Radio Galaxies from the MRC/1Jy sample

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Abstract

We present here the newly defined MRC/1Jy sample comprising 557 extragalactic radio sources. We discuss the evolution of linear sizes and radio spectral index of radio galaxies and the steep spectrum radio cores and large rotation measures observed in MRC/1Jy galaxies at z > 2.

1 The MRC/1Jy Sample

We have defined a new complete sample of extragalactic radio sources, the MRC/1Jy sample, comprising 557 radio sources (see Kapahi et al 1998 and McCarthy, this volume, for details). The results presented here highlight the motivation behind the definition and the study of this sample, viz. (i) The discovery and study of an unbiased sample of high redshift galaxies (in particular, without using the steep spectrum criterion) and (ii) the definition of a large and complete sample of extragalactic radio sources with complete optical identification and redshift information for statistical studies.

The sample consists of 111 quasars and 423 galaxies, apart from 24 unidentified radio sources. Spectroscopic redshifts are now available for 103 quasars and 268 galaxies; another 130 galaxies have K-magnitude redshift estimates.

To date, the 3CRR is the only large sample of extragalactic radio sources with complete optical identification and redshift information. However, the tight correlation between redshift and luminosity in the 3CRR (as in any other flux limited sample) makes it very difficult to disentangle the dependences of radio source properties on these two parameters. The MRC/1Jy sources were selected to be ~5 times fainter than the 3CRR sources. A comparison of sources in the two samples would assist in separating the redshift and luminosity dependences.

2 MRC/1Jy galaxies at z > 2

A representative sample of 15 galaxies at z > 2 were studied in the radio using the VLA. The multifrequency polarisation images were used to study their morphological, spectral and polarisation properties. See Athreya (1996) and Athreya et al. (1997, 1998) for detailed analyses of the results presented below.

2.1 Steep Spectrum Radio Cores

In sharp contrast to the flat spectra of radio cores in almost all galaxies at lower redshifts, we find that 8 of the 12 galaxies at z > 2 have a steep spectrum core (Figure 1). The flat spectra of radio cores are believed to arise from the superposition of synchrotron self-absorbed spectra of multiple components contained within. In this model, the core spectrum is expected to steepen above the turnover frequency, ν_{SSA}, of the smallest component. We can understand the steep spectrum cores at high redshift if the rest-frame frequencies (15–30 GHz) at which they have been studied are higher than ν_{SSA}. In fact, the flat spectra of quasar cores are known to steepen but at much higher rest-frame frequencies.

An increase in the rest-frame ν_{SSA} as one goes from radio galaxies to quasars is to be expected in the context of the unified scheme (Barthel 1989). We suggest that in the rest-frame of the jet, cores have flat spectra at $\nu \lesssim 20$ GHz but steepen at higher frequencies. However, the cosmological rest-frame (**crf**) of a source is different from the rest frame of the emitting plasma. The intrinsic ν_{SSA} in the plasma frame is blueshifted to higher frequencies in the **crf** for quasars and redshifted for galaxies due to the different angles made by their jet axes to the line of sight — quasar axes are aligned closer to the line of sight while those of galaxies are closer to the sky plane.

Using the theory of synchrotron self-absorption and the observed spectra, we derived estimates of the size (~1 parsec), magnetic field (~1 gauss) and the electron density (~1000 cm^{-3}) for the radio cores of both galaxies and quasars. We emphasize that the identification of ν_{SSA} for galaxy cores provides us with

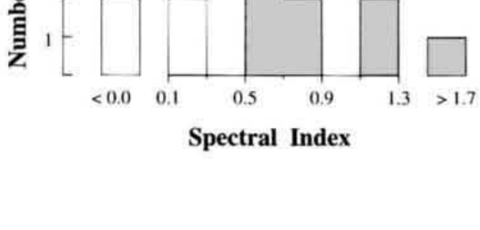

Figure 1. Radio core spectral indices ($\alpha^{4.7GHz}_{8.4GHz}$ Obs. frame) of galaxies at z > 2.

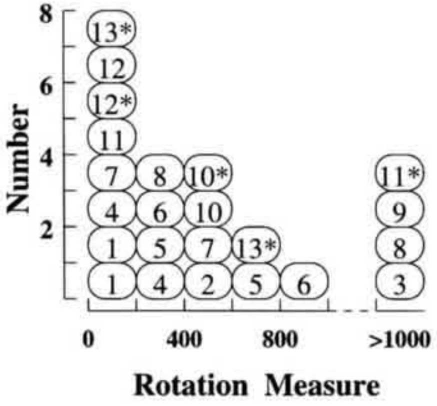

Figure 2. Intrinsic Rotation measures ($\mathrm{rad\,m^{-2}}$) of the radio lobes of galaxies at $z > 2$. The lobes of the same source have the same number. An asterisk (*) indicates a negative value.

a size estimate which is a 100 times smaller than the telescope resolution; this phenomenon is therefore very useful for estimating the physical parameters of radio galaxy cores which are usually too weak to be studied by VLBI.

2.2 Large Rotation Measures

We find that the circumgalactic media of these radio sources form deep Faraday screens with RMs of over $1000\,\mathrm{rad\,m^{-2}}$ in several, the highest being 1138–262 at $z = 2.17$ with $\gtrsim 6000\,\mathrm{rad\,m^{-2}}$(Figure 2). In comparison, most galaxies at low redshifts have RMs less than a few tens $\mathrm{rad\,m^{-2}}$. A small fraction of radio sources at low redshifts also have very high RMs of many thousands $\mathrm{rad\,m^{-2}}$. These high RM sources at low redshifts are either found in dense cooling-flow clusters or are compact (sub-galactic size) radio sources. Such high RM values require strong and large scale magnetic fields (the product of the field and the correlation length $\sim$ 10–100 μG-kpc) in the extended environments of these sources. It is still not clear what processes can generate and maintain fields of that magnitude in the intracluster medium. In most models, magnetic fields are generated by an exponential amplification of a seed field over the Hubble time to their value in present day clusters. However, the presence of such strong large-scale fields even at $z > 2$ poses a considerable problem; the Universe was only a sixth of its present age by $z \sim 2.5$ and models involving an exponential amplification of the seed field would hardly provide any field by those redshifts.

The association of large RMs with cooling-flow clusters at low redshift suggests that cooling-flows may be responsible for the Faraday rotation. However, we find that the available time at high redshifts is insufficient to set up massive cooling-flows by those epochs and cooling-flows are unlikely to have a significant role in forming deep Faraday screens at $z > 2$. We suggest that the Faraday screens in these high redshift sources are dense sub-galactic clouds of magnetised plasma in the path of the radio jet. The passage of the bowshock of the jet would increase the plasma density, align and possibly even magnify the magnetic field; all these factors could considerably increase the RM of the cloud compared to its unshocked state. This model, in which the screen is local to a radio lobe, is better for explaining the large lobe-to-lobe difference in RM within a radio galaxy, rather than a global screen like a cooling flow.

2.3 Redshift – Radio spectral index correlation

While the correlation between spectral index and redshift/luminosity has been exploited intensively to search for galaxies at high redshift, the reason behind it is still not well understood. Since our galaxies at $z > 2$ were selected from a complete sample, unbiased by the steep spectrum criterion, we have compared them with a set of matched luminosity 3CRR galaxies at a lower redshift to disentangle the luminosity–redshift degeneracy of the dependence of α.

We calculated the 1-pt spectral index, which is the tangent to the spectrum, at several rest-frame frequencies between 1 and 16 GHz (as against the usual 2 frequency α, which is only an approximation used in the absence of adequate frequency sampling). Figure 3 shows that the median spectral indices for the MRC galaxies are significantly steeper than the values for the lower redshift 3CRR galaxies. Since the two samples are matched in luminosity, this indicates the primary correlation of α is with redshift. The data at 1.4 GHz is best fit by $\alpha = (0.82 \pm 0.08) + (0.40 \pm 0.20) \log(1+z)$. This relationship accounts for much of the spectral steepening indicating that a luminosity– α correlation, if it exists, is not very important.

Most explanations for the redshift – α correlation involve a steepening of the spectra due to more rapid electron energy losses at higher redshifts. However, Figure 3 shows no significant difference in the rate of steepening in the two samples. We propose that the steeper spectra of high redshift sources may be due to steeper initial electron spectra. This is also indicated by the very steep $\alpha \simeq 1.3$ at high frequencies which suggests that the initial α (at low frequencies) must be as high as 0.8 (the difference being the maximum allowed by synchrotron theory for an active source). In a Fermi process, the acceleration in shock-fronts with lower Mach numbers results in steeper spectra. It is possible that the denser ambient medium at high redshift slows the propagation of the jet resulting in lower Mach numbers and steeper spectra.

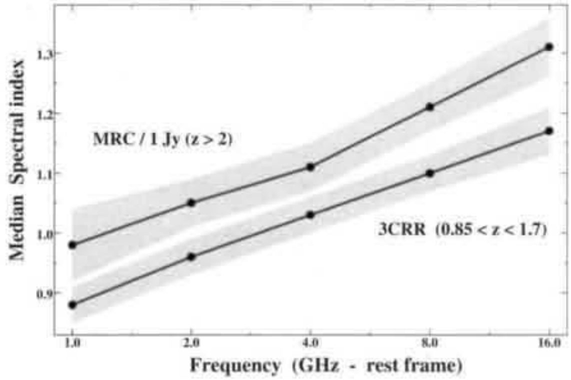

Figure 3. Median rest frame spectral indices of matched luminosity radio galaxy samples. The shaded areas indicate the errors.

3 Linear Size Evolution of Radio Galaxies

By comparing the linear sizes of MRC/1Jy and 3CRR galaxies we find that the median linear size is given by $L_{med} = 317^{370}_{272}\ P_{27}^{0.33\pm0.05}\ (1+z)^{2.81\pm0.26}$ for $H_o = 50\,km\,s^{-1}\,Mpc^{-1}$ and $q_o = 0.5$. When compact steep spectrum (CSS) sources ($<$ 20 kpc) are excluded the dependence is $L_{med} = 296^{349}_{251}\ P_{27}^{0.18\pm0.09}\ (1+z)^{1.58\pm0.33}$

Different workers have reached different conclusions on the magnitude and even the nature of the size evolution (e.g. Singal 1993; Eales, this volume). The major drawback of all studies has been the unavailability of a large and complete sample with full redshift information to complement the 3CRR. An examination of Figure 4 throws some light on the reasons behind the conflicting claims. The redshift and luminosity dependences are interlinked and an error in the estimation of one will reflect on the other. So, statistical errors and biases introduced by small and/or incomplete samples could have led to the conflicting results. Further, the luminosity and redshift dependences are such that they tend to cancel each other. An examination of the 3CRR data alone suggests (erroneously) that linear sizes are independent of redshift and luminosity. However, the plot also shows that MRC galaxies, which are less luminous, are also smaller at all redshifts. Accounting for this luminosity dependence necessitates an inverse dependence on redshift as well.

It is also not clear whether CSS sources should be included in the analysis or not. The answer is important since the CSS content of radio source samples is a

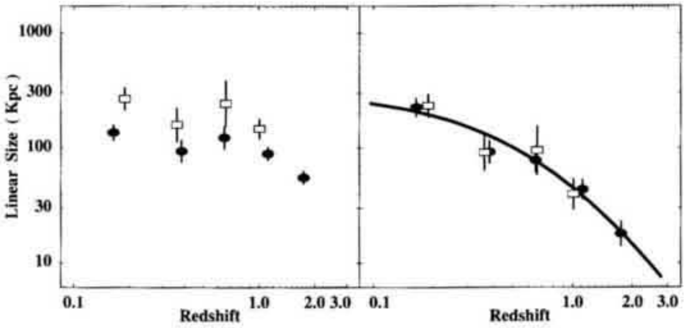

Figure 4. Median linear sizes of radio galaxies (3CRR: open rectangles; MRC/1Jy: dark ellipses). The median sizes plotted in the left panel are plotted in the right panel after being normalised to $P = 10^{27}$ Watt Hz^{-1}. The solid line is the best fitting size evolution equation given in the text.

function of their selection frequency and flux limit. The 3CRR has hardly any CSS sources while 20 % of MRC/1Jy galaxies are CSS sources. If the nature of CSS sources is in fact different from that of extended sources, then the evolution we have derived by excluding the CSS represents a lower limit to the evolution of extended sources (since any size evolution would result in some of the extended sources masquerading as CSS sources at high redshifts).

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