On the Origin of the Fanaroff–Riley Dichotomy

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Abstract. A small fraction of double radio sources show a peculiar and striking hybrid morphology; they have a distinctly FR I structure on one side of the nucleus, and a FR II structure on the other. We argue that the mere existence of these HYMORS is quite incompatible with the theoretical explanations for the Fanaroff–Riley dichotomy that are based upon the nature of the jet plasma, or those invoking an intrinsic property of the central engine. Rather, these HYMORS strongly support models that explain the difference between FR I and FR II sources in terms of asymmetry of interaction of the jets with the external environments. We further show that a model for radio source dynamics we had earlier proposed can neatly reproduce the observed dependence of the radio power dividing the two FR classes on the optical luminosity of the host galaxy, as found by Owen & White and Ledlow & Owen.

1. Introduction

The vast majority of extragalactic radio sources can be easily classified into the more powerful, edge-brightened FR II sources and the weaker, edge-dimmed FR I sources (Fanaroff & Riley 1974). The boundary between these classes in terms of monochromatic radio power was shown to rise with increasing optical luminosity of the host galaxy: $P_R^* \propto L_{\text{opt}}^{1.65}$ (e.g., Ledlow & Owen 1996, Fig. 1).

The large number of explanations for the Fanaroff-Riley dichotomy can be divided into intrinsic models, where some property of the central engine launches entirely different types of jets, and extrinsic models, where very similar jets are ejected in both FR classes but interactions with the environment determine their large-scale morphologies (Gopal-Krishna & Wiita 2000a — GKW00, and references therein). Among the better developed intrinsic models are those where: faster spinning black holes launch FR II jets and FR I jets come from slower spinning BHs; jet plasma is composed of $e^- - p$ for FR II's and $e^- - e^+$ for FR I's; advection dominated accretion disks yield FR I's while standard thin disks yield FR II's. Possible support for such models comes from the differences between the properties of the host galaxies of the two FR classes (e.g., Baum et al. 1995).
Various extrinsic models all argue that the jets differ, if at all, only in their power or thrust, so the morphological dichotomy arises from the differences in the interactions of the jets with the gaseous media. Weaker and/or poorly collimated jets, or those ploughing through a more disruptive environment, quickly lose their terminal hot-spots (Gopal-Krishna & Wiita 1988), or are subject to instabilities that dramatically increase the entrainment of ambient gas (e.g., De Young 1993; Bicknell 1984, 1995), both processes leading to a FR I morphology. Probably the strongest evidence for the basic similarity of the jets comes from the VLBI observations showing that the jets in most FR I, as well as FR II, radio sources start off with relativistic bulk velocities; however, only FR II jets are able to remain relativistic to very large distances (e.g., Laing et al. 1999 and references therein).

2. HYMORS Support Extrinsic Models

An observational clue for discriminating between the intrinsic and extrinsic models comes from HYbrid Morphology Radio Sources, or HYMORS (GKW00). These sources have a clearly FR I structure on one side of the host galaxy and a FR II structure on the other side. Some good examples gleaned from over 1000 published radio maps are listed in Table 1 (see GKW00 for maps and references). It is seen that HYMORS occur among all basic radio loud AGN types — QSR, BL Lac and radio galaxy (RG); their linear sizes range from subgalactic to ‘giant’; their powers are close to $P^*_R$. A few candidate HYMORS at higher redshift also exist and have powers above the nominal FR I/FR II break (GKW00).

HYMORS are extremely difficult to reconcile with radio jet models that rely upon intrinsic differences in the central engines to produce the FR dichotomy. This entire class of models would predict that both lobes of any double radio source are either FR I type or FR II type (rather than having distinctly different FR morphologies, as seen in HYMORS). On the other hand, within extrinsic models, modest differences in the clumpiness, density or velocity of the ambient medium on the two sides of the host galaxy could trigger the transition from a FR II jet to a slower jet producing a FR I appearance on one side (Gopal-Krishna & Wiita 1988; GKW00). The more asymmetrical gas distributions suspected in HYMORS may be detectable, e.g., with Chandra.

| Object       | Type       | $z$  | Size (arcmin) | Size (kpc) | Log ($L_R$) (1 GHz) W/Hz |
|--------------|------------|------|---------------|------------|--------------------------|
| 0131−367     | RG         | 0.029| 14.2          | 483        | 25.4                     |
| 0521−364     | BL Lac     | 0.055| 0.3           | 22         | 25.4                     |
| 1004+130     | QSR        | 0.240| 1.8           | 524        | 26.3                     |
| 1452−517     | RG         | 0.08 | 20.3          | 812        | 25.4                     |
| 1726−038     | RG (0.05)  |      | 0.6           | 35         | 24.8                     |
| 2007+777     | BL Lac     | 0.342| 0.6           | 213        | 24.8                     |

\[^a]H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}, Q_0 = 0.5, \text{ spectral index} = -1.
\[^b]Estimated \text{ redshift from POSS plate; see GKW00.}
3. The Radio Power Division and Host Galaxy Luminosity

The realization that only very powerful radio sources yield FR II morphologies if their host galaxies are highly luminous (e.g., Owen & White 1991; Ledlow & Owen 1996) begged for an explanation, and several were put forward. Although the ‘magnetic switch’ model (Meier 1999) can provide a decent fit to this $P_R \propto L_{\text{opt}}^{1.7}$ relation, as an ‘intrinsic’ model it is difficult to reconcile with the existence of HYMORS. Venturing well outside the standard jet paradigm, the gravitational slingshot mechanism does appear able to both produce HYMORS and roughly reproduce the Owen–Ledlow relation (Valtonen & Heinämäki 2000). Considering the growth of instabilities in relativistic jets in an ‘extrinsic’ jet model, Bicknell (1995) put forward a complex, but plausible, explanation for this $P_R - L_{\text{opt}}$ relation, though this model yields a slope of $\sim 2.1$.

Here, motivated by our earlier study of ‘Weak Headed Quasars’ (WHQs) (Gopal-Krishna, Wiita & Hooda 1996), we propose a variant ‘extrinsic’ scheme. We argued that the lack of a hotspot in WHQs could be best explained through the onset of a jet’s decollimation when the hotspot’s (or, nearly equivalently, the bow shock’s) velocity becomes transonic relative to the external medium and, therefore, the jet begins to advance like a plume. The concomitant cessation of the ‘backflow’ of the jet plasma accelerates entrainment into the jet, owing to the diminution of the protective cocoon around the jet which had hitherto separated the latter from the ISM material. This is further compounded by the weakening of the confining effect of internal reconfinement shocks in the jet engendered by impinging cocoon vortices (e.g., Hooda & Wiita 1998). These effects naturally produce FR I morphologies.

We follow Bicknell (1995) by making use of the same empirical relations between the elliptical’s blue magnitude, $M_B$, and its soft X-ray emission, $L_X$, stellar velocity dispersion, $\sigma$, and X-ray core radius, $a$. However, we adopt a jet propagation model which gives the hot-spot velocity, $v$, as a function of distance, $D$, from the central engine (Gopal-Krishna, Wiita, & Saripalli 1989):

$$v(D) = \frac{X c [1 + (D/a)^2]^{\delta/2}}{D + X [1 + (D/a)^2]^{\delta/2}},$$

(1)

Here $X = (4L_b/\pi c^3 \theta^2 n_0 m_p \mu)_{1/2}$, where $L_b$ is the jet (beam) power, $\theta$ is the jet’s effective opening angle, $m_p$ and $\mu$ have their usual definitions, and $n_0$ is the central density of the ISM, which is taken to fall off as (e.g., Canizares, Fabbiano, & Trinchieri 1987), $n(D) = n_0 [1 + (D/a)^2]^{-\delta}$. Observations give $\delta \simeq 0.75$ and $\theta \simeq 0.1$ rad; also, $n_0 \lesssim 1 \text{ cm}^{-3}$ (e.g., Conway 2000).

Noting that the transition to FR I morphology is typically seen to occur at or before $D = 10$ kpc, we equate $v(D^*) = c_s$ at $D^* \lesssim 10$ kpc. Clearly $c_s$ is related to $\sigma$, and empirically $\sigma$ depends directly on $M_B$, as does $a$; furthermore $n_0$ and $a(\sim 1 \text{ kpc})$ are related to $L_X$, which also depends on $M_B$. We derive and solve the following equation for $L_b$ (via $X$) as a function of $M_B$

$$\text{dex}(\log_{10} c_{\text{opt}} + 0.0959 M_B = \frac{X}{D^*/[1 + (D^*/a)^2]^{\delta/2} + X}.$$  

(2)

For $D^* = 10$ kpc, Eqn. (2) yields an approximate power-law: $L_b \sim L_{\text{opt}}^{1.56}$, normalized with $L_b^* = 3.6 \times 10^{42} \text{ erg s}^{-1}$ at $M_B = -21.0$. This produces an
excellent fit to the slope of the FR division in the Owen–Ledlow diagram if the efficiency, $\epsilon$, with which $L_b$ is converted to radio emission is essentially constant. The normalization is also good if $\epsilon \simeq 0.1$ (Gopal-Krishna & Wiita, 2000b, in preparation).

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