A single population scheme for
FR I and FR II radio sources

Ignas Snellen & Philip Best

Institute for Astronomy, University of Edinburgh, UK

Abstract

The presence of two distant FR I radio galaxies in the Hubble Deep Field plus Flanking Fields indicates that the number density of these objects is about $10^{-50}$ times higher at $z>1$ than in the local universe. This is in strong contrast with the idea that FR Is undergo no cosmological evolution. We advocate that the cosmological evolution of radio sources may be independent of FR class, and instead solely a function of radio power. In this scenario the evolutionary properties of extragalactic radio sources can be fully described within a ‘single population scheme’.

Key words: surveys - galaxies:active - radio continuum:galaxies

1 Historic background

Early statistics of radio sources indicated that the space density of radio sources was much higher at early cosmological epochs than in the present universe (Ryle & Clarke 1961). Subsequent deeper radio surveys showed a turnover in the number counts, implying that this strong cosmological evolution must have been confined to only the most powerful radio sources (Longair 1966), and a simple model was developed with two distinct population of radio sources; one low-luminosity non-evolving population, and one high-luminosity strongly-evolving population (Doroshkevich, Longair & Zeldovich 1970). Wall (1980) suggested that these two populations of non-evolving and strongly evolving radio sources correspond to the Fanaroff & Riley (1974) Class I and II galaxies respectively. This idea of a ‘dual population scheme’ has formed the basis of a comprehensive study by Jackson & Wall (1999), who in addition linked through orientation the non-evolving and strongly evolving populations of FR I and FR II radio galaxies to BL Lacs and flat spectrum quasars respectively. A similar scheme has recently been developed by Willott et al. (2001), but here a weakly evolving and a strongly evolving population
correspond to radio galaxies with low and high optical line luminosity, not to FR class.

In the mean time, substantial differences were found between the host galaxies of FR I and II radio sources. Owen & Laing (1989) found that FR Is are hosted by larger galaxies than FR IIs. In addition, Zirbel & Baum (1995) showed that at the same radio power, FR IIs have $5-30$ times more optical line luminosity than FR Is. It was therefore proposed that the FR dichotomy may be due to fundamental differences in the structural properties of the central engines in these two types of sources, such as the accretion rate and/or the spin of the central black hole.

However, more recently it has been shown by Ledlow and Owen (1996) that the Owen & Laing result was caused by the combination of a sample selection effect and a strong positive correlation between the FR I/II radio luminosity cutoff and the absolute magnitude of the host-galaxy. This means that FR I and FR II radio sources are actually found in very similar galactic environments. In addition, Gopal-Krishna & Wiita (2000) have pointed out a class of double radio sources in which the two lobes exhibit clearly different FR morphologies. Although these objects are rare, their existence appears to be in conflict with the class of explanations that posit fundamental differences in the central engine.

2 FR Is in the Hubble Deep Field

If FR I and FR II radio galaxies undergo distinctly different cosmological evolutions, then observations and/or models which require a close link between the two classes of object are difficult to reconcile. So why are the two FR classes thought to undergo different evolutions? Firstly, the radio source counts undoubtedly show that high luminosity sources undergo a much stronger evolution than sources of low radio luminosity. However, it is not at all clear whether this behaviour is due to a gradual change in the evolution with radio power, or caused by two distinct populations, one strongly evolving - assumed to be powerful FR IIs, and one non/weakly evolving - assumed in the Jackson & Wall models to be FR Is. Secondly, the $V/V_{\text{max}}$ test is different for FR I and FR II radio galaxies, which has been brought forward as evidence for a difference in evolution (eg. Jackson & Wall 1999). However, in a flux density limited sample such as 3C, low luminosity sources cover a much smaller redshift range than high luminosity sources, and therefore the evolution signal is measured over a much larger range in cosmological epoch for FR II ($z<2$) than for FR I ($z<0.2$) radio galaxies. A fair comparison can only be made using the $V/V_{\text{max}}$ test if sources at similar radio power are compared. We show in Snellen & Best (2001) that the $V/V_{\text{max}}$ test differentiated in radio power does not show
any difference between FR Is and FR IIs (see also Jackson & Wall 2001), and therefore provides no evidence that FR IIs evolve differently from FR I (at the same radio power).

It would be highly valuable if we would be able to directly measure the high redshift space density of FR I radio galaxies and subsequently their evolution. However, this is more easily said than done: a luminous FR I radio galaxy at \( z=1 \) will only appear as a source with a flux density of not more than a couple of milli-Jansys at 1.4 GHz. Moreover, to be able to morphology classify a radio source as an FR I at these redshifts requires much deeper \( (\sigma \approx 10^{\mu} \text{Jy}) \) observations at (sub-)arcsecond resolution.

The only observations so far which comply to these limits are those of the Hubble Deep Field (HDF) and Flanking Fields (HFF), which have been imaged with the VLA at 8.4 GHz, with the VLA and MERLIN at 1.4 GHz, with the WSRT at 1.4 GHz, and the EVN at 1.6 GHz (Richards et al. 1998; Muxlow et al. 2002; Garrett et al. 2000; 2001), all to \( \mu \text{Jy} \) flux density levels. Importantly, the two brightest radio sources in this field are distant FR I galaxies (Snellen & Best 2001); one at \( z=1.101 \) (log \( P_{178 \text{MHz}} = 24.8 \text{ W Hz}^{-1}\text{sr}^{-1} \)), and one without spectroscopic redshift but with such a faint and red magnitude that it must be at \( z > 1 \) \( (\log P_{178 \text{MHz}} > 25.3 \text{ W Hz}^{-1}\text{sr}^{-1}) \). We showed that it is very unlikely to find two FR I radio galaxies at these luminosities and redshifts in such a small area of sky if FR Is undergo no cosmological evolution. Consequently, the actual high redshift space density is estimated to be 10–50 times higher than in the local universe (Snellen & Best 2001).

## 3 A single population scheme

The results described above indicate that FR I radio galaxies do evolve with redshift. We suggest that FR I and FR II radio galaxies should not be treated as intrinsically distinct classes of objects, but that the cosmological evolution is simply a function of radio power with FR I and FR II radio galaxies of similar radio powers undergoing similar cosmological evolutions. Since low power radio galaxies have mainly FR I morphologies and high power radio galaxies have mainly FR II morphologies, this results in a generally stronger cosmological evolution for the FR IIs than the FR Is.

Basically, this “single population scheme” is similar to the models used by Dunlop & Peacock (1990), in which the evolution of the radio source population is only dependent on radio power. Their models (a series of pure luminosity evolution and luminosity/density evolution) fit the number counts and redshift distributions of bright radio sources well. In addition they predict number densities which are comparable to that found in the HDF and HFF,
Fig. 1. The 1.4 GHz radio power as function of black hole mass, for the FR Is (1) and FR IIs (2) of Ledlow & Owen (1996), and optically selected ellipticals from Faber et al. (1989), with the closed and open circles corresponding to those with extended and unresolved NVSS emission respectively. The upper line is the FR I/II cutoff as given by Ledlow & Owen, and the lower line is the radio power - $M_{bh}$ correlation as proposed by Franceschini.

and are consistent with the general mJy population in the LBDS Hercules sample, as shown by Waddington et al. (2001).

The main benefit of treating the two FR classes as a single population is that their physics can be closely linked. A popular paradigm is that the population of radio-loud AGN come with a range of jet outputs, of which the more powerful may be strong enough to maintain their integrity until they impact on the intergalactic medium (IGM) in a shock. This results in an FR II. However, if the jet is too weak, it may dissipate its energy by entraining IGM material,
resulting in a more turbulent FRI. This may also explain the dependence of the FRI/FRII radio power divide on the luminosity of the host galaxy: in more luminous galaxies, which reside in denser environments or which have denser ISM, only jets of higher power can keep their integrity. It also leaves open the possibility that during the lifetime of a radio source, its morphology could change FR-class from FRI to FRII or vice versa.

It may be interesting to note that the dependence of the FR cutoff on absolute magnitude of the host galaxy does not simply imply that this must be caused by an environmental effect. Since it has now been clearly established that the absolute magnitude of a galaxy is related to the mass of its central black hole (eg. McLure, this volume), the Ledlow & Owen diagram also implies that FRI/II cutoff depends on the mass of the central black hole; the more massive the black hole, the higher the FR I/II cutoff luminosity. This is shown in Figure 1, where the radio luminosity is plotted as function of black hole mass, $M_{\text{bh}}$: for the radio sources from the Ledlow & Owen (1996) sample $M_{\text{bh}}$ is derived from the $M_{\text{opt}}$-$M_{\text{bh}}$ relation given in Kormendy & Gebhardt (2001), whilst for the optically selected galaxies from Faber et al. (1989) $M_{\text{bh}}$ is derived using the $\sigma$-$M_{\text{bh}}$ relation found by Gebhardt et al. (2000). Interestingly the slope of the FR I/II cutoff is very similar to that of the correlation between radio power and black hole mass as first proposed by Franceschini et al. (1996). The latter was initially believed to have only a small scatter, but subsequent work has shown that the scatter is at least several orders of magnitudes when powerful radio galaxies and quasars are included. It seems though that there is a lower limit to the radio power for a given black hole mass (eg. Dunlop et al. 2002; Snellen et al. 2002), and maybe also an upper limit. This picture indicates the black hole mass or other fundamental properties of the central engine can not be ruled out of influencing the FRI/II divide.

4 Future work: A new VLA survey

We are continuing this field of research with a deep wide-field survey conducted with the Very Large Array at 1.4 GHz in A configuration over two fields of 30' diameter, using spectral line mode. A noise level of 15 $\mu$Jy/beam is reach at a resolution of 1". In this way we sample a volume about an order of magnitude larger than that of the HDF+HFF survey. The fields overlap with those of Windhorst et al. (1984; Lynx and Her.1), for which previous low resolution radio observations and some optical observations are available. To be able to morphologically classify all radio sources, inevitably some objects will require to be followed up using the new VLA-Pietown link and/or MERLIN.

With this study we hope to firmly establish the cosmological space density evolution of FRIs, and investigate whether the evolution of radio-loud AGN
is dependent on FR class, or solely a function of radio power. Secondly, we will
determine possible variation of the FRI/II cutoff with redshift. This may shed
new light on the physical connection between FRI and FRII radio galaxies.

References

[1] Doroshkevich A.G., Longair M.S., Zeldovich Y.B., 1970, MNRAS, 147, 139
[2] Fanaroff B.L. and Riley J.M., 1974, MNRAS, 167, 31
[3] Dunlop J.S., Peacock J.A., 1990, MNRAS, 247, 19
[4] Dunlop J.S., McLure R.J., Kukula M.J., Baum S.A., O’Dea C.P., Hughes
   D.H., 2002, MNRAS, in press
[5] Faber S.M., Wegner G., Burstein D., Davies R.L., Dressler A., Lynden-
   Bell D., Terlevich R.J., 1989, ApJS, 69, 763
[6] Franceschini A., Vercellone S., Fabian A.C., 1998, MNRAS, 297, 817
[7] Garrett M.A., de Bruyn A.G., Giroletti M., Bann W.A., Schilizzi R.T.,
   2000, A&A, 361, 41
[8] Garrett M.A., Muxlow T., Garrington S.T. et al., 2001, A&A, 366, 5
[9] Gebhardt K., Kormendy J., Ho L.C., et al., 2000, ApJ 543, L5
[10] Gopal-Krishna and Wiita P.J., 2000, A&A, 363, 507
[11] Jackson C.A. and Wall J.V., 1999, MNRAS, 304, 160
[12] Jackson C.A. and Wall J.V., 2001, in “Blazar Demographics and
   Physics” ASP Conf. Series, eds P. Padovani and C.M. Urry., 227, 242
[13] Kormendy J, Gebhardt K., 2001, in the 20th Texas Symp. on Rel. Astropysic.
   ed. H. Martel & J.C. Wheeler, AIP, 586, 383
[14] Ledlow M.J. and Owen F.N., 1996, Astronomical Journal, 112, 9
[15] Longair M.S., 1966, MNRAS, 133, 421
[16] McLure, 2002, this volume
[17] Muxlow et al., 2002, in preparation
[18] Ryle M. and Clarke R.W., 1961, MNRAS, 122, 349
[19] Owen F.N., Laing R.A., 1989, MNRAS, 238, 357
[20] Richards E.A., Kellerman K.I., Fomalont E.B., Windhorst R.A., Partridge
   R.B., 1998, AJ, 116, 1039
[21] Snellen I.A.G. & Best P.N., 2001, MNRAS, 328, 897
[22] Snellen I.A.G., Lehnhrt M., Bremer M.N., Schilizzi R.T., MNRAS, submitted
   [astro-ph/0209380]
[23] Waddington I., Dunlop J.S., Peacock J.A., Windhorst R.A., 2001, MNRAS,
   328, 882
[24] Wall, J.V., 1980, Phil. Trans. R. Soc., A296, 367
[25] Wilott C.J., Rawlings S., Blundell K.M., Lacy M., Eales S.A., 2001,
   MNRAS, 322, 536
[26] Windhorst R.A., van Heerde G.M., Katgert P., 1984, A&AS, 58, 1
[27] Zirbel E.L. and Baum S.A., 1995, AJ, 448, 521