ON THE INJECTION SPECTRUM OF RELATIVISTIC ELECTRONS IN HIGH-REDSHIFT RADIO GALAXIES

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ABSTRACT

We point out that the remarkable linearity of the ultra-steep radio spectra of high-redshift radio galaxies reflects a previously reported general trend for powerful radio galaxies, according to which the spectral curvature is less for sources having steeper spectra (measured near rest-frame 1 GHz). We argue based on existing theoretical and observational evidence that it is premature to conclude that the particle acceleration mechanism in sources having straight, ultra-steep radio spectra gives rise to an ultra-steep injection spectrum of the radiating electrons. In empirical support for this we showed that the estimated injection spectral indices available for a representative sample of 35 compact steep spectrum radio sources are not correlated with their rest-frame (intrinsic) rotation measures, which are known to be typically large, indicating a dense environment, as is also the case for high-z radio galaxies.

Key words: galaxies: active – galaxies: clusters: intracluster medium – galaxies: high-redshift – galaxies: ISM – galaxies: jets – radio continuum: galaxies

1. INTRODUCTION

A few decades ago it was noted that radio galaxies having steeper decimetric spectra tend to appear optically fainter and smaller in radio angular size (Tielens et al. 1979; Blumenthal & Miley 1979; Gopal-Krishna & Steppe 1981; see also, Pauliny-Toth & Kellermann 1968). Since then, ultra-steep radio spectrum ($\alpha < -1.1$, $S_{\nu} \propto \nu^{\alpha}$) has been exploited as a remarkably effective tool for finding high-z radio galaxies (hereafter HzRGs; see the review by Miley & De Breuck 2008), although a few extremely distant radio galaxies with a normal radio spectrum have also been discovered (e.g., Jarvis et al. 2009; Lilly 1988).

Until the 1970s, sources having ultra-steep radio spectra were almost exclusively found in nearby rich clusters of galaxies (e.g., Slingo 1974a, 1974b). This clear trend continues to be witnessed in much larger samples of radio galaxies (e.g., Bornancini et al. 2010). From early on, the association of such sources with denser galaxy environments has been attributed to radiative aging of the relativistic plasma in the radio lobes whose detectability, however, gets prolonged beyond about $10^8$ yr due to an effective confinement by the pressure of the hot ambient gas, the intracluster medium (ICM; Baldwin & Scott 1973). Tielens et al. (1979) indeed drew a distinction between the low power Ultra Steep Spectrum Radio Sources (USSRS) found in nearby clusters and the radio luminous high-z USSRS by pointing out that the ultra-steep spectral index of the former was defined in the meter/decameter wavelength range, while for the high-z USSRS it referred to the decimeter regime.

Salient explanations suggested for the observed propensity of HzRGs to be USSRS are the following.

1. Radio spectra of powerful RGs at medium redshifts typically show a downward curvature (e.g., Laing et al. 1983; see also, Murgia et al. 2002; Kühr et al. 1981; Bornancini et al. 2007), as already reported for the well known powerful radio galaxies Cygnus A (e.g., Mitton & Ryle 1969) and 3C 295 (Kellermann et al. 1969; Jones & Preston 2001).

Therefore, a “radio K-correction” could be substantial and cause the radio spectra of HzRGs to appear steeper in a given radio-frequency band (e.g., Bolton 1966; De Breuck et al. 2000; Jarvis et al. 2004; see, however, Klammer et al. 2006; Miley & De Breuck 2008). The downward spectral curvature is expected to be even stronger for HzRGs, due to increased inverse Compton losses in a much stronger cosmic microwave background (e.g., Rees & Setti 1970; Gopal-Krishna et al. 1989; Krolik & Chen 1991; Martínez-Sansigre et al. 2006). Some empirical evidence for this was reported, based on an analysis employing, for the first time, the rest-frame radio spectra of powerful radio galaxies (Gopal-Krishna 1988; see also van Breugel & McCarthy 1990; Athreya & Kapahi 1998). However, the alternative explanation invoking the correlation between spectral steepness and radio luminosity cannot at present be excluded (e.g., Pauliny-Toth & Kellermann 1968; Gopal-Krishna & Wiita 1990 and references therein, Krolik & Chen 1991). In this case, Malmquist bias could spuriously cause the correlation of ultra-steep radio spectrum with redshift (e.g., Blundell et al. 1999).

2. The other possibility is that the radio spectra of HzRGs are intrinsically steeper because, like the USSRS in nearby clusters, the HzRGs are aging in denser galaxy environments (see above). There is indeed growing evidence, e.g., from Ly$\alpha$ imaging, that HzRGs are located in overdense regions in the early universe; they are often seen to be surrounded by protoclusters (Miley & De Breuck 2008 and references therein). Another key piece of evidence for the putative dense gaseous medium surrounding HzRGs comes from radio polarimetric measurements that often reveal very large rotation measures (RMs) for the RGs with $z > 2$; typical values of intrinsic RM are $>500$ rad m$^{-2}$ (e.g., Carilli et al. 1994, 1997; Athreya et al. 1998; Pentericci et al. 2000).

3. An alternative to the above suggestions, motivated by the dense environments of HzRGs combined with the remarkable straightness of their spectra from meter to centimeter wavelengths (Section 3), is that the particle acceleration process in their hot spots leads to abnormally steep energy spectra of the injected electrons (Athreya & Kapahi 1998; Klammer et al. 2006). In this paper we revisit this view point.
2. DO HzRGs HAVE AN ULTRA-STEEP INJECTION SPECTRUM?

A potentially useful clue to the physical mechanism in HzRGs emerges from their similarity in radio luminosity and RM to the so-called compact steep spectrum (CSS) radio galaxies, suggesting that the two classes of radio galaxies arise from powerful jets propagating in dense environments (see below). Typically, the powerful CSS radio galaxies of Fanaroff–Riley class II (FR II, Fanaroff & Riley 1974) extend just to the Galactic scale, i.e., no larger than ~15 to 20 kpc, and account for nearly 15% and 30% of the bright radio sources in samples selected at meter and decimeter wavelengths, respectively (Kapahi 1981; Peacock & Wall 1982; Gopal-Krishna et al. 1980; see also O’Dea 1998; Saikia et al. 2001). Radio polarimetry of CSS sources has revealed that their intrinsic RMs are typically very large (median around 500 rad m$^{-2}$), compared to the normal population of FR II radio galaxies which are more extended (e.g., Mantovani et al. 2009; see also O’Dea 1998; Rossetti et al. 2006). This reinforces the view that the jets in CSS RGs are still propagating through a considerably denser ambient medium, namely the interstellar medium (ISM) of the host galaxy, akin to the situation envisaged for HzRGs (Section 1). The question posed in this paper then translates to asking whether any evidence exists for the relativistic particles in CSS RGs to have an ultra-steep energy injection spectrum (i.e., much steeper than the canonical value which corresponds to $\alpha = -0.5$ to $-0.7$)?

In this context, we note that Murgia et al. (2002) have presented detailed synchrotron modeling of the radio spectra of a fairly large set of 45 lobe-dominated, broadly symmetric double radio sources with sizes less than ~15 kpc. The spectra used in their analysis of these CSS sources span a wide frequency range from 74 MHz to 230 GHz. Spectral flattening toward higher frequency is rarely observed in their sample and, typically, the spectra are seen to steepen with frequency, with the spectral index changing by $\Delta \alpha \sim 0.5$. This is reminiscent of the spectral break observed near 2 GHz in the powerful CSS RG 3C 295 which is a ~5 arcsec double radio source (e.g., Perley & Taylor 1991) identified with the central galaxy of a rich cluster at $z = 0.46$ (see Figure 5 in Jones & Preston 2001). For their sample of 45 symmetric CSS RGs, Murgia et al. have further shown that the radio spectra are generally well fit by a synchrotron aging model with continuous injection of synchrotron plasma (Kardashev 1962; Kellermann 1964). The injection spectral indices, $\alpha_{\text{inj}}$, estimated in their analysis range between $-0.35$ and $-0.8$, with a median value of $-0.63$ (Table 1). Note that the range in $\alpha_{\text{inj}}$ can be partly attributed to uncertainties in the analysis procedure. At frequencies well above the spectral break, the spectral index steepens to values $<-1$ and therefore the source would be readily classified as USSRS if the spectral measurements sampled mainly the steepened segment of the radio spectrum (e.g., due to the spectral bend having already drifted out of the radio window typically sampled; see, e.g., Murgia et al. 2002).

Thus, based on the above detailed spectral modeling, there is at present no credible evidence for an ultra-steep injection spectrum in symmetric CSS RGs and, by inference, also for HzRGs which are also radio-powerful and situated in a fairly dense environment (Section 1). This point is further examined below.

3. LINEARITY OF RADIO SPECTRA IN HzRGs

Given that the radio spectra of a large majority ($\sim$70%) of powerful 3CR radio galaxies, which are located at moder-

\begin{table}[h]
\centering
\caption{Parameters of the 35 CSS Sources with Known RMs}
\begin{tabular}{cccccc}
\hline
Source Name & $\alpha$ & $\Delta \alpha$ & $|RM|$ & $\Delta |RM|$ & Ref. \\
\hline
0127+23 & 1.46 & 0.76 & 105 & 590 & 635.4 & b \\
0134+32 & 0.37 & 0.15 & 197 & ... & 148.3 & a \\
0221+67 & 0.31 & 0.56 & 1 & ... & 1.7 & a \\
0316+16 & 1.00 & 0.81 & 246 & 6 & 984 & g \\
0345+33 & 0.24 & 0.58 & 339.1 & 9.2 & 521.4 & h \\
0429+41 & 1.02 & 0.49 & 1813 & 47 & 7397.8 & b \\
0518+16 & 0.76 & 0.47 & 1 & ... & 3.1 & a \\
0538+49 & 0.55 & 0.44 & 1648 & 117 & 3959.3 & b \\
0740+38 & 1.06 & 0.75 & 40 & 11.3 & 169.7 & c \\
0758+14 & 1.2 & 0.79 & 114 & 14 & 551.8 & g \\
1005+40 & 0.88 & 0.57 & 141 & 5 & 498.3 & d \\
1019+22 & 1.62 & 0.77 & 18 & 20 & 123.5 & d \\
1203+64 & 0.37 & 0.66 & 86 & 11 & 161.4 & d \\
1250+56 & 0.32 & 0.39 & 93.7 & 8.5 & 163.3 & h \\
1328+30 & 0.85 & 0.38 & 0 & 1 & 0 & i \\
1328+25 & 1.06 & 0.47 & 148 & 0.8 & 628 & a \\
1416+06 & 1.44 & 0.5 & 42.5 & 1 & 253.0 & c \\
1443+77 & 0.27 & 0.64 & 24 & 13 & 38.7 & g \\
1447+77 & 1.13 & 0.62 & 57 & 10 & 258.6 & d \\
1458+71 & 0.9 & 0.65 & 60 & ... & 216.6 & a \\
1517+20 & 0.75 & 0.69 & 498 & ... & 1525.1 & a \\
1607+26 & 0.47 & 0.71 & 16 & 2.5 & 34.6 & h \\
1634+62 & 0.99 & 0.65 & 21.9 & 10.5 & 86.7 & h \\
1637+62 & 0.75 & 0.62 & 186.7 & 16.1 & 571.8 & h \\
2248+71 & 1.84 & 0.69 & 49 & 2 & 395.2 & d \\
2249+18 & 1.76 & 0.72 & 88 & ... & 670.3 & a \\
2252+12 & 0.54 & 0.62 & 68 & ... & 161.3 & a \\
2258+04 & 0.55 & 0.53 & 164.9 & 15.9 & 396.2 & f \\
1025+390B & 0.361 & 0.65 & 41.7 & 3.3 & 77.2 & f \\
1233+418 & 0.25 & 0.51 & 10 & ... & 15.6 & e \\
1350+432 & 2.149 & 0.84 & 152 & ... & 1507.3 & e \\
\hline
\end{tabular}
\end{table}
jet speed in FR II sources remains relativistic all the way to the terminal hot spot. These estimates imply an upward revision of the bulk velocity from about 0.6c inferred for kiloparsec-scale jets by Wardle & Aaron (1997).

An appropriate treatment of the first-order Fermi acceleration of relativistic plasma with underlying relativistic bulk flow was also considered by Kirk & Schneider (1987) who generalized the same problem considered earlier by Blandford & Ostriker (1978) for non-relativistic bulk velocities. The essential result is displayed in Figure 5 of their paper which plots $(3 - 2\alpha_{\text{inj}})$ against the upstream velocity, $v_1$ (approximately the jet velocity). Taking $v_1$ in the range $(0.9–1) c$, as justified above, and interpolating between the curves computed for the two models (with and without isotropization of pitch angles) yields a narrow range for $\alpha_{\text{inj}}$ between $-0.55$ and $-0.65$, with the latter value corresponding to the anisotropic case. This is in excellent agreement with the typical injection spectral index estimated empirically by Murgia et al. (2002) for their sample of CSS sources. On the other hand, for a jet velocity of $0.8c$, their Figure 5 indicates that $\alpha_{\text{inj}}$ can be as steep as $-1.3$, mirroring the claim by Athreya & Kapahi (1998), who hypothesize lower upstream (jet) velocities $v_1$ in HZRGs due to their denser environment. However, the link between larger ambient density and bulk speed of the jet remains unclear within the canonical picture of FR II sources where a cocoon of relativistic plasma surrounds the relativistic jet and protects it from the ambient medium. As stated earlier, Georganopoulos & Kazanas (2003) argue that the bulk speed even in kiloparsec-scale jets remains relativistic ($v_1 \sim c$) all the way up to the shock preceding the terminal hot spot where most of the particle acceleration occurs (see also Mullin et al. 2008).

Interestingly, a denser ambient medium at high redshifts (e.g., Klamer et al. 2006) might even yield a flatter injection spectrum. This is because in the first-order Fermi process a higher ambient density would increase the probability $P$ of the particles in the downstream to remain within the acceleration region without enhancing the fractional energy gain per crossing (hence maintaining a constant $\beta$, where $E = E_0\beta^8$ at the $k$th crossing as determined by the upstream and downstream velocities; Bell 1978; Longair 1994). Heuristically, it means that $s = 1 - \Delta n P / \Delta n \beta$ would decrease, implying a flatter $\alpha_{\text{inj}}$. Thus, at least on theoretical grounds there appears to be no compelling reason to expect a steeper $\alpha_{\text{inj}}$ due to a denser ambient medium.

We next look for any empirical clue to test the suggestion that first-order Fermi acceleration operating within the hot spots of FR II radio sources injects a steeper electron energy spectrum if the jets are expanding against a denser ambient medium. We shall employ the empirically determined quantity, RM, which is also widely used as an indicator of the ambient density. It is known that very high RMs are common for HZRGs (see above) and also for radio sources residing in the cores of cooling flow clusters (e.g., Carilli & Taylor 2002; Clarke et al. 2001; Taylor et al. 1994). Thus, based on the plausible premise that a large RM is a reliable indicator of a dense environment, we proceed to check if indeed the denser ambient medium associated with CSS RGs results in a steeper injection spectrum of relativistic electrons in their hot spots. For the 45 FR II CSS RGs in the Murgia et al. (2002) sample (Section 1), for which $\alpha_{\text{inj}}$ values have been estimated in their study, we have carried out a literature search to obtain RM values. The search was successful for 35 of the 45 sources and those estimates are listed in Table 1. The corresponding diagram showing the intrinsic
(rest-frame) values of $\text{RM}_{\text{int}} = \text{RM}(1+z)^2$ against $\alpha_{\text{inj}}$ is displayed in Figure 1. We believe this subset of 35 sources to be representative of the parent sample of 45 CSS RGs (since the availability of RM estimates in the literature was our sole criterion for deriving the subset).

From Figure 1 no conspicuous trend is apparent to support the case that a higher RM should correlate with a steeper injection spectrum of the radiating particles. The Spearman rank correlation test gives a correlation coefficient of just 0.132, amounting to a $p$ value (from the Student $t$ distribution) of 0.24, supporting the null hypothesis that $\alpha_{\text{inj}}$ is uncorrelated with $\text{RM}_{\text{int}}$. Also, using a Fisher transformation to find the significance and applying the result to the normal distribution, the probability that they are uncorrelated turns out to be 0.83. Thus, the evidence emerging from this admittedly limited (but expectedly representative) sample does not support the assertion that steeper injection spectra are generic to HzRGs. Given the importance of this issue, it would be valuable to extend the RM and radio spectral measurements to the larger samples of CSS and HzRG sources.

4. CONCLUSIONS

Using both observational and theoretical perspectives about classical double radio sources, we have argued that the straightness of ultra-steep radio spectra of HzRGs, highlighted by Klamer et al. (2006), is likely to manifest the late stage of radio spectral evolution, instead of an ultra-steep injection spectrum of the relativistic electron population. The latter possibility has been favored by some authors in view of the likelihood of HzRGs residing in denser environments compared to moderately distant FR II radio galaxies (see Klamer et al. 2006; Athreya & Kapahi 1998). In the context of such FR II sources, the theory of first-order Fermi acceleration at relativistic shocks compressing relativistic jet fluid could indeed yield a very steep injection spectrum ($\alpha_{\text{inj}} < -1.3$) for upstream bulk speeds of $\leq 0.8c$. However, on theoretical grounds, such modest speeds are not favored for the large-scale jets typical of HzRGs (e.g., Wang et al. 2011). Also, the well-known association of ultra-steep radio spectra with cluster radio sources is widely interpreted in terms of prolonged synchrotron losses enabled by a dense ambient ICM whose presence is independently inferred from the very large RM values (Clarke et al. 2001; Carilli & Taylor 2002).

Interestingly, very large RM values are also found to occur for another class of FR II radio galaxies called CSS sources which are also therefore believed to lie in dense environments. We have highlighted a study of 45 CSS sources by Murgia et al. (2002) in which they have modeled the radio spectra and found $\alpha_{\text{inj}}$ to lie in the range $-0.35 \leq \alpha_{\text{inj}} \leq -0.8$, with a median value of $-0.63$. We have shown here that the intrinsic RMs of these sources do not correlate with $\alpha_{\text{inj}}$ as estimated by Murgia et al. (2002). Thus, the observed remarkable straightness of the ultra-steep radio spectra of HzRGs, instead of being an outcome of very steep injection spectra, is more likely a result of the spectral bend caused by radiative losses that has drifted out of the standard window to sub-GHz frequencies. Such an interpretation would also be consistent with the empirical finding that for FR II sources, in general, a steeper radio spectrum at decimeter wavelengths is anti-correlated with spectral curvature (Mangalam & Gopal-Krishna 1995).

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REFERENCES

Athreya, R. M., & Kapahi, V. K. 1998, J. Astrophys. Astron., 19, 63
Athreya, R. M., Kapahi, V. K., McCarthy, P. J., & van Breugel, W. 1998, A&A, 329, 809
Baldwin, J. E., & Scott, P. F. 1973, MN+As, 165, 259
Bell, A. R. 1978, MNRAS, 182, 443
Blandford, R. D., & Ostriker, J. P. 1978, ApJ, 221, L29
Blumenthal, G., & Miley, G. 1979, A&A, 80, 13
Blandell, K. M., Rawlings, S., & Willott, C. J. 1999, AJ, 117, 677
Bolton, J. G. 1966, Nature, 211, 917
Bornancini, C. G., De Breuck, C., de Vries, W., et al. 2007, MNRAS, 378, 551
Bornancini, C. G., O’Mill, A. L., Gurovich, S., & Lambas, D. G. 2010, MNRAS, 406, 197
Broten, N. W., MacLeod, J. M., & Valley, J. P. 1988, Ap&SS, 141, 303
Carilli, C. L., Owen, F. N., & Harris, D. E. 1994, AJ, 107, 480
Carilli, C. L., Roettgering, H. J. A., van Ojik, R., Miley, G. K., & van Breugel, W. J. M. 1997, ApJS, 109, 1
Carilli, C. L., & Taylor, G. B. 2002, ARA&A, 40, 319
Chambers, K. C., Miley, G. K., & van Breugel, W. J. M. 1990, ApJ, 363, 21
Clarke, T. E., Kronberg, P. P., & Böhringer, H. 2001, ApJ, 547, L111
Conway, R. G., Birch, P., Davis, R. J., et al. 1983, MNRAS, 202, 813
De Breuck, C., van Breugel, W., Röttgering, H. J. A., & Miley, G. 2000, A&A, 143, 303
Falle, S. A. E. G. 1991, MNRAS, 250, 581
Fanaroff, B. L., & Riley, J. M. 1974, MNRAS, 167, 31P
Fanti, C., et al. 2004, A&A, 427, 465
Garrington, S. T., Leahy, J. P., Conway, R. G., & Laing, R. A. 1988, Nature, 331, 147
Georganopoulos, M., & Kazanas, D. 2003, ApJ, 589, L5
Gopal-Krishna. 1988, A&A, 192, 37
Gopal-Krishna, Reuss, E., & Schilizzi, R. T. 1980, Nature, 288, 344
Gopal-Krishna, & Steppe, H. 1981, A&A, 101, 315
Gopal-Krishna, & Wiita, P. J. 1990, A&A, 236, 305
Gopal-Krishna, Wiita, P. J., & Saripalli, L. 1989, MNRAS, 239, 173
Inoue, M., Tabara, H., Kato, T., & Aizu, K. 1995, PASJ, 47, 725
Jarvis, M. J., Cruz, M. J., Cohen, A. S., Röttgering, H. J. A., & Miley, G. 2000, A&A, 331, 147
Jarvis, M. J., Teimourian, H., Simpson, C., et al. 2009, MNRAS, 398, L83
Jones, D. L., & Presto, R. A. 2001, ApJ, 551, 2940
Kapahi, V. K. 1981, A&A, 88, 809
Kapahi, V. K. 1981, A&AS, 43, 381
Kardashev, N. S. 1962, SvA, 6, 317
Kellermann, K. I. 1964, ApJ, 140, 969
