect that results in the predicted values of θ_m at the high S (using a 2.7 GHz parent sample) to be lower than observed (Section 2; and Kapahi, Kulkarni and Subrahmanya, in preparation).

At the low S end the α-S relation can indeed provide important constraints to evolutionary models (Fig 5). But the detailed interpretation of the α-S relation at low S depends crucially on whether α correlates with P or with z. Observations to determine the spectral indices of the LBDS sample of sources discussed in Sections 2 and 3 could help resolve this question.

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