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Extragalactic radio sources with hybrid morphology: implications for the Fanaroff-Riley dichotomy

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Abstract. We provide observational and theoretical perspectives on the currently much debated issue of the Fanaroff-Riley (FR) morphological dichotomy of extragalactic radio sources. In this context we introduce a new, albeit rare, class of double radio sources in which the two lobes exhibit clearly different FR morphologies. It is argued that such 'HYbrid MOrphology Radio Sources', or HYMORS, could be used to effectively constrain the theoretical mechanisms proposed for the FR dichotomy. Basically, the existence of HYMORS supports explanations for the FR dichotomy based upon jet interaction with the medium external to the central engine, and appears quite difficult to reconcile with the class of explanations that posit fundamental differences in the central engine, such as black hole spin or jet composition, to be responsible for the two FR classes of double radio sources.

Key words: black hole physics – galaxies: active – galaxies: elliptical and lenticular, cD – galaxies: jets – galaxies: nuclei – radio continuum: galaxies

1. Introduction

A quarter of a century ago, using the first set of synthesis maps of 3CR radio sources, Fanaroff & Riley (1974) demonstrated that the morphology of extended double radio sources undergoes a relatively sharp transition across a critical radio luminosity, L_R^*, corresponding to $P_{178\mathrm{MHz}} \simeq 2 \times 10^{25} h_{50}^{-2}$ W Hz^{-1} sr^{-1}. Most sources below this luminosity exhibit FR I type structures, which are distinguished by diffuse radio lobes having their brightest regions within the inner half of the radio source. Such edge-dimmed radio sources include: fairly symmetrical twin-jets; fat doubles; Wide Angle Tail; and Narrow Angle Tail (or head–tail) sources. On the other hand, the more powerful FR II type double sources show less bending, and their brightness peaks occur near the outer edges of the two radio lobes, which are often identified as hot-spots. Interestingly, L_R^* was found to lie near the observed break in the radio luminosity function of elliptical galaxies (Meier et al. 1979) and also to correspond to a transition in the properties of nuclear optical emission lines (Hine & Longair 1979). More detailed studies based on improved radio maps later established that the radio luminosity separating FR I from FR II sources is actually a rising function of the optical output of the parent elliptical galaxy, $L_R^* \propto L_{\mathrm{opt}}^{1.7}$ (Owen & White 1991; Ledlow & Owen 1996).

The origin of the FR I/FR II dichotomy continues to be a much debated outstanding issue in the astrophysics of extragalactic radio sources (e.g., Scheuer 1996). Several authors have linked the morphological differences primarily to the transition of an initially supersonic, but relatively weak, jet to a transonic/subsonic flow decelerated substantially though entrainment of thermal plasma within the inner ($\sim$ 1 kpc) region of the host elliptical galaxy (e.g., De Young 1993; Bicknell 1984, 1994, 1995; Komissarov 1994; Bowman et al. 1996; Kaiser & Alexander 1997). In contrast, several others have argued in favor of more fundamental differences existing between the two classes, involving the nature of the central engine (e.g., Baum et al. 1992; Baum et al. 1995; Reynolds et al. 1996a; Meier et al. 1997, Meier 1999), or the possibility of composition of jet plasma being different, with e^-–e^+ plasma inferred for FR I sources (Reynolds et al. 1996b), while e^-–p jets may be preferred for FR II sources (Celotti et al. 1997). In our earlier work we had attributed the FR I/FR II dichotomy primarily to differences in the jet's power/thrust which, together with the properties of the circumgalactic medium, would determine how soon the advance of the hot-spot becomes subsonic relative to the ambient medium; this would lead to the disruption of the jet's collimation due to its weakened Mach disk (Gopal-Krishna & Wiita 1988; Gopal-Krishna 1991; also, Blandford 1996). Further evidence for this scheme, which assumes no fundamental differences between either the central engines or the jets of FR I and FR II sources, was presented by Gopal-Krishna et al. (1996), based on a representative set of Weak Headed Quasars. A growing body of VLBI observations also indicates similar jet velocities in FR I and FR II type sources close to the galactic nucleus (e.g., Giovannini et al. 1995; also Parma et al. 1987).

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The goal of this communication is to present a new type of evidence in favor of environmental factors being the primary determinant of the FR dichotomy. In order to do so, it is necessary that we first present perspectives of the observational status (Sect. 2) and theoretical inferences (Sect. 3) bearing on the question of the FR I/FR II dichotomy. We then endeavor to constrain some of the proposed theoretical explanations by introducing a new class of double radio sources, where the two lobes on the opposite sides of the galactic nucleus exhibit clearly different FR morphologies (Sect. 4). Although rare, these HYbrid MOrphology Radio Sources, or HYMORS, provide a valuable probe of the physical origin of the Fanaroff–Riley morphological divide. A brief report on this class was made in Gopal-Krishna & Wiita (2000). Our main conclusions are summarized in Sect. 5.

2. Observational aspects of the FR I/FR II dichotomy

Out of the vast amount of literature now available on this topic, we attempt here to recapitulate some of the prominent distinctions claimed to exist between the two FR classes. It is now well established that: FR II jets on kpc scales are distinctly more asymmetric and better collimated than FR I jets; the magnetic field in a FR II jet remains aligned with the jet along most of its length, while in a FR I jet the magnetic field is predominantly transverse on multi-kpc-scales (e.g. Bridle & Perley 1984). Also, the radio nucleus is more prominent in the FR I sources (e.g. Morganti et al. 1993); however, the difference vanishes if FR I and FR II sources of the same radio luminosity are considered (Zirbel & Baum 1995). VLBI measurements of nuclear jets, which often exhibit superluminal motions, strongly suggest that FR II jets are relativistic on parsec scales, and there are now many cases where FR I jets also appear to flow relativistically on such scales (Giovannini et al. 1995; Bridle 1996; Laing 1999; Biretta et al. 1999; Xu et al. 2000). Doppler boosting can explain the facts that powerful FR II jets appear one-sided while weaker FR I jets exhibit large brightness asymmetries only near their origins, and typically have short, one-sided basal regions (Bridle & Perley 1984; Parma et al. 1987). Moreover, the Laing-Garrington (e.g., Garrington et al. 1988) depolarization asymmetry is exhibited by the lobes of some FR I sources as well as by the FR II sources in which it was discovered (Parma et al. 1987; Laing et al. 1999). On the other hand, while the evidence for FR II jets retaining their relativistic bulk velocities up to the multi-kpc scale is very strong, with the brighter large scale jet always seen on the same side as the nuclear jet and towards the less depolarized radio lobe (Scheuer 1987; Garrington et al. 1988; Bridle 1996), the diffuse nature of FR I sources, the brightness asymmetries of their jets decreasing with distance from the core, and often, the strong bends seen in FR I jets, imply that much slower flows exist on larger scales (e.g., O'Dea 1985; Feretti et al. 1999; Laing et al. 1999, and references therein).

Soon after their discovery it was noted that FR I sources tend to be associated with dynamically evolved cD or D type galaxies in clusters; in contrast, the hosts of FR II sources at similarly small redshift appear to avoid rich clusters (Longair & Seldner 1979; Seldner & Peebles 1978; Prestage & Peacock 1988; Owen & Laing 1991; Zirbel 1997), but more frequently have companion galaxies and/or isophotal distortions which signify recent galaxy mergers (e.g., Heckman et al. 1986; Hutchings 1987; Baum et al. 1992; Zirbel 1997). Furthermore, the hosts of FR I's are found to have an excess in optical size (relative to radio-quiet ellipticals of the same optical magnitude) that correlates with L_R, while no such correlation is found for FR II's (Zirbel 1997). Hill & Lilly (1991) argued that the environment of FR II sources changes with cosmic epoch, in the sense that by moderately high redshifts ($z \sim 0.5$), they begin to be found inside rich clusters; also see Zirbel (1997). Recent work (McLure & Dunlop 2000; Wold et al. 2000), however, indicates that there may be negligible cosmological evolution of the environment, and that powerful AGN do not really avoid clusters, even at small redshifts. Similarly, the well known statistical trend for the host galaxies of FR II sources to be about 0.5 magnitude fainter than those of FR I sources (Lilly & Prestage 1987; Prestage & Peacock 1988; Smith & Heckman 1989; Owen & Laing 1991) has recently been explained as a selection effect arising from a combination of the $\sim L_{\rm opt}^2$ dependence of the radio power at the FR I/FR II transition and the steepness of the radio luminosity function of elliptical galaxies (Scarpa & Urry 2000).

Additional differences between the optical properties of the host galaxies of FR I and FR II sources have been noted. Although FR II's exhibit roughly an order of magnitude stronger optical line emission than do FR I's of the same radio luminosity, the optical line emission seems to correlate with the host's optical magnitude only for FR I's (Baum et al. 1992; Zirbel & Baum 1995). The indicated internal origin of the gas in FR I's would be consistent with the recently inferred origin of dusty material detected in FR I sources, which appears to be generated either within the elliptical host itself, or acquired in close encounters with gas-rich galaxies (in contrast to an origin through violent mergers in the case of FR II's) (de Koff et al. 2000). Further, in contrast to FR II's, only a weak correlation of optical line emission with L_R is found for FR I's (Baum et al. 1995). Spectroscopic observations have indicated that the kinematics of the ionized gas in FR I's is turbulence dominated, while some ordered bulk rotation is present in the ionized gas associated with FR II hosts, and this rotation axis tends to be aligned with the radio axis (Baum et al. 1992). The emission line ratios of these "rotator"-type nebulae found in FR II sources are consistent with photoionization by the nuclear continuum, since the [O I] 6300, [N II] 6584 and [S II] 6717 forbidden lines are very weak relative to Hα. Recent HST images of FR I nuclei reveal a deficiency of the thermal UV emission which is usually attributed to the nuclear accretion disk; this may account for the faintness of nuclear optical line emission (Chiaberge et al. 1999; also Zirbel & Baum 1995). Interestingly, Chiaberge et al. (2000) also found a similar situation for some of the FR II sources of modest radio luminosity.

Another notable difference between FR I and FR II hosts pertains to the amount of mid/far-IR (MFIR) emission: for samples matched in radio luminosity, FR II hosts typically have ~ 4 times stronger MFIR emission, perhaps attributable to nuclear starbursts induced by galaxy mergers, which is also consistent with the higher rate of occurrence of optical distortion found for the FR II host galaxies (Heckman et al. 1994).

3. Some theoretical considerations related to the morphological dichotomy

3.1. Jet deceleration

In light of the evidence for relativistic jet velocities persisting up to multi-kpc scales in FR II sources, coupled with the likelihood that the jets in both FR types start out with bulk relativistic speeds, many theoretical studies have stressed the need for deceleration of the jet flow in FR I sources. Begelman (1982) argued that viscous dissipation in jets can balance adiabatic heating and cause a rather rapid deceleration of weaker jets to transonic or subsonic speeds. These jets could remain undisrupted for substantial distances, thereby yielding typical FR I morphologies, provided the external pressure gradient is appropriately steep. De Young (1993) noted that the Owen-Ledlow transition from FR II to FR I at a fixed L_R and increasing $L_{\rm opt}$ could correspond to a supersonic (perhaps relativistic) jet being severely decelerated in the inner ~ 1 kpc of the parent galaxy, where more gas is likely to be available for entrainment. Plausibly, enough of such gas could arise from stellar winds, or perhaps from cooling flows onto the cD galaxies which often host FR I sources.

Bicknell (1984, 1994, 1995) focused on the idea that turbulent entrainment of cool interstellar medium at the jet boundary could dramatically decelerate a jet. His original work (Bicknell 1984) assumed non-relativistic FR I jets throughout, and ran into some difficulties (e.g., Laing et al. 1999). But the later model (Bicknell 1994, 1995), which assumed initially relativistic jets which eventually come into pressure balance with the external medium, is quite successful in reproducing many aspects of the observations. Bicknell argued that the instability to Kelvin-Helmholtz modes that would produce jet flaring, and thus an FR I morphology, tended to occur at Mach numbers of ~ 2 or flow velocities of ~ 0.6c. This result was shown to hold for wide ranges of initial relativistic velocities and of initial ratios of cold to relativistic matter in the jet (Bicknell 1995). By incorporating the known empirical relationships between the optical and X-ray properties of elliptical galaxies, Bicknell's (1995) model could effectively account for the observed slope (and approximate intercept) of the Owen-Ledlow boundary for the FR I/FR II transition in the L_R–$L_{\rm opt}$ plane. Self-similar models for radio source growth by Kaiser & Alexander (1997) feature a turbulent shear layer that could disrupt weaker jets, turning them from FR II into FR I type morphologies if the external density gradient was rather shallow. Komissarov (1994) and Bowman et al. (1996) also considered entrainment as leading to jet deceleration in FR I sources. Bowman et al. (1996) argued that FR I plasma was initially hotter and stressed the importance of cool stellar matter directly swept up by the jets. They showed that this could produce substantial deceleration, even if the jets were highly relativistic initially, without causing a precipitous dissipation of the jet's kinematic power and the ensuing dramatic brightening, which is not observed (see, Scheuer 1983).

Observational support for the models invoking decelerating FR I jets comes from the anti-correlation found between the apparent brightness ratio and the width ratio of the twin jets in FR I sources, which is readily understood in terms of Doppler boosting of a centrally peaked velocity profile (Laing et al. 1999, and references therein). A wide variety of the observed characteristics of the radio jets in FR I sources, such as the emission gaps seen near the nucleus (Komissarov 1990), the asymmetries in apparent emission from the two jets, and their magnetic field patterns, are reasonably explained if the jets in these sources consist of a narrow "spine" of relativistic flow with a predominantly transverse magnetic field, surrounded by a slower moving "sheath" contaminated by entrained material (a shear layer) where the magnetic field is stretched into a predominantly longitudinal configuration (Laing 1993, 1996; Laing et al. 1999). This picture is in accord with Bicknell's (1995) transonic relativistic jet models which are confined by external pressure at large distances, and where the deceleration usually occurs within ~ 2 kpc of the core.

3.2. Jet composition

Total energy and synchrotron radiation constraints led Celotti & Fabian (1993) to conclude that FR II jets were made of e^-–p plasma, since they argued that e^-–e^+ plasma of the required density would yield too much annihilation radiation. On the other hand, Reynolds et al. (1996b) used similar energetic and radiation constraints to conclude that the jet in the FR I source M87 was likely to be made of e^-–e^+ plasma. A similar argument favors an electron–positron jet in the Optically Violently Variable Quasar 3C 279 (Hirotani et al. 1999). If all of these arguments are taken at face value, one might infer that the main difference between FR I and FR II sources lies in the composition of the jet plasma, and this would imply the existence of a qualitative difference between their central engines. However, evidence for the presence of pair plasma jets, even in FR II sources, comes from the interpretation of the radio power–linear-size (P–D) diagram in terms of a model for self-similar growth of double radio sources (Kaiser et al. 1997). Furthermore, there are viable alternatives to the annihilation constraint invoked by Celotti & Fabian (1993) to argue against pair plasmas in FR II jets; for example, the earliest stage of the energy transport could be predominantly via Poynting flux (Reynolds 1999, private communication), in which case the radiating relativistic matter in all jets could indeed be essentially an e^-–e^+ plasma.

The "spine/sheath" model (Sect. 3.1) is broadly reminiscent of the two-fluid-type configuration for jets, put forward by Pelletier & Roland (1989). (See also Sol et al. 1989.) They suggest that the spine of the jet is relativistic, at least on parsec scales, and is composed of a pair plasma, while the outer sheath is made of e^-–p plasma, and carries the bulk of the energy to the outer lobes.

3.3. Galactic mergers

Substantial isophotal distortions are observed in the ellipticals hosting both FR I and FR II sources, strongly implying that galactic encounters/mergers have occurred (Heckman et al. 1986; Colina & de Juan 1995). However, the distinctive sharpness of the distortions seen in the FR II hosts (Smith & Heckman 1989), combined with the presence of strong optical emission lines and significantly higher MFIR emission (Heckman et al. 1994) suggests the occurrence of a starburst due to merger of a gas rich spiral with the elliptical host (Smith & Heckman 1989; Colina & de Juan 1995). In contrast, elliptical–elliptical mergers have been invoked in the case of FR I galaxies (Colina & de Juan 1995).

Consecutive mergers of galaxies containing central supermassive black holes (SMBHs) could produce multiple SMBH systems. Such triple systems usually become unstable and eject a single black hole in one direction, and the recoil sends the surviving binary black hole system in the opposite direction; this is the core idea of the gravitational slingshot model for radio source production (e.g., Saslaw et al. 1974). In this scenario, FR I sources correspond to SMBHs ejected at less than the escape velocity from the merged host galaxy, while FR II sources arise from SMBHs that do escape (Valtonen & Heinämäki 2000). Since this picture naturally produces different velocities for SMBHs of different masses, it could both produce HYMORS, and even make actual predictions as to their frequency. Valtonen & Heinämäki (2000) also argue that the slingshot model can roughly account for the dependence of L_R^* on L_{opt}, as well as for many other properties of radio galaxies.

3.4. Spin of the central engine

Some hydromagnetic process is now widely believed to be responsible for launching relativistic jets from the vicinity of the accretion disk/supermassive black hole combination which is believed to constitute the central engine in all AGN, although the details remain highly contentious (e.g., Scheuer 1996; Wiita 1996). A possible hint that the angular momentum of the central engine is important in launching powerful FR II jets comes from the rotational kinematics of the (presumably accreted) ionized gas observed in FR II host galaxies (Baum et al. 1992). The idea that a merger of two SMBHs belonging to a merged pair of elliptical galaxies could yield a single rapidly spinning SMBH, which propels powerful relativistic jets, was advocated by Wilson & Colbert (1995). While the black hole spin may well be an important ingredient for ejection of powerful jets, the existence of HYMORS (Sect. 4) disfavors differences in the SMBH spin as the principle mechanism for the FR dichotomy.

One basic class of scenarios involves variants of the Blandford-Znajek (1977, B-Z) mechanism, which could tap the SMBH's rotational energy via magnetic field lines threading the SMBH horizon. While extremely efficient in principle, and capable of providing powerful radio jets with minimal optical thermal emission if an ion-supported torus forms in the innermost region (Rees et al. 1982), the viability of this mechanism has recently been questioned on several grounds. Ghosh & Abramowicz (1997) argued that the strength of the magnetic field that could actually thread the SMBH horizon may have been substantially overestimated. Even if the B-Z mechanism works, Livio et al. (1999) have claimed that the emitted power is dominated by energy output from the inner disk regions, at least for the standard thin accretion disks, and therefore the efficiency is much reduced. This last limitation may be overcome if the accretion disk is actually thick in the inner regions (Armitage & Natarajan 1999). An additional potential problem for the B-Z mechanism was recently pointed out by Li (2000); he argued that the plasma screw instability must set in and this implies that even if the B-Z mechanism does work locally, any jet it launches would be severely limited in its overall length.

While none of the above critical arguments can be considered to be watertight, they tend to support the alternative basic scenario, which involves hydromagnetic launching of the jets from the accretion disk, rather than from the immediate vicinity of the SMBH (e.g., Blandford 1994). Most of these disk-origin models of jets (e.g. Appl & Camenzind 1993; Chiueh et al. 1991) can be considered to be variants of the Blandford-Payne (1982) scheme. However, it should be noted that if the screw-instability argument of Li (2000) turns out to be valid, it probably also applies to disk-launched jets and would cause difficulties for any MHD dominated jet formation process.

One possible approach for producing asymmetric jets by a single central engine was proposed by Wang et al. (1992). They took a semi-analytical approach to the force-free Grad-Shafronov equation and found solutions in which the bulk of the power was carried by the Poynting flux, while most of the angular momentum in the jet was carried by the magnetic fields emerging from the accretion disk. Wang et al. (1992) found that substantially more thrust could flow off of one side of the disk than the other if sufficiently large asymmetries could be maintained in the magnetic field within the disk.

The idea that the accretion disk corona can generate two fundamentally different types of jet has been proposed recently (Meier et al. 1997; Meier 1999). Fast (highly relativistic, FR II) jets are ejected when the coronal plasma is unbound by the magnetic field, while slower (transrelativistic, FR I) jets, moving at roughly the disk's escape velocity, are produced when the corona is inertially bound to the SMBH. The original version of this "magnetic switch" mechanism (Meier et al. 1997) could explain how jets of very different speeds arise from otherwise similar sources, but this version fails to explain how these differences can persist over the extended lifetimes of FR I sources (Meier 1999). In his revised scenario, Meier (1999) argued that the difference in radio jet power among galaxies of the same mass arises from different speeds of rotation of the magnetic field lines associated with their central engines, which are in turn produced by different spin rates of their SMBHs. (The idea that the SMBH spin was critical had been put forward already by Baum et al. (1992, 1995) based on observational inferences about the merger of the host galaxy with a high angular momentum, gas-rich, disk galaxy in the case of FR II sources.) The transition occurs at a critical power when the MHD luminos-

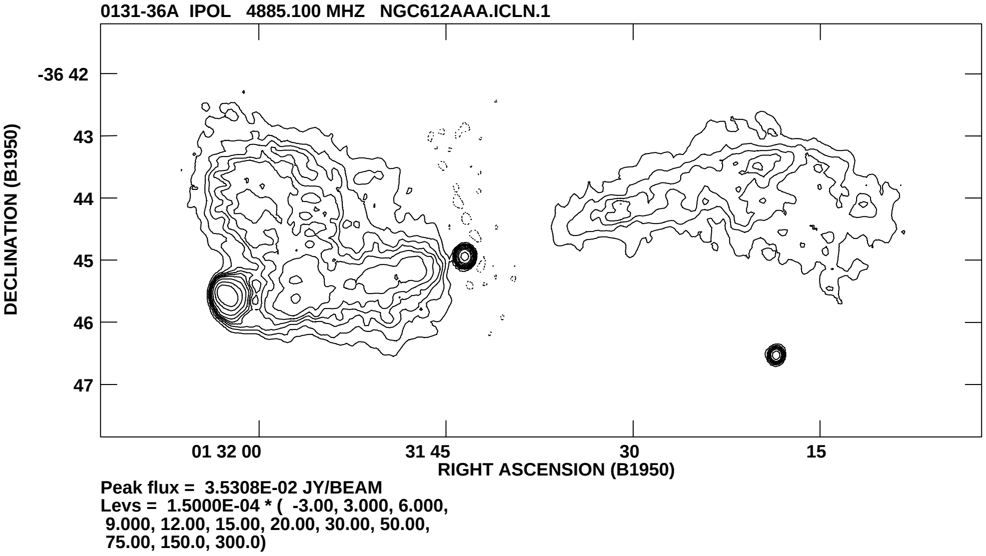

Fig. 1a. Maps reproduced from the literature showing the hybrid morphology of six double radio sources: **a** 0131−367, reprinted with permission from Morganti et al. (1993), copyright, Royal Astronomical Society; **b** 0521−364, reprinted with permission from Keel (1986), copyright, American Astronomical Society; **c** 1004+130, reprinted with permission from Fomalont (1982), copyright, Kluwer Academic Publishing; **d** 1452−517, reprinted with permission from Jones (1986), copyright Astronomical Society of Australia; **e** 1726−038, reprinted with permission from Jackson et al. (1999), copyright, European Southern Observatory; **f** 2007+777, reprinted with permission from Murphy et al. (1993), copyright Royal Astronomical Society

ity, $L_{\rm MHD} = B_{p0}^2 R_0^3 \Omega/2$, (where B_{p0} is the poloidal magnetic field, R_0 is the size of the magnetic rotator, and Ω its angular velocity) exceeds a critical luminosity, defined as the liberation of an escape energy in a free-fall time:

$$L_{\rm crit} = \frac{E_{\rm esc0}}{\tau_{\rm ff0}} = 4\pi\rho_{c0} R_0^2 \left(\frac{GM}{R_0}\right)^{3/2}. \qquad (1)$$

In Meier's scenario, this magnetic switch luminosity plays the same role in MHD acceleration as does the Eddington luminosity in radiative acceleration. Note that this magnetic switch model relies on extracting substantial power from a portion of the accretion disk extending within the ergosphere, thereby avoiding the problem highlighted by Livio et al. (1999). This model is capable of yielding a decent match to the Owen-Ledlow variation in the value of L_R^* with $L_{\rm opt}$ in terms of a critical SMBH spin (Meier 1999).

The possibility that Advection Dominated Accretion Flows (ADAFs; e.g., Narayan & Yi 1995), which are inefficient radiators, are present in FR I radio galaxies was first proposed by Reynolds et al. (1996a). In this picture, which is an intriguing option (e.g., Jackson 1999), standard thin accretion disks, which radiate more efficiently, yield FR II radio sources (Reynolds et al. 1996a). A good fit to the low-frequency radio and X-ray emission of M87 (Reynolds et al. 1996a) as well as to that of several quiescent ellipticals (Di Matteo & Fabian 1997; Mahadevan 1997) could be attained using ADAF models. However, the ADAF models grossly overpredict the high-frequency radio and sub-mm emission from these quiescent galaxies unless: the magnetic fields are very much below equipartition; or there is enough cold material for free-free absorption of the synchrotron absorption to be very important; or powerful winds remove much of the energy, angular momentum and mass from the inner part of the accretion flow (Di Matteo et al. 1999).

4. HYMORS: a new observational clue to the FR dichotomy

As mentioned in Sect. 1, the remarkable differences between a wide range of characteristics of the FR I and FR II sources, as summarized in Sect. 2, have led several authors to the viewpoint which ties the origin of these differences to the properties of the central engine itself (Sects. 3.2–3.4). It is clearly important to confront this somewhat radical stand with any discriminating observational results available. One possible strategy is to look for double radio sources whose radio structures on the two sides of the nucleus exhibit *different* Fanaroff-Riley morphologies. Even a few examples of such clearly hybrid morphology double radio sources would call into question models that attribute the FR dichotomy to the properties of the central engine, since in a given double source both radio lobes are presumably caused by a single central engine. On the other hand, such a hybrid morphology may be readily accommodated within a scenario where the ambient media on the two sides of the nucleus have sufficiently dissimilar properties so as to impose different fates upon the two jets emanating from the nucleus.

Following the above reasoning, we have carried out a substantial, though certainly not exhaustive, search of the published literature and have located several cases of *HYMORS*, which illustrate our point. Below we briefly comment on these individual examples, whose basic properties are summarized in Table 1.

0131−367 (NGC 612, z = 0.029): This bright SO galaxy with a prominent dust-lane is the host of a prominent double radio

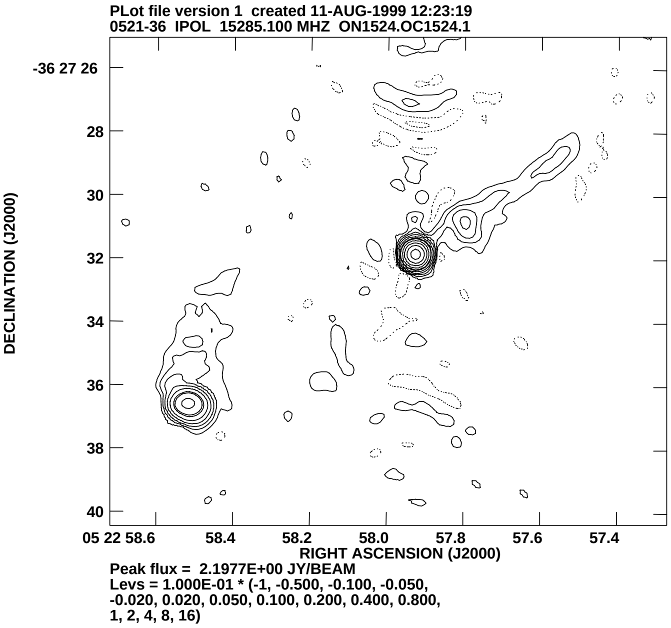

Fig. 1b.

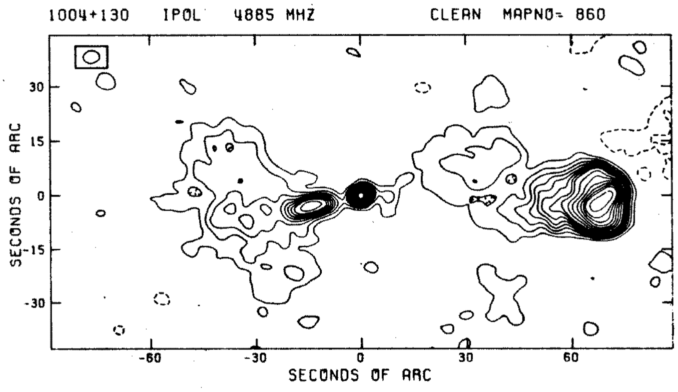

Fig. 1c.

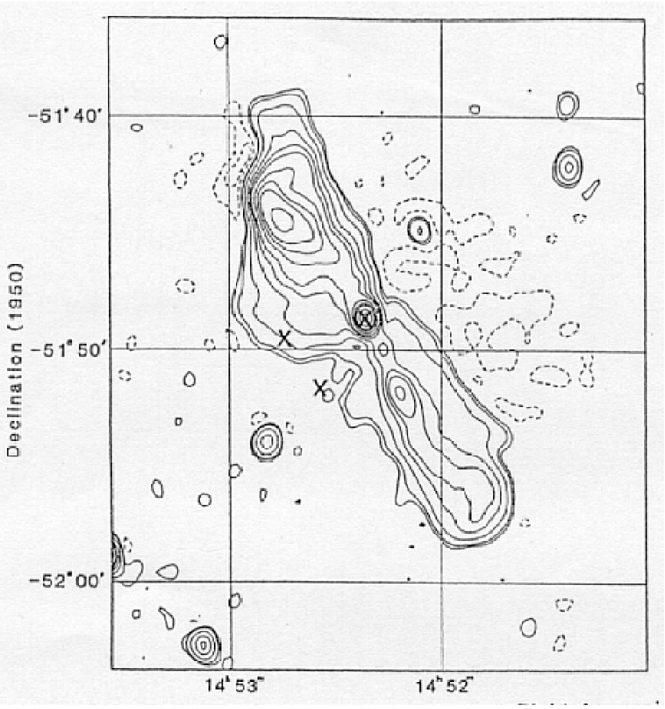

Fig. 1d.

Table 1. Properties of the HYMORS

Object	z	Size (arcmin)	Size^{a} (kpc)	Log (L_R) (1 GHz) W/Hz^{a}
0131−367	0.029	14.2	483	25.4
0521−364	0.055	0.3	22	25.4
1004+130	0.240	1.8	524	26.3
1452−517	0.08	20.3	812	25.4
1726−038	(0.05)^{b}	0.6	35	24.8
2007+777	0.342	0.5	213	24.8

^{a} H_0 = 75 km s^{-1} Mpc^{-1}, $q_0 = 0.5$, spectral index = -1.
^{b}Estimated redshift (Sect. 4).

source (Ekers et al. 1978). The hybrid nature of its radio structure is evident from its 5 GHz VLA map which shows a weak core flanked by two radio lobes; the eastern lobe has a bright hotspot near its outer edge (FR II type), whereas the western lobe exhibits a jet-like structure which widens steadily and fades into a diffuse radio plume (FR I) (Fig. 1a; Morganti et al. 1993).

0521−364 (z = 0.055): This well-known blazar, found to be a source of $\gamma-$rays above 100 GeV (Thompson et al. 1995), is another fine example of hybrid radio morphology. It consists of a radio/optical synchrotron jet which does not terminate in a hot spot, and a bright radio hot spot on the counter-jet (SE) side, all embedded in a radio halo (Fig. 1b; Keel 1986).

1004+130 (4C+13.41, z = 0.240): The hybrid morphological nature of this quasar is apparent from its 5 GHz VLA map made by Fomalont (1982; Fig. 1c). The radio lobe westward of the bright nuclear core is strongly edge-brightened, typical of FR II sources. In contrast, the eastern lobe is clearly edge-darkened (FR I type), and its structure is dominated by a jet which progressively fades away from the nucleus.

1452−517 (z = 0.016): A 843 MHz MOST map of this giant radio galaxy, made by Jones (1986), is shown in Fig. 1d (see, also, Jones & McAdam 1992). Whilst the N lobe is edge-brightened (FR II type), the other lobe is edge-darkened (FR I) (Jones 1986). A higher resolution map is needed to ascertain if the elongated radio feature seen in the S lobe is indeed a jet. An alternative possibility in the context of such giants is that the emission peak recessed from the outer edge could be the current working surface of a rejuvenated jet which had already reached a much greater extent but was cut off by the instabilities which are particularly likely to afflict such giant, old, radio sources (e.g., Hooda et al. 1994).

1726−038 (4C−03.64): This double source is a good example of a HYMORS. As seen from a recent 4.9 GHz VLA map (Fig. 1e; Jackson et al. 1999), the extremity of the NE lobe is marked by a bright hot spot (FR II type). In contrast, the SW side of the nucleus exhibits a prominent jet which progressively

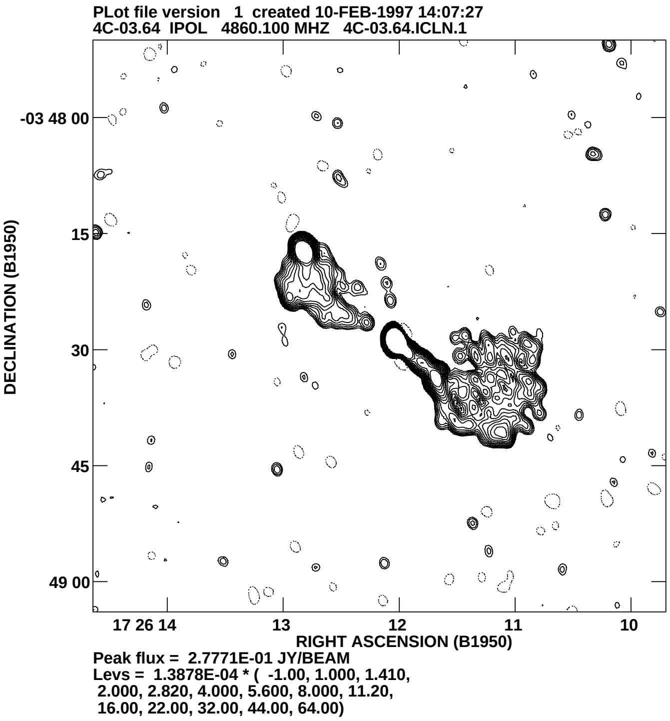

Fig. 1e.

fades away outwards, a standard FR I pattern. Unfortunately, the authors provide no redshift measurement; using the digitized POSS we have attempted to obtain a crude estimate of the redshift. We tentatively identify the source with an elliptical galaxy of approximately 10 arcsec extent. This angular size of the host galaxy suggests a redshift of ~ 0.05, taking the intrinsic diameter to be 10 kpc and a Hubble constant of H_0 = 75 km s^{-1} Mpc^{-1}.

2007+777 (z = 0.342): This moderately distant, core dominated BL Lacertae object has been mapped with the VLA at 1.5 GHz by Murphy et al. (1993). As seen from Fig. 1f, the eastern side of the nucleus exhibits a prominent hot spot, whereas the western side is marked by a jet which gradually fades into oblivion at about 10 arcsec from the nucleus.

Some high redshift examples of HYMORS can be identified from the quasar sample imaged by Lonsdale et al. (1993), using the VLA at 5 and 15 GHz. **0038−019** (4C −02.04; z = 1.690) is a good example of hybrid morphology, with a hot-spot in the N lobe and a southward jet without a terminal hot-spot. **1258+404** (3C 280.1, z = 1.659) has a hot-spot on the NW and only a jet to the SE. **1323+655** (4C 65.15, z = 1.618) is another possible HYMORS, with a compact hot-spot to the NE and a bent jet on the SW. The peculiar structures of the first and third of these sources were noted by Lonsdale et al. (1993).

Among the AGN associated with disk galaxies, a HYMORS-like source has recently been mapped in the Seyfert galaxy, Mrk 3 (UGC 3426). Mrk 3 has an extremely low level of nuclear radio activity and its overall radio size is only $\sim$ 0.5 kpc (Kukula et al. 1999). The E jet shows knots close to the nucleus and fades outwards in an FR I pattern, while the W jet terminates in a typical FR II hot spot and lobe.

In addition, 0905−353, which was mapped at low-resolution by Jones & McAdam (1992), is another possible HYMORS. We plan to employ the high resolution and sensitivity of the the Giant Metrewave Radio Telescope to ascertain if this object indeed has a hybrid morphology.

Although Fanaroff & Riley (1974) classified radio sources solely in terms of whether the separation of points of peak intensity were less than (FR I) or greater than (FR II) half of the largest size of the source, more subtle classification schemes have since been proposed. Probably the most widely adopted of these separates double sources into categories depending upon: (a) whether the extended emission is best described as plume-like or bridge-like; and (b) whether the lobes possess compact features or not, and if they do, whether the compact emission is dominated by hotspots, weak jets or strong jets (Leahy 1993, 2000; Laing 1993). Since almost all FR II sources would fall into a the category which is dominated by bridges on large scales and hotspots on small scales, this scheme mainly serves to stress the wide range of types commonly clubbed together in the FR I fold, a few of which might be called ‘FR 1.5’ (Leahy 2000).

Other types of structures intermediate between FR I and FR II morphologies have been noted earlier (Zirbel & Baum 1995 and references therein). Owen & Laing (1989) discuss a small group of “Fat Doubles”, with bright outer rings and rounded lobes, which they argue are best considered as FR I/II transitional sources. We would not consider any of these as an example of a HYMORS. In their list of some 334 sources, for which they had good enough maps to classify 212, Zirbel & Baum (1995) list only 7 sources as being ‘FR I/II’ (in their paper this means different categorizations had appeared in the literature) and only 3 as being ‘Transitional’. Published maps could be located for 7 of these 10; we would call four of these clearly FR II, one clearly FR I, one (3C 17) as being very confused, perhaps involving a chance superposition of an FR II and an FR I (Morganti et al. 1993), and only one case (3C 15) that might legitimately be transitional; however, it did not fit our definition of a HYMORS. Nor does PKS 1313−33, a source Morganti et al. (1993) call transitional. In addition, transitional type sources housing plumes and tails along with well collimated jets and weak hot spots, have been seen in three intermediate power radio galaxies (Capetti et al. 1995) and in some low luminosity radio sources (Parma et al. 1987); again, none of these are good examples of HYMORS. Thus, while the sobriquets ‘FR 1.5’ and ‘FR I/II’ have appeared occasionally in the literature, their meanings are imprecise, and we consider ourselves justified in introducing the more specific term HYMORS to describe sources with definite FR I morphology on one side and distinct FR II morphology on the other.

5. Concluding remarks

Our main objective in this study was to highlight the existence of double radio sources whose structures are characterized by a hybrid morphology in terms of the Fanaroff-Riley classification scheme. Table 1 summarizes the basic radio and optical data for six good examples of such HYMORS (Sect. 4). It is seen that

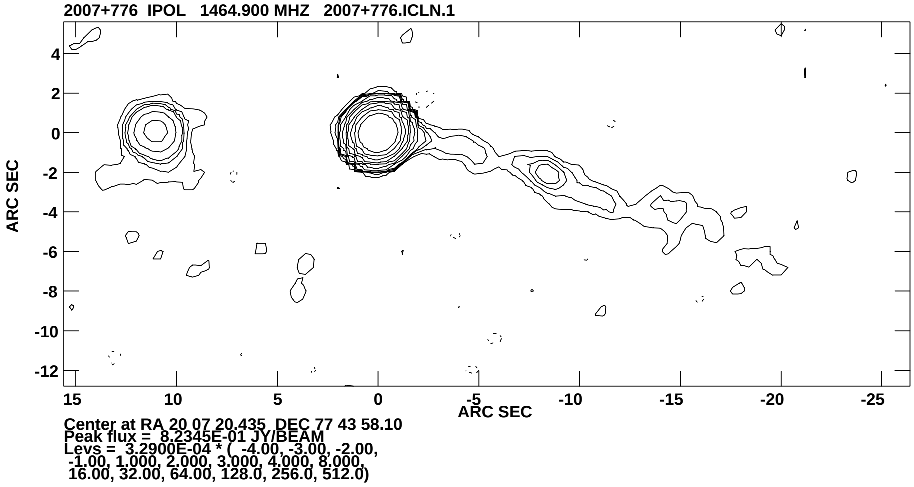

Fig. 1f.

the hybrid radio morphology can be associated with all three major classes of radio powerful AGNs (i.e., galaxies, quasars and BL Lac objects), and with radio sources extending from galactic up to megaparsec dimensions. Although the radio powers of these HYMORS are below or around the critical value for the FR I/FR II transition, this probably is due to the modest redshifts of these sources; their counterparts may well exist at high redshifts ($z > 1$, Sect. 4). From Fig. 1 it may also be noted that in some of the cases the FR I classification of a radio lobe is based on the detection of a radio jet without a terminal hot spot; in the other cases a diffuse radio lobe without a hotspot (FR I type) is found associated with a jet. We note that since the missing hotspot in HYMORS is often on the side with the jet, the morphological asymmetry cannot be explained by postulating even an implausibly strong Doppler boosting of the hotspot radiation.

Because we have examined very heterogeneous samples of radio maps in order to produce our set of HYMORS, it is not possible to give an accurate estimate of their frequency. We examined roughly 1000 radio maps overall to come up with the 6 good examples highlighted above. Among relatively well defined samples, we found: 1 HYMORS out of 181 3CRR galaxies considered by Laing et al. (1983); 1 case among the 150 4C maps presented by Jackson et al. 1999; and 0 cases in the 98 maps of steep spectrum 4C sources considered by Rhee et al. (1996). These are consistent with very low rates of less than about 1%. The higher redshift sample of Lonsdale et al. (1993), however, yielded 3 HYMORS out of 70 sources.

Although rare, HYMORS can serve as a very useful discriminator between the wide range of theories that have been put forward to explain the origin of the FR dichotomy. The mere existence of HYMORS seems to disfavor the class of models that posit fundamental differences between the central engines, such as spin or jet composition, as being the dominant cause for the two morphological types (Sects. 1, 3). The scheme of Wang et al. (1992) (Sect. 3.4), where the central engine is argued to be capable of ejecting jets of grossly unequal power, could conceivably be reconciled with the existence of HYMORS. However, even if such an asymmetry could somehow be maintained over most of the source lifetime, there is no significant evidence in our sample of HYMORS for the positively correlated asymmetries in radio luminosities and lobe lengths that this scenario would predict. (If one leaves the standard jet paradigm and considers gravitational slingshot scenarios (e.g., Valtonen & Heinämäki 2000), then some HYMORS would be expected, though the predicted lobe length asymmetry cannot be verified using the present small sample.)

Thus, at least in the case of HYMORS, it appears that some type of jet-medium interaction on kiloparsec scales is playing a crucial role in creating the morphological asymmetry about the nucleus. If the asymmetric jet/medium interaction is such that the jet collimation is quite different on the two sides, the side with poorer collimation, and therefore more rapid slowdown, would lose its hotspot sooner. Earlier, environmental asymmetries have been argued to be important for the Compact Steep Spectrum radio sources (Gopal-Krishna & Wiita 1991; Saikia et al. 1995; Jeyakumar et al. 2000). A more extensive search for HYMORS, allowing a reliable statistical estimate of their frequency and structural asymmetries, is likely to provide a deeper insight into the origin of the Fanaroff-Riley morphological dichotomy.

A recent study appears to underscore the dominant role of accretion in the jet formation. Serjeant et al. (1998) show that for steep spectrum quasar cores, radio and optical outputs are strongly correlated; this implies a close link between the formation of jets and accretion onto the SMBH, improving on the similar argument made by Rawlings & Saunders (1991; see also Falcke & Biermann 1999).

Finally, in the context of HYMORS it may be pertinent to quote Lilly & Prestage (1987): “It is important to stress that the environment must be influencing not just the outer radio lobes, but also nuclear phenomena, such as the strength of the optical emission lines and the properties of the radio jets.” We surmise that the observed differences between the properties of the host galaxies of FR I and FR II sources engender the dichotomy by creating different environmental conditions to be encountered by the jets, rather than by producing fundamentally different kinds of central engines.

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