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The Redshift Dependence of Spectral Index in Powerful Radio Galaxies

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Abstract. We present and discuss in this paper the rest frame radio spectra (1–25 GHz) of a sample of fourteen radio galaxies at $z > 2$ from the newly defined MRC/1Jy complete sample of 558 radio sources. These galaxies are among the most powerful radio sources known and range in luminosity from 10^{28}–$10^{28.8}$ watt Hz^{-1} at 1 GHz. We find that the median rest frame spectral index of this sample of galaxies at $z > 2$ is significantly steeper than that of a matched luminosity sample of 3CRR galaxies which are at a much lower redshift ($0.85 < z < 1.7$). This indicates that spectral index correlates primarily with redshift, at least in the luminosity range considered here. The difference between the distributions of rest frame spectral curvatures for the two samples does not appear to be statistically significant.

We suggest a new explanation for the steeper spectra of radio galaxies at high redshift involving steeper electron energy spectra at injection. Electron energy spectra are expected to steepen in a first-order Fermi acceleration process, at both non-relativistic and relativistic shock fronts, as the upstream fluid velocity decreases. This may well be the case at high redshifts: the hotter and denser circum-galactic medium at high redshifts could result in slower speeds for the hotspot and the jet material behind it. The smaller sizes of radio sources at higher redshifts provide support to this scenario.

Key words. Galaxies: radio spectra, high redshift radio—synchrotron electron acceleration.

1. Introduction

We have undertaken a multifrequency radio polarisation study of a sample of fifteen radio galaxies at $z > 2$. These galaxies were selected from the newly defined MRC/1Jy complete sample of 558 radio sources (McCarthy *et al.* 1996; Kapahi *et al.* 1998a, b). This project has resulted in several interesting and surprising discoveries including steep spectrum radio cores and large rotation measures in many of the sources (Athreya 1996; Athreya *et al.* 1997, 1998). We discuss in this paper the rest frame radio spectra of these high redshift radio galaxies.

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Since Whitfield (1957) first reported that the more distant radio galaxies appeared to have steeper radio spectra, several workers have confirmed and improved the statistics of the correlation between radio spectral index (α: $S_\nu \propto \nu^{-a}$) and radio luminosity (P) or redshift (z). The correlation has in fact been very successsfully exploited to search for high redshift galaxies among radio sources with steep spectral indices (e.g. Chambers & Miley 1990; McCarthy *et al.* 1991; Rottgering *et al.* 1994). Due to the strong P–z correlation in flux-limited radio samples, there has been much debate on whether α correlates primarily with P or with z, though most initial workers have tended to favour an α–P correlation (Laing & Peacock 1980; Macklin 1982; Gopal-Krishna 1988; Wieringa & Katgert 1991).

Using spectral indices defined at a constant rest frame frequency instead of the usual spectral index defined between two fixed observed frequencies Gopal-Krishna (1988) drew attention to the importance of K-correction in spectral index studies because of the steeper spectral index at higher frequencies for many sources. However, all the correlation between α and P cannot be attributed to high frequency spectral steepening, as indeed had been suggested by a much earlier work in which radio sources with straight spectra (same α at all frequencies) also showed an α–P correlation (Bridle *et al.* 1972). Using spectral indices at 1.4 GHz (rest frame) van Breugel & McCarthy (1990) have shown that 3CR galaxies at $z \sim 1.5$ are steeper on the average by ~ 0.1 than galaxies at $z < 0.5$.

The reason for the observed α–P (or α– z) correlation is, however, not clear. Gopal-Krishna & Wiita (1990) have suggested that intrinsically more powerful jets undergo multiple shocks before they are completely randomised and the successive shocks lead to steeper and steeper spectra, resulting in a luminosity correlation. Krolik & Chen (1991) suggest that the increase in the energy density of the cosmic microwave background radiation at higher redshifts would result in faster depletion of high energy electrons and hence steeper spectra due to increased inverse Compton scattering of CMBR photons. Alternatively, they suggest that the correlation may be a selection effect in which the P–z correlation in flux limited samples selects higher magnetic fields (to increase emissivity) which leads to more rapid spectral steepening. Kapahi & Kulkarni (1990) explore the possibility that the correlation is an artifact of the high flux density limits of low frequency radio samples and predict a weaker α–z correlation at fainter flux limits.

The 3CRR sample of extragalactic radio sources happens to be the only large sample with complete optical identification and redshift content; but, the strong P–z correlation in the sample makes it difficult to disentangle the luminosity and redshift dependences of radio source properties. We have been involved with a major observational programme to define and study a new complete sample of 558 extra-galactic radio sources from the Molonglo Reference Catalogue (McCarthy *et al.* 1996; Kapahi *et al.* 1998a, b). The sources in the sample satisfy $S_{408\ \mathrm{MHZ}} > 0.95$ Jy, $-20° > \delta > -30°$ and Galactic latitude $|b| > 20°$. About 96 per cent of the MRC/1Jy sources have already been optically identified. We have obtained spectroscopic redshifts for about 60 per cent of the 447 galaxies so far (the other 111 sources are quasars) and another 21 per cent of the galaxies have redshift estimates from the K-band Hubble relation (McCarthy *et al.* 1999). An important feature of this sample is that more than a third of the galaxies are at $z > 1$, with a substantial fraction extending to $z > 2$. The MRC/1Jy sample is on the average about five times fainter in flux density than the 3CRR. Consequently, at similar redshifts, the 3CRR sources are five times more luminous than the MRC/1Jy sources. However, the MRC/1Jy sample goes to much higher redshifts than the 3CRR. A comparison of sources in the 3CRR and MRC/1Jy samples should therefore facilitate the disentangling of the redshift and luminosity dependences of source properties. In particular, the nature of the spectral index correlation was one of the questions which motivated this project.

While redshifts are not yet available for all the sources, we have attempted to distinguish between redshift and luminosity as the primary spectral index correlate using a sample of MRC/1Jy galaxies at $z > 2$. In this paper we have compared the spectra of these high redshift radio galaxies (HRRG) with those of a matched luminosity sample of 3CRR galaxies at lower redshifts. The analysis indicates that the primary correlation of spectral index is with redshift and not luminosity.

2. Sample selection

2.1 *High redshift radio galaxy (HRRG) sample at* $z > 2$

Seventeen MRC/1Jy galaxies had been spectroscopically confirmed to have $z > 2$ by 1993. Fifteen of these were observed using the VLA radio telescope in early 1993; the other two had to be left out due to constraints of the range of LST allocated to our project. Subsequently, four more galaxies have been discovered in the sample at $z > 2$. Infrared K-band magnitudes of another twenty galaxies indicate that they are also likely to be at $z > 2$. However, the analysis in this paper is confined to the data on the 15 MRC/1Jy galaxies at $z > 2$ which were observed using the VLA in 1993. The lack of spectroscopic redshifts and/or the insufficient frequency coverage for the others made them unsuitable for inclusion in this work. The possible biases introduced by the incompleteness of the HRRG sample is discussed in detail in section 5.1. The GHz spectra of compact radio sources are often modified by synchrotron self-absorption. For this reason, the compact source 0030–219 was left out of this analysis.

The 14 HRRGs in this study have $P_{1\ \mathrm{GHz}}$ (luminosity at 1 GHz) of $10^{28.0}$–$10^{28.8}$ $\mathrm{watt Hz^{-1}}$ (median value of 28.37) and range in redshift from 2.0 to 3.13 (median value of 2.38)[2].

2.2 *Matched luminosity 3CRR radio galaxies – IRRG samples*

We have chosen a statistically complete subset of 3CRR radio galaxies which match the $P_{1\ \mathrm{GHz}}$ of the HRRG sample. There are 37 3CRR galaxies with $P_{1\ \mathrm{GHZ}} > 10^{28}$ watt Hz^{-1}, the most powerful at $P_{1\ \mathrm{GHz}} = 10^{28.71}$ watt Hz^{-1}. Two of the radio galaxies are smaller than 10 kpc in linear size and have been excluded for the reason given before. The rest of the 35 sources range in redshift from $z = 0.25$ to 1.8.

The MRC/1Jy sample is defined at 408 MHz which corresponds to ~ 1–2 GHz in the rest frame for HRRGs. However, the 3CRR sample was selected at 178 MHz i.e. 0.3–0.5 GHz in the rest frame. Since the original selection frequency of 3CRR is not the one at which the luminosity criterion has been applied in this work, there is the

[2] H_o = km sec^{-1} Mpc^{-1} and $\Omega_o = 1$ used throughout this paper.

possibility that any subset of 3CRR that we choose will be biased towards flatter spectral indices. This is because 3CRR galaxies with a spectrum steeper than a critical value would have $L_{1G} < 10^{28}$ and hence would not be selected by us. However, all the galaxies in the 3CRR with $z > 0.81$ have $P_{1\ \mathrm{GHz}} > 10^{28}$ watt Hz^{-1}. So, selecting 3CRR sources at $z > 0.81$ will take care of this bias.

The chosen subsample should contain all the galaxies within a certain range in z for achieving completeness; this subsample should also be statistically similar to the HRRG sample in its $P_{1\ \mathrm{GHz}}$ distribution. Further, the range of z must satisfy the conflicting requirements of large sample size as well as distinctness from the redshift distribution of the HRRG sample (since we are examining the redshift dependence of α). Taking all these factors into consideration, we define the Intermediate Redshift Radio Galaxy (IRRG) sample which comprises all the 21 3CRR galaxies at $0.85 < z < 1.7$ and linear size > 10 kpc. These sources have $P_{1\ \mathrm{GHz}}$ in the range 10^{28}–$10^{28.68}$; the median value is 28.37 and the difference between the luminosity distribution of the IRRG and HRRG samples is not statistically significant (from a Kolmogorov-Smirnov test).

It is likely that the IRRG sample, as defined here, is biased towards a steeper median spectral index. This is because sources with $P_{1\ \mathrm{GHz}} > 1028$ watt Hz^{-1} and a spectral index flatter than a certain value will not be selected into the 3CRR and hence will not be in the IRRG sample. However the lack of radio samples selected at

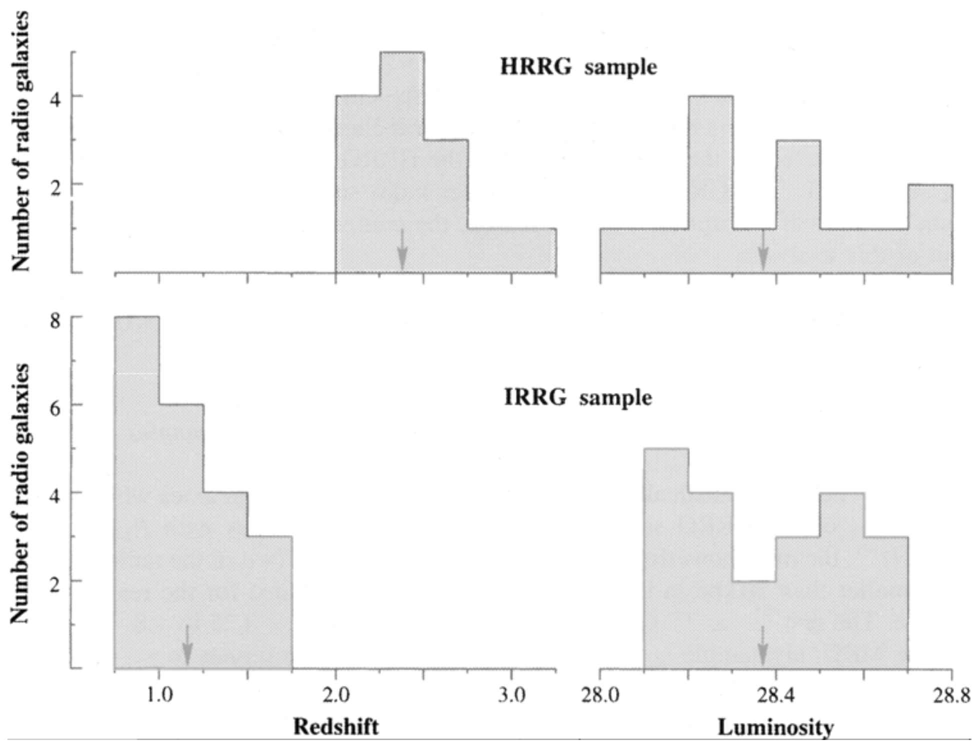

Figure 1. The redshift and luminosity distributions of the radio galaxy samples. The luminosity (at 1 GHz) is in units of log(wattHz^{-1}). The arrowheads indicate the median values.

around 1 GHz with complete redshift information makes it difficult to estimate this effect. We have elaborated on this aspect in section 5.1.

The redshift and luminosity distributions of the galaxies are shown in Fig. 1.

3. The data

The flux densities of HRRGs and the details of the observations from which they were obtained are given in Athreya (1999). In brief, the flux densities were available for most sources at 408 MHz (Large *et al.* 1981), 843 MHz (Subrahmanya & Hunstead, pers. comm), 1.43 GHz, 4.71 GHz, 4.86 GHz, 8.21 GHz and 8.44 GHz (the last 5 from VLA observations). The flux density scale for the VLA observations was that of Baars *et al.* (1977) along with the corrections determined and incorporated into the AIPS[3] package (version 15OCT95) by Perley. The fluxes at the first two frequencies were measured with a telescope beam larger than the sizes of the HRRGs. The high resolution radio images obtained at the higher frequencies did not show any other confusing source in the vicinity of the HRRGs strong enough to affect the estimated flux densities significantly. So neither over-resolution nor contribution from an unrelated source are expected to have corrupted the values at 408 MHz and 843 MHz. The same holds for the flux densities at 1.425 and 4.8 GHz which were estimated from observations with resolutions of 3–4″ arc. The observations at 4.71, 8.21 and 8.4 GHz with a higher resolution of 0″.5 arc are insensitive to structures larger than ~20″ arc. However the considerably smaller total sizes of most of the HRRGs (only 1 source is larger than 12″ arc) make it unlikely that there is a significant underestimation of the flux densities at these frequencies. The standard error in the flux densities of all sources is estimated to be ~5%, most of which is due to the uncertainty in the primary flux density scale itself.

The spectra are plotted in Fig. 2 and Table 1 lists the parameters of the analytic functions used to fit the flux densities. Four different functions of log (ν_{GHZ}) were tried for fitting the log (S_{Jy}) data for each source, viz. (**i**) $A_0 + A_1 \log(\nu)$, (**ii**) $A_0 + A_1 \log(\nu) + A_2[\log(\nu)]^2$ (**iii**) $A_0 + A_1 \log(\nu) + A_2 \exp[+\log(\nu)]$ and (**iv**) $A_1 \log(\nu) + A_2 \exp[-\log(\nu)]$. The last two functions were found to provide the best fit (least χ^2) to the data in each source. The best fits were chosen for calculating the flux densities at other frequencies. The form of the fitting functions is *not* expected to reflect on the nature of the underlying phenomena; they were solely used as aids in interpolation (and perhaps extrapolation a little way beyond the extreme points on either side). The fits are fairly good with 65 per cent of the residuals being less than 3 per cent of the observed values and only 4 per cent of the residuals larger than 10 per cent. The spectrum of 0349–211 is rather poorly fit even by the best fitting function. The concave spectral curvature seen in this source is likely to be due to the inverted spectrum ($\alpha < 0$) of its prominent core. The fitting functions were used to calculate the spectral indices (tangents to the functions) of the HRRGs at various frequencies to investigate the shape of their spectra.

A similar procedure was adopted for the IRRG sample. The analytical fits to the spectra were calculated from the flux densities at 0.178, 0.750, 1.4, 2.695, 5.0, 10.7 and 14.9 GHz (observed) listed in Laing & Peacock (1980), which are also based on

[3] Astronomical Image Processing Systems, distributed by the NRAO.

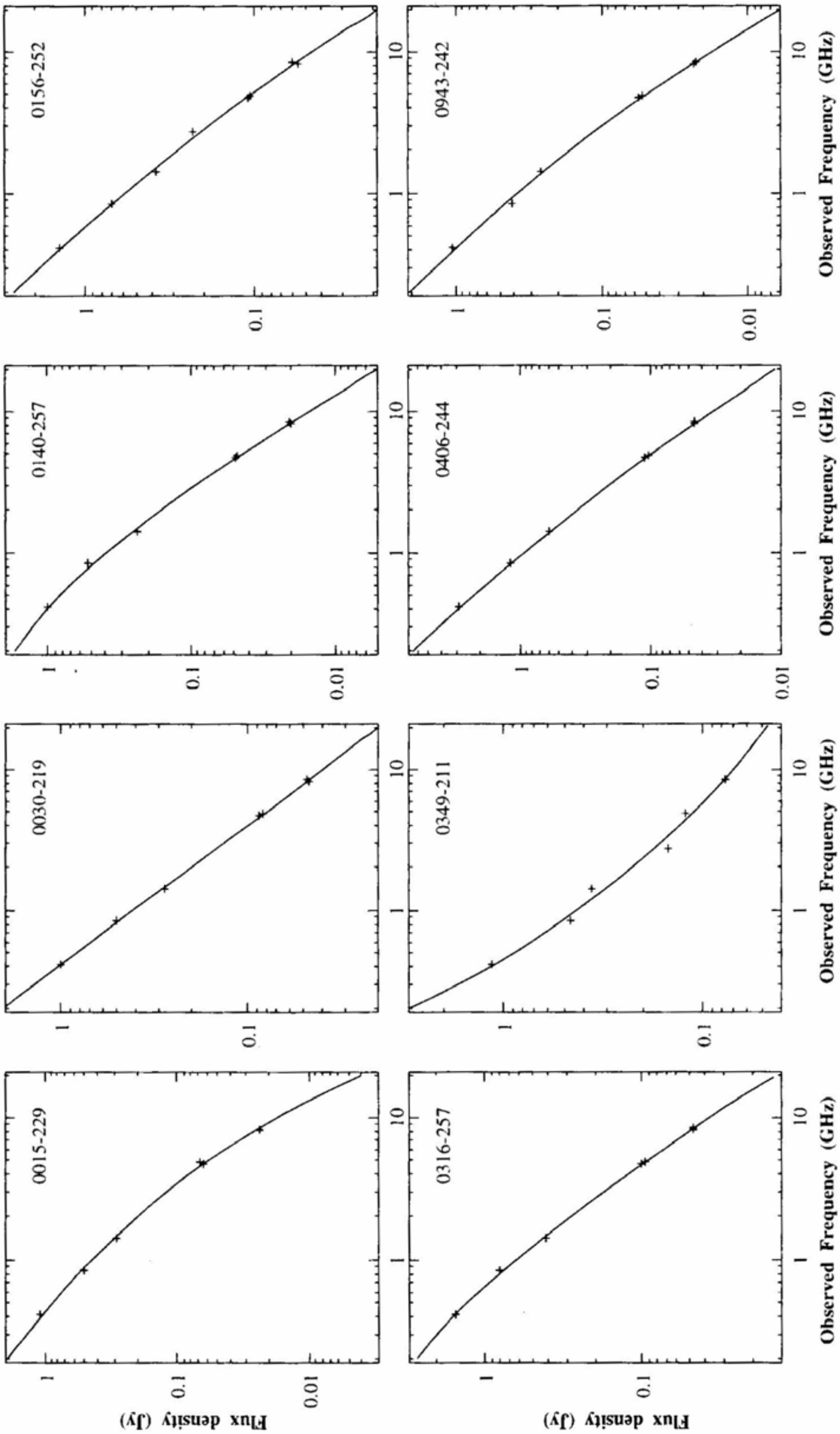

Figure 2. *(Continued)*

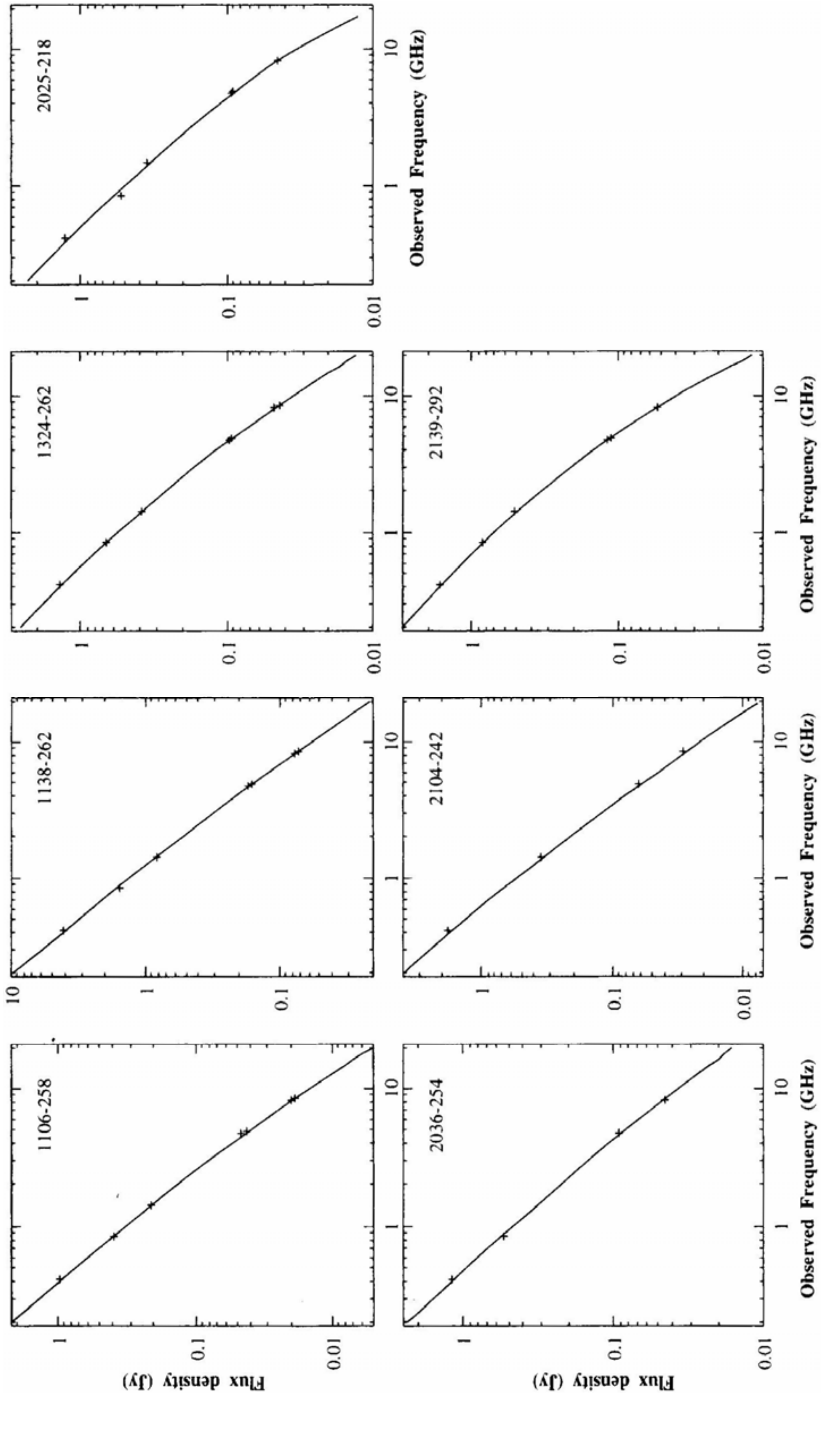

Figure 2. The radio spectra of MRC/1Jy galaxies at $z > 2$ (HRRG sample).

Table 1. Some properties of MRC/1Jy high redshift radio galaxies.

Source	z	$P_{1\,GHz}$ watt Hz^{-1}	Size arcsec	Co-effs. of the spectral fits $e^{\pm}$	A_0	A_1	A_2	$\alpha^T_{1.4G}$	C^{α}_{4G}
0015–229	2.01	28.07	11.2	+	0.130	−0.573	−0.481	0.92	0.54
0030–219	2.17	28.14	<0.1	+	−0.390	−1.016	0.002	1.01	0.00
0140–257	2.64	28.29	3.8	−	0.246	−1.825	−0.643	0.86	0.62
0156–252	2.09	28.23	6.9	+	−0.072	−0.829	−0.162	0.94	0.18
0316–257	3.13	28.64	6.9	−	0.207	−1.491	−0.403	0.85	0.41
0349–211	2.31	28.28	7.2	−	−0.893	−0.460	0.519	1.21	−0.48
0406–244	2.44	28.75	7.4	+	0.181	−1.095	−0.205	1.23	0.22
0943–242	2.93	28.43	3.6	+	−0.146	−0.857	−0.277	1.03	0.28
1106–258	2.43	28.25	3.6	+	−0.326	−1.066	−0.159	1.17	0.17
1138–262	2.17	28.76	11.4	+	0.240	−1.152	−0.122	1.24	0.14
1324–262	2.28	28.32	1.7	+	−0.025	−0.816	−0.225	0.97	0.24
2025–218	2.63	28.40	4.1	+	−0.135	−0.860	−0.166	0.97	0.17
2036–254	2.00	28.12	5.9	+	−0.221	−0.921	−0.108	1.00	0.12
2104–242	2.49	28.53	21.7	−	−0.009	−1.579	−0.249	1.21	0.23
2139–292	2.55	28.49	7.3	+	0.215	−0.644	−0.360	0.89	0.38

Notes:

1. $P_{1\,GHz}$: Luminosity at 1 GHz.
2. Size: Linear distance between the outer hotspots.
3. The analytical fits to the observed spectra are of the form log (S) = ± A_0 A_1 log(v)+ A_2 exp(± log(v)), where S is the flux density in Jy, v is the observed frequency in GHz and the sign of the exponential is listed in column 5.
4. $\alpha^T_{1.4G}$: Spectral index (≡ d log S/d log v) at 1.4 GHz (rest frame).
5. C^{α}_{4G}: Spectral curvature ($-d^2(\log S)/(d \log v)^2$)) at 4 GHz (rest frame).

the flux density scale of Baars *et al.* (1977). The spectral fits for these galaxies are listed in Table 2.

The flux densities used in this work arc the total flux densities for the sources and not that of just the extended emission. While it appears from previous studies that the spectral index correlation is a property of the extended emission (Laing & Peacock 1980), very few radio sources have been observed with sufficiently high resolution over a wide frequency range for obtaining the radio spectra of their cores. The discovery of steep spectrum radio cores in the HRRG sample (Athreya *et al.* 1997) at GHz frequencies did not allow us the liberty of assuming the same flux density for the cores at all frequencies (i.e. α = 0) as has hitherto been done for radio sources. Nevertheless, this is unlikely to affect the analysis as the fraction of the total flux density contributed by the core in most sources in less than 1 per cent.

We have compared the distribution of the spectral indices of the HRRG and the IRRG samples at rest frame frequencies of 1, 2, 4, 8 and 16 GHz. These frequencies lie within the range of rest frame frequencies used to fit the spectra for both the samples. Given the strong spectral curvature, it is not clear how dependable are extrapolations of the spectra outside the observed range.

The spectral index values used here are α^T_v = –(d log S/d log $v)_v$ instead of the usual α^{v2}_{v1} = – (log S_{v1} – log S_{v2})/ (log $v1$ – log $v2$). The tangent to the spectrum at $v(\alpha^T_v)$ is the proper definition of spectral index, of which α^{v2}_{v1} is only an

Table 2. The observed spectra of the intermediate redshift radio galaxv sample.

Source	z	$P_{1\,\mathrm{GHz}}$ watt Hz^{-1}	Co-effs. of the spectral fits $e^{\pm}$	A_0	A_1	A_2	$\alpha^{T}_{1.4G}$	C^{α}_{4G}
3CR 13	1.351	28.48	−	0.701	−1.337	−0.278	0.99	0.22
3CR 22	0.937	28.17	+	0.636	−0.736	−0.129	0.85	0.18
3CR 65	1.176	28.52	−	1.151	−1.452	−0.504	0.84	0.39
3CR 68.2	1.575	28.54	+	0.519	−1.028	−0.296	1.26	0.36
3CR 175.1	0.920	28.10	+	0.617	−0.734	−0.171	0.88	0.24
3CR 184	0.994	28.25	+	0.759	−0.693	−0.244	0.90	0.33
3CR 217	0.898	28.15	−	0.962	−1.508	−0.474	0.97	0.34
3CR 252	1.104	28.16	−	0.299	−1.143	−0.035	1.10	0.03
3CR 266	1.275	28.32	−	0.321	−1.098	−0.027	1.07	0.02
3CR 267	1.140	28.37	+	0.539	−0.885	−0.042	0.92	0.06
3CR 268.1	0.974	28.56	+	1.097	−0.480	−0.176	0.63	0.24
3CR 280	0.998	28.53	+	0.966	−0.678	−0.143	0.80	0.19
3CR 289	0.967	28.22	−	0.798	−1.247	−0.292	0.91	0.21
3CR 322	1.681	28.66	−	0.782	−1.373	−0.364	0.89	0.31
3CR 324	1.206	28.48	+	0.766	−0.766	−0.223	0.95	0.29
3CR 325	0.860	28.28	−	1.137	−1.362	−0.441	0.87	0.32
3CR 356	1.079	28.18	+	0.449	−0.941	−0.134	1.05	0.18
3CR 368	1.132	28.22	−	0.334	−1.413	−0.102	1.29	0.08
3CR 437	1.480	28.68	−	0.712	−1.029	−0.132	0.86	0.11
3CR 469.1	1.336	28.43	+	0.507	−0.901	−0.128	1.00	0.16
3CR 470	1.653	28.64	+	0.760	−0.580	−0.309	0.81	0.37
3CR 6.1	0.840	28.22	+	0.887	−0.628	−0.220	0.82	0.31
3CR 226	0.818	28.10	+	0.752	−0.764	−0.224	0.97	0.32
3CR 239	1.781	28.71	+	0.417	−1.047	−0.089	1.11	0.10
3CR 263.1	0.824	28.21	−	0.858	−1.213	−0.223	0.96	0.16
3CR 265	0.811	28.18	−	0.809	−1.254	−0.204	1.03	0.14
3CR 294	1.786	28.63	+	0.485	−0.890	−0.215	1.05	0.25

1. See the notes under Table 6 for an explanation of the columns.
2. The 6 sources in a separate block at the bottom are not part of the IRRG sample but have been used for determining the redshift dependence of spectral index (Fig. 4).

approximation necessitated by lack of data at sufficiently large number of frequencies. It is possible to examine spectral properties in finer detail using α^{T}_{ν}. We have also investigated the differences in the spectral curvature ($C^{\alpha} \equiv -\mathrm{d}^2(\log S)/(\mathrm{d}\log \nu)^2$) distributions for the two samples.

4. Results

The median spectral indices of the radio galaxy samples at different rest frame frequencies are plotted in Fig. 3. The 1-tailed Kolmogorov-Smirnov test shows that the spectra of HRRGs are steeper than those of IRRG galaxies at all frequencies though at different levels of significance (Table 3); in fact, the alternative hypothesis

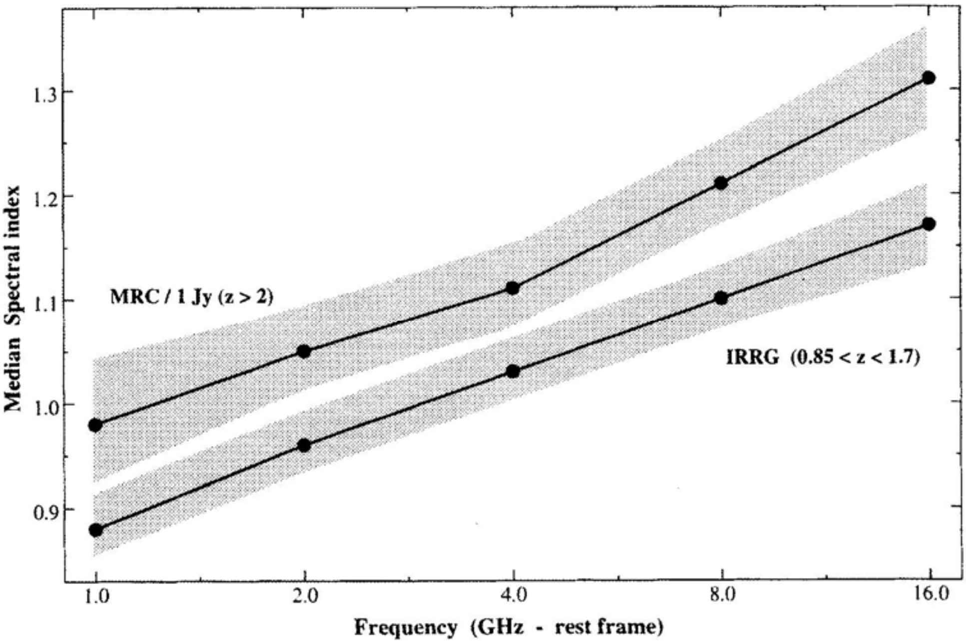

Figure 3. A plot of median spectral index (α_u^T) *versus* frequency for the radio galaxy samples. The shaded area indicates the error on the median values.

Table 3. Kolmogorov-Smirnov tests of the spectral differences between the HRRG and the IRRG samples.

	Spectral index				Spectral curvature			
ν_{Ghz}	$\alpha^T_{\mathrm{HRRG}} > \alpha^T_{\mathrm{IRRG}}$		$\alpha^T_{\mathrm{HRRG}} < \alpha^T_{\mathrm{IRRG}}$		$C^\alpha_{\mathrm{HRRG}} > C^\alpha_{\mathrm{IRRG}}$		$C^\alpha_{\mathrm{HRRG}} < C^\alpha_{\mathrm{IRRG}}$	
	Δ	Σ	Δ	Σ	Δ	Σ	Δ	Σ
1.0	0.381	>0.90	0.095	~0.15	0.143	nc	0.167	nc
2.0	0.357	>0.85	0.095	~0.15	0.143	nc	0.095	~0.15
4.0	0.286	nc	0.048	<0.05	0.238	nc	0.095	~0.15
8.0	0.429	>0.95	0.048	~0.05	0.262	nc	0.071	<0.10
16.0	0.476	~0.98	0.071	<0.10	0.403	>0.90	0.071	<0.10

Notes:

1. Δ: The maximum difference between the cumulative probability distributions.
2. Σ: The probability that the above difference is not due to chance. A value close to 1 recommends the acceptance of the hypothesis (listed in the header of the column) while a value close to 0 recommends rejection of the same; 'nc' indicates that the test was not conclusive (Σ = 0.2-0.8).

that the spectra of IRRGs are steeper may be rejected at a high level of significance. However, the distributions at different frequencies are not strictly independent.

A surprising result is that differences in the spectral curvatures of the two samples are not statistically significant except possibly at the highest frequency of 16 GHz. Though median spectral indices changed by ~0.3 over the frequency range, the differential steepening between the two samples is $\lesssim 0.04$. The median value of the

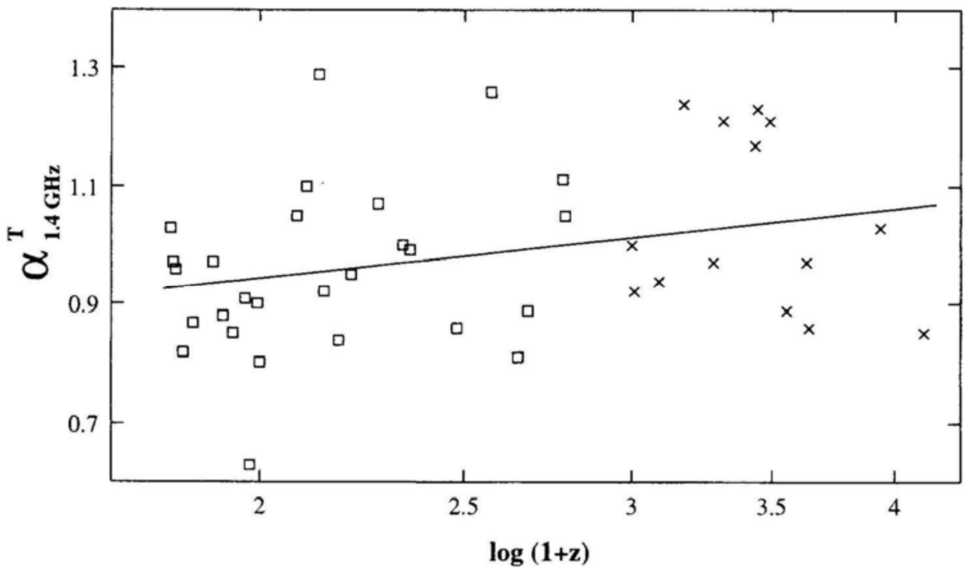

Figure 4. A plot of spectral index *versus* redshift for radio galaxies. The '×' are HRRGs while the open squares are IRRGs. The spectral index values are calculated at 1.4 GHz in the rest frame. The solid line is the best fit for the data.

spectral curvature is 0.23 ± 0.04 for HRRG and 0.18 ± 0.04 for IRRG samples at 1.4 GHz.

The α at 1.4 GHz (rest frame) of 41 radio galaxies is plotted against their redshift in Fig. 4. These 41 galaxies consist of all the sources in the HRRG and IRRG samples and an additional six sources from the 3CRR sample with $P_{1\ \mathrm{GHz}} > 10^{28}$ watt Hz^{-1} and $0.81 < z < 0.85$ or $z > 1.7$. The data may be fitted by a linear function of the form $\alpha = (0.82 \pm 0.08) + (0.40 + 0.20) \log (1 + z)$ at 1.4 GHz. The fit has a correlation co-efficient of 0.301, the confidence co-efficient of the correlation being >95 per cent. The plot (and the correlation co-efficient) shows that the scatter about the best fit line is considerable. However, we find that the residuals of the fits are not correlated with luminosity (correlation co-efficient of –0.067, confidence co-efficient 33 per cent).

5. Discussion

5.1 *The α–z correlation*

Since the two samples used here are matched in luminosity, our result indicates a primary relationship between a and z in the luminosity range of 10^{28}–10^{29} watt Hz^{-1}. The fit is consistent with a spectral index difference of 0.1 at 1.4 GHz between 3CR galaxies at $z < 0.5$ and $z \sim 1.5$ reported by van Breugel & McCarthy (1990)—i.e. the redshift dependence is sufficient to explain the change of spectral index within the 3CRR. This, together with the lack of a residual luminosity-spectral index correlation in our study (although the statistics are not sufficient to rule out the correlation either) suggests that the luminosity dependence of spectral index, if any, is not important.

However, the best way of confirming this would be to select sources at a fixed redshift but spanning a wide range in luminosity.

One of the principal objectives behind the definition and study of the MRC/1Jy sample was the discovery and study of high redshift radio galaxies (see McCarthy *et al.* 1991; Athreya 1996, 1999; Athreya *et al.* 1997, 1998). To this end, spectroscopy was first carried out for those MRC/1Jy sources more likely to be at high redshifts, i.e. small angular sized sources with steep radio spectra between 408 and 843 MHz ($\alpha > 0.9$). The spectroscopy of most of the other *normal spectrum* ($\alpha < 0.9$) galaxies was carried out subsequently. All the 38 MRC/1Jy $z > 2$ galaxies presently known are from the steep spectrum sample only and none of the 121 normal spectrum galaxies have been found to be at $z > 2$. Therefore, though the initial selection of the HRRG sample suggested a strong steep spectrum bias, subsequent results show that the HRRG sample is likely to be representative of the complete set of MRC/1Jy $z > 2$ galaxies as far as their radio spectra are concerned.

We have already explained in section 2 that the median spectral index of the IRRG sample may be biased towards a steeper value and also the problem associated with quantifying this effect. However, any such bias would only make our conclusion more significant. We tried to estimate this bias using sources in the MRC/1Jy sample. We selected all the sources satisfying $0.85 < z < 1.75$, $P_{1\ \mathrm{GHz}} > 10^{28}$ watt Hz^{-1} and with $S_{178} < 10$ Jy. The redshift range is identical to that of the IRRG sample but the median redshift of the sample is ~ 1.6 which is considerably higher than ~ 1.2 of the IRRG sample. The MRC selection frequency of 408 MHz corresponds to a rest frame frequency of ~1 GHz for these sources which is appropriate for our purpose. These sources should represent the 1 GHz selected population which would not be in the 3CRR because of the above bias. We only have $\alpha_{5\mathrm{G}}^{408\mathrm{G}}$ (observed frame) for these sources, which to first order corresponds to $\alpha_{1.4G}^{T}$ (observed) or $\alpha_{3.7G}^{T}$ (rest frame). The median spectral index of this sample is 1.06. Compensating for the higher redshift (using our α-z relationship) reduces this median value to 1.03 which is the same as that of the IRRG sample. Given the incompleteness of this subsample, the inadequate frequency coverage and the error bars, we can only say that the bias is unlikely to be significant.

One other question is how significant is the use of a particular cosmological model for this result. The increase in the luminosity of sources is larger for more distant sources as the deceleration parameter decreases. This would affect our result by modifying the selection of sources. For example, using $q_0 = 0.2$ (instead of 0.5), would brighten the sources at $z = 1.2$ and 2.3 by factors of ~4.5 and 2, respectively. As a result we would have to eliminate some of the lower luminosity (and hence redshift) sources from the IRRG sample and some of the higher luminosity/redshift sources from the HRRG sample to ensure that the luminosity distributions are the same. Doing so, we found that the median value of $\alpha_{1.4\mathrm{G}}^{T}$ remained unchanged at 0.91 for the IRRG sample despite the removal of five sources; the median reduced by 0.02 for the HRRG sample with the elimination of three sources. However the difference in the redshifts of the two modified samples is less than before and the change is sufficient to account for the reduction in the spectral index difference. But the change of 0.02 in the median value is not statistically significant and we believe it is as likely to be due to statistical noise as due to a change in the redshift distribution. It would be safe to say that cosmology is not a critical parameter here (excepting that more extreme cosmologies would sharply reduce the number of useful sources in the two sub-samples!)—given the small numbers of sources involved we feel that a more elaborate analysis of the effect of cosmological parameters would not be useful.

5.2 *Steeper electron energy spectra at high redshifts*

The similar spectral curvature seen in the two samples is rather surprising. All the explanations for the spectral steepening with redshift invoke an increased steepening of the spectrum *in the rest frame* at higher redshifts due to a more rapid evolution of the synchrotron spectral break to lower frequencies which is not indicated by this data. Perhaps, one must also consider the possibility of steeper electron injection spectra at higher redshifts.

Synchrotron electrons are believed to be accelerated to ultrarelativistic energies by a first-order Fermi process at the shock front between the hotspot and the ambient medium. In the case of non-relativistic shocks, the index of the electron injection spectrum in this process, s (i.e $N(E) \propto E^{-s}$)is related to the Mach number, M, (through the compression ratio) of the shock front by $s = 2(M^2+1)/(M^2 - 1)$ for a monotomic gas (Longair 1994). The injection spectral index is given by $\alpha_i = (s - 1)/2$. This expression provides a lower limit of $\alpha_{\mathrm{i}} = 0.5$ (for strong shock conditions, i.e. $M \gg 1$). The observed lack of extended radio sources with spectral indices flatter than 0.5 is explained by this acceleration process.

A similar result has been shown in the case of relativistic shocks. For example, Kirk & Schneider (1987) show that the electron energy index is a very sensitive function of the bulk velocity upstream of the shock. Starting with $s \approx 2$ ($\alpha = 0.5$) for velocity $\sim c$, the spectrum steepens to $s = 2.8$ and 3.6 (i.e. $\alpha = 0.9$ and 1.3) for velocities of 0.9c and 0.8c respectively.

Thus, in the case of radio sources, any reduction in the bulk velocity of plasma, would result in the production of electrons with a steeper energy distribution. This would be true in the diffuse regions in radio lobes (non-relativistic shocks) as well as in the vicinity of hotspots (relativistic shocks).

The conditions at higher redshifts may well result in steeper electron spectra. We know that linear sizes of radio sources decrease with redshift (Oort *et al.* 1987; Kapahi 1987; Athreya 1996). This is usually taken as evidence of lower expansion speeds due to higher gas density at high redshifts (for e.g. Swamp & Subramanian 1990; Gopal-Krishna & Wiita 1990). The phenomenon of cluster cooling flows suggests that the temperature of the ambient medium evolves with redshift. At higher redshifts, the radio jet would have to work against the higher pressure of the denser and hotter circumgalactic medium. This would slow down the hotspot propagation speed as well as the bulk flow of the jet material behind the hotspot. Consequently, Fermi acceleration would lead to steeper electron energy distributions. In this model, the large scatter seen in the redshift-spectral index plot reflects the object-to-object variation of the temperature and density of the circumgalactic (or intracluster) medium.

It also follows from this model that one should not see any correlation between redshift and spectral index at very low redshifts which is indeed the case (for example, Laing & Peacock 1980). As the circumgalactic gas density and temperature decrease at low redshift, the electron index rapidly tends towards the asymptotic value.

An additional pointer to steeper electron injection spectra at high redshifts is the steep spectral index values at high frequencies. Synchrotron radiation results in a faster depletion of high energy electrons and a progressive steepening of the high frequency spectrum from its initial a corresponding to the injected (i.e. unmodified) electron spectrum. Under conditions of a continuous replenishment of ultra-relativistic particles, as is most probably the case in these active radio sources, it has been shown that the spectral index at high frequencies cannot be steeper by more than 0.5 of the value corresponding to the initial electron spectrum (Pacholczyk 1970). The median α of 1.31 at 16 GHz (rest frame) suggests that the median α corresponding to the initial electron spectrum is ≥ 0.8.

6. Conclusion

- A comparison of the spectra of sub-samples of matched luminosity radio galaxies from the 3CRR and the MRC/1Jy samples indicates that spectral index correlates primarily with redshift; the luminosity dependence, if any, is not likely to be significant.
- It is suggested in this paper that the electron energy spectrum at injection itself may be steeper at higher redshifts; we have also shown that the typical values of the relevant parameters for radio sources are indeed in the right ballpark to make such a model plausible. However, the idea needs to be worked out in detail.

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