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Distant FR I radio galaxies in the Hubble Deep Field: implications for the cosmological evolution of radio-loud AGN

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ABSTRACT

Deep and high-resolution radio observations of the Hubble Deep Field and flanking fields have shown the presence of two distant edge-darkened FR I radio galaxies, allowing for the first time an estimate of their high-redshift space density. If it is assumed that the space density of FR I radio galaxies at $z > 1$ is similar to that found in the local Universe, then the chance of finding two FR I radio galaxies at these high radio powers in such a small area of sky is < 1 per cent. This suggests that these objects were significantly more abundant at $z > 1$ than at present, effectively ruling out the possibility that FR I radio sources undergo no cosmological evolution. 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. We believe that additional support from the $V/V_{\rm max}$ test for evolving and non-evolving population of FR IIs and FR Is respectively is irrelevant, since this test is sensitive over very different redshift ranges for the two classes.

Key words: surveys – galaxies: active – cosmology: observations – radio continuum: galaxies.

1 INTRODUCTION

1.1 Radio source counts and the cosmological evolution of radio galaxies

Already in the early days of radio astronomy it was realized that number counts of radio sources contain important information about the distribution of radio sources as a function of redshift. Early results showed that they were inconsistent with the predictions of a steady-state cosmology (Ryle & Clarke 1961), but that they could be explained by evolutionary cosmological models in which there were many more powerful radio sources at epochs earlier than the present. This could be directly inferred from the slope of the $\log N - \log S$ curve above Jy levels being steeper than the $-\frac{3}{2}$ power law which the static, uniform, Euclidian Universe must show. At sub-Jy levels the slope changes gradually to a law flatter than the $-\frac{3}{2}$ law, as it must to escape the radio equivalent of Olbers's paradox. Longair (1966) showed that the strong evolution must have been confined to the most powerful radio sources, because the observed range in power for radio sources was more than 5 orders of magnitude, while the turnover in the radio source counts covered less than 2 orders of magnitude.

The initial steep slope and its turnover were subsequently accounted for by two distinct populations of radio sources. One population consisted of high radio luminosity sources undergoing strong cosmological evolution (e.g., with comoving number densities about 2–3 orders of magnitude higher at large redshifts), the other population was of low-luminosity sources undergoing little or no evolution with cosmological epoch. Wall (1980) suggested that these two populations of non-evolving and strongly evolving radio sources corresponded to the Fanaroff & Riley (1974) class I and class II galaxies respectively. This idea has been further developed by Jackson & Wall (1999), who use the source counts at several frequencies and redshift information of the 3C sample, to link the FR I and FR II radio sources as the unbeamed parent populations of BL Lac objects and flat-spectrum quasars respectively. Willott et al. (2001) also defined a dual-population scheme, but slightly different from that of Jackson & Wall (1999). In their scheme, the low-luminosity population is associated with radio galaxies with weak emission lines (both FR Is and FR IIs), and the high-luminosity population is associated with radio galaxies and quasars with strong emission lines (almost all FR IIs).

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In contrast, Dunlop & Peacock (1990, hereafter DP90) do not make a distinction between FR Is and FR IIs in their analysis of the statistics of steep-spectrum radio sources, but allow for a luminosity-dependent cosmological evolution.

1.2 Fanaroff & Riley Class I and II radio sources

Fanaroff & Riley (1974) showed that there is a distinct morphological difference between radio sources of high and low luminosity. The more powerful sources have their regions of highest surface brightness at the ends of a double-lobed structure (FR II – edge-brightened), while the lower power objects show a variety of forms in which the highest brightness occurs near their centres, excluding their cores (FR I – edge-darkened). Fanaroff & Riley found a sharp division between the two classes at $P_{178\,\mathrm{MHz}} \sim 2 \times 10^{25}\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$.

Early optical work indicated that there is also a difference between the host galaxies of FR I- and FR II-type radio galaxies. Owen & Laing (1989) found that FR II sources reside in normal giant elliptical galaxies with absolute magnitudes near M_* of the Schechter luminosity function, considerably fainter than first-ranked galaxies in rich clusters, while FR I sources reside in galaxies which can generally be described as D or cD galaxies. However, more recently it has been shown by Ledlow & Owen (1996) that this result was caused by the combination of a sample selection effect and a strong positive correlation between the FR I/II radio luminosity cut-off and the absolute magnitude of the host galaxy, with an increase of the transition luminosity from $L_{1.4\,\mathrm{GHz}} \approx 10^{24}\,\mathrm{W\,Hz^{-1}}$ at $M_R = -21$, to $L_{1.4\,\mathrm{GHz}} \approx 10^{26}\,\mathrm{W\,Hz^{-1}}$ at $M_R = -24$. Due to the small range of radio luminosity in the Owen & Laing sample, this correlation resulted in the FR IIs generally residing in lower luminosity galaxies than the FR Is. The Ledlow & Owen result suggests that both FR I and FR II radio sources live in similar environments, but that the properties of the host galaxies may strongly influence the morphological appearance of the radio sources, at least for those near the division of the two classes.

Zirbel & Baum (1995) found that for the same total radio power, FR II galaxies produce 5–30 times more emission-line luminosity than FR I galaxies. In this light, Baum, Zirbel & O'Dea (1995) put forth the possibility that the FR dichotomy is due to qualitative differences in the structural properties of the central engines in these two types of sources, like the accretion rate and/or the spin of the central black hole. In contrast, Gopal-Krishna & Wiita (2000) point out a class of double radio sources in which the two lobes exhibit clearly different FR morphologies. Although these objects are rare, their existence supports explanations for the FR dichotomy based upon jet interaction with the external medium, and appears quite difficult to reconcile with the class of explanations that posit fundamental differences in the central engine.

1.3 Radio observations of the Hubble Deep Field

Due to observational limitations, no direct measurements of the high-z space density of FR I radio galaxies yet exist. The Hubble Deep Field (HDF) (Williams et al. 1996) and the surrounding Hubble Flanking Fields (HFFs) are the best-studied areas of sky to date. The random region is unbiased, although it was chosen for the absence of any bright objects at any wavelength. Recently, several groups have observed the HDF in the radio regime, using the VLA, MERLIN, WSRT and the EVN (see Table 1). This allows a first estimate of the high-redshift space density of FR I radio sources, which is discussed in this paper.

Richards et al. (1998) have observed the HDF at 8.4 GHz using the VLA in A, CnB, C, DnC and D configurations, corresponding to angular resolutions ranging from 0.3 to 10 arcsec. They detected 29 radio sources in a complete sample within 4.6 arcmin of the HDF centre and above a flux density limit of 9 μJy, of which seven are located in the HDF itself. Muxlow et al. (1999 and in preparation) have observed the HDF at 1.4 GHz, using the VLA for 42 hours and MERLIN for 18 days. They have detected a complete sample of 87 sources in a $10 \times 10\,\mathrm{arcmin}^2$ region with flux densities above 40 μJy. These have all been imaged with the MERLIN + VLA combination to produce images with 0.2-, 0.3-, and 0.5-arcsec resolution with an rms noise-level of 3.3 μJy. In addition, Garrett et al. (2000) have observed the HDF with the WSRT at 1.4 GHz, resulting in an angular resolution of 15 arcsec and a noise-level of 8 μJy. They detect 85 regions of radio emission ($>5\sigma$) in a $10 \times 10\,\mathrm{arcmin}^2$ field centred on the HDF, with four sources not previously detected at 1.4 GHz. Garrett et al. (2001) have taken deep European VLBI Network (EVN) observations of the HDF, with a resolution of 25 milliarcsecond. This has resulted in the detection of three sources above a flux density level of 210 μJy.

The deep optical/radio observations of the HDF and HFF indicate that ~60 per cent of the faint sub-mJy and μJy radio sources are identified with star-forming galaxies at moderate redshifts ($z \sim 0.2 - 1$), often showing morphologically peculiar, interacting/merging galaxies with blue colours and H II-like emission spectra (Richards et al. 1998). Another 20 per cent of the sources are as yet unidentified in the optical down to $I = 25.5$ in the HFFs and $I = 28.5$ in the HDF. These faint systems may be distant galaxies obscured by dust. The remaining 20 per cent of the faint radio population seem to be identified with relatively low-luminosity AGN.

This paper concentrates on the two brightest radio sources at 1.4 GHz, both exhibiting a clear FR I radio morphology. We will discuss the implications of their presence in the HDF and HFFs for the cosmological evolution of these objects. Throughout this paper we assume a cosmology with $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0.5$, for consistency with previous studies.

Table 1. Radio observations of the Hubble Deep Field and Flanking Fields. The columns give the telescope used, the observing frequency, resolution, flux density limit, number of detected sources, and the reference to the observation.

Telescope	Frequency (GHz)	Resolution (arcsec)	Flux limit (μJy)	Number of Sources	Reference
VLA A,CnB, C, DnC & D	8.4	0.3–10	9	29	Richards et al. (1998)
VLA + MERLIN	1.4	0.2	40	87	Muxlow et al. (in preparation)
WSRT	1.4	15	40	85	Garrett et al. (2000)
EVN	1.6	0.025	210	3	Garrett et al. (2001)

2 FR I RADIO GALAXIES IN THE HDF AND HFF

2.1 HDF123644+621133

The radio source HDF123644+621133 is the brightest object in the HDF at 8.4 GHz. It has an 8.4-GHz flux density of 477 μJy. Muxlow et al. (in preparation) give a total 1.4-GHz flux density of 1.2 mJy using VLA + MERLIN data, while Garrett et al. (2000) report a total flux density of 1.6 mJy using the WSRT. This higher flux density is probably a result of the lower resolution of the WSRT observations, containing a larger proportion of the total source flux. The radio source consists of an unresolved core with a relatively flat spectrum ($\alpha_{1.4\text{–}8.4\,\mathrm{GHz}} = -0.3 \pm 0.2$, with $f(\nu) \propto \nu^{\alpha}$), which is surrounded by steep-spectrum ($\alpha_{1.4\text{–}8.4\,\mathrm{GHz}} = -1.2 \pm 0.2$) emission oriented north–south and extending about 30 arcsec (Fig. 1). The radio source shows a prototypical FR I morphology. It is optically identified with a bright $R_{\mathrm{AB}} = 20.5$ elliptical galaxy at $z = 1.013$ (Richards et al. 1998). Assuming the flux densities and spectral indices of the core and extended structure given above, HDF123644+621133 has an observed flux density at 178-MHz rest frequency (88 MHz observed) of $S_{178\,\mathrm{MHz}} = 24$ mJy. This corresponds to a total radio power of $P_{178\,\mathrm{MHz}} = 10^{24.8}\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$.

2.2 HFF123725+621128

The radio source HFF123725+621128 is the brightest radio source in the HDF and HFFs at 1.4 GHz, with a total flux density of ~6 mJy. The high-resolution MERLIN + VLA image, crucial for a morphological classification, shows it to be 5 arcsec in extent with two high-brightness regions (peak brightness of 200 μJy beam^{-1}) close to its centre, making it an FR I radio source (Fig. 1). The two diffuse extended lobes at the east and west side are both slightly bent towards the south, giving the object the appearance of a wide-angle tail (WAT). At low redshift these are mostly found in galaxy-cluster environments. Richards et al. (1998) quote a spectral index for this source of $\alpha_{1.4\text{–}8.4\,\mathrm{GHz}} = -1.0 \pm 0.1$. Its detection in the WENSS survey at 325 MHz (Rengelink et al. 1997) of 25 mJy is consistent with this.

The radio source is optically identified with a compact, possibly elliptical galaxy located between the two regions of high brightness (Richards et al. 1998). It has an R_{AB} magnitude of 24.1, a G_{AB} magnitude of ~26.5, and an $H + K$ magnitude of 18.7, which corresponds to $K \approx 19.0$. To date, no redshift has been measured. However, its faint optical magnitude and its red optical to near-infrared colours makes it highly unlikely it is at $z < 1$. Comparison with the K–z diagram for powerful radio galaxies (e.g. Lilly & Longair 1984) also makes it most likely that this object is located at $z > 1$. If we assume a lower limit in redshift of $z = 1$, its rest frame 178-MHz power must be higher than $P_{178\,\mathrm{MHz}} \gtrsim 10^{25.3}\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$, making it at least a few times more luminous than HDF123644+621133. If it is located at $z = 1.5$, it would have $P_{178\,\mathrm{MHz}} \approx 10^{25.7}\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$. This is such a high luminosity that it would be comparable to the most powerful FR Is found in the local Universe, i.e., those near the FR I/II division with the optically most luminous host galaxies (Ledlow & Owen 1996).

2.3 Other FR I radio sources in the HDF?

To identify a radio source at high redshift as one with an FR I morphology, the radio observations have to be of both sufficient resolution (e.g., using MERLIN) and of sufficient sensitivity to detect the low-level extended emission. The edge-darkened emission, characteristic for an FR I radio source, is in the case of HDF123644+621133 and HFF123725+621128 detected only at a

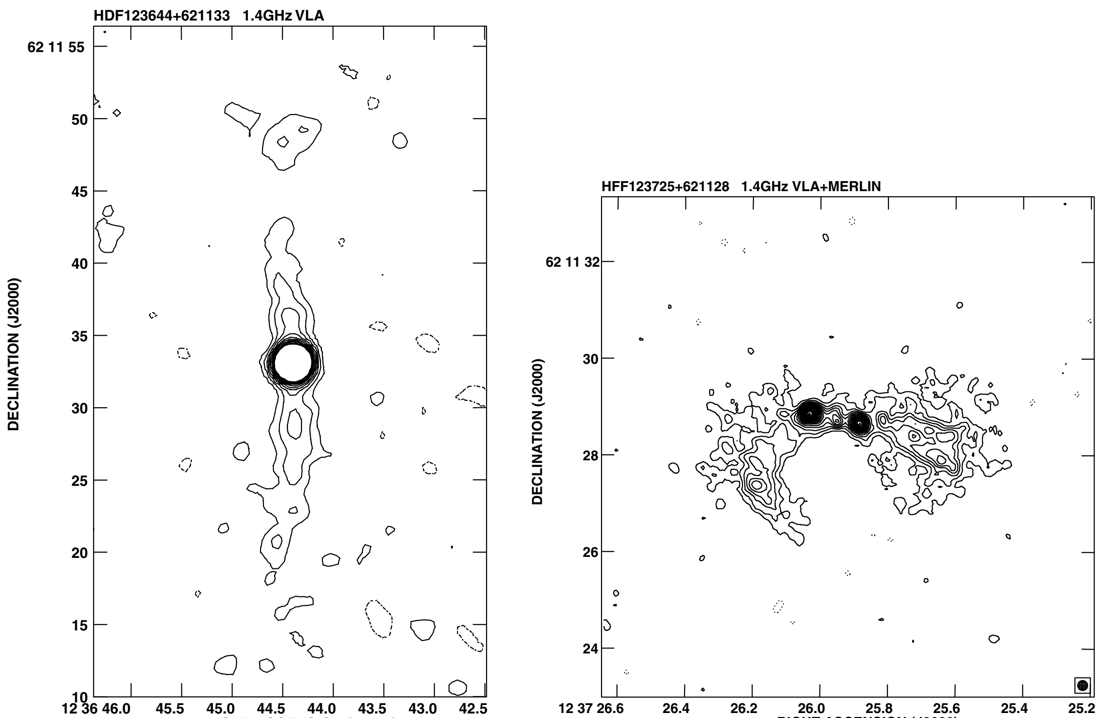

Figure 1. The 1.4-GHz image of the FR I radio sources HDF123644+621133 from VLA data (left) and of HFF123725+621128 from VLA + MERLIN data (right), kindly provided by T. Muxlow (Muxlow et al., in preparation).

few-σ level, while these sources are two of the brightest objects in the HDF and HFFs. Muxlow et al. (1999) have identified 14 much fainter sources which appear to have compact two-sided emission. For a significant fraction of those, fainter emission on larger extended scales may have been missed, hampering their classification as FR Is. We therefore believe that using the existing VLA and MERLIN data, only sources down to mJy levels can reliably be classified as FR Is.

3 THE COSMOLOGICAL EVOLUTION OF FR I RADIO SOURCES

3.1 The local space density of FR I radio sources

We first want to assess the question of how many luminous FR I radio galaxies one would expect in an area of sky as large as the HDF + HFFs for a non-evolving cosmological evolution scenario. As a luminosity cut-off we take the luminosity of HDF123644+621133, which is the weaker of the two, independent of the exact redshift of HFF123725+621128.

First, the local space density of FR I radio sources has to be determined. We used the complete subsample of 3CR as defined by Laing, Riley & Longair (1983) for this purpose. It identifies 30 FR I radio galaxies in an area of sky with $\delta > 10°$ and $|b| > 10°$ (4.24 sr). Using the 3CR flux density cut-off of 10.9 Jy at 178 MHz and an average spectral index of $\alpha = -0.75$, a radio galaxy with $P_{178\,\mathrm{MHz}} = 10^{24.8}\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$ can be seen out to $z = 0.042$. Four FR I galaxies are found with $P_{178\,\mathrm{MHz}} > 10^{24.8}\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$ in the comoving volume of $2.2\times10^7\,\mathrm{Mpc^3}$ ($z < 0.042$), which corresponds to a local space density of 170 FR Is per $\mathrm{Gpc^3}$. Note that we obtain a very similar value of 200 FR Is per $\mathrm{Gpc^3}$ brighter than $P_{178\,\mathrm{MHz}} > 10^{24.8}\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$, using DP90's local luminosity function of steep spectrum radio sources, assuming that all sources with $P_{2.7\,\mathrm{GHz}} > 10^{24.2}\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$ ($\equiv P_{178\,\mathrm{MHz}} > 25.3\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$) are FR IIs, and all the fainter sources are FR Is. We will use the latter value in our calculations.

3.2 Implication for a no-evolution scenario for FR I radio galaxies

Hence, what is the chance of finding two FR I radio sources in an area as large as the HDF and HFFs for a non-evolving population? The area of sky surveyed by the VLA and MERLIN covers $10\times10\,\mathrm{arcmin^2}$. The main parameter involved is the maximum redshift, z_{max}, at which the radio sources still would have been detected and classified as FR Is. To estimate this is a difficult task, not least due to the uncertain redshift of one of the objects. We believe that the limiting factor for z_{max} for both sources is the low surface brightness level of the extended emission in their lobes, which is proportional to $(1+z)^{-4}$, assuming a spectral index in the lobes of $\alpha = -1.0$.

In both objects, the extended emission is detected at about a 10σ level, implying that HDF123644+621133 could have been detected out to $z \approx 1.7$ at $> 3\sigma$. We do not know the redshift of HFF123725+621128 but, as we argued above, we believe it will probably be in the range $1 < z < 1.5$–2. If it were at $z = 1$, it would have a z_{max} of ~ 1.7. If it were at $z = 1.5$ or $z = 2.0$, it would have a z_{max} of ~ 2.4 or ~ 3.0. We therefore do the calculation for $z_{\mathrm{max}} = 1.5$, 2.0, 2.5 and 3.0. The data are presented in Table 2, with the z_{max} in column 1, the comoving volume densities in column 2, and the expected number of FR Is in the HDF and HFFs with $P_{178\,\mathrm{MHz}} > 24.8\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$ in column 3. The chance, P_2, of finding *two or more* objects in this volume, if the expected number is p, is

$$P_{>2} = \mathrm{e}^{-p}(\mathrm{e}^{p} - 1 - p), \qquad (1)$$

which is derived using a Poisson distribution. This is given in column 4 of Table 2. It indicates that the presence of two FR I radio galaxies in the HDF and HFFs is inconsistent (< 1 per cent) with a no-evolution scenario for FR Is, and that their comoving space density at $z = 1$–2 was about an order of magnitude higher than at the present time.

3.3 Constraints on other cosmological evolution models

Now that we have determined that it is unlikely that FR I radio sources undergo no cosmological evolution from $z = 0$ to $z = 1$, we want to investigate whether FR I and FR II radio sources have to be treated as to distinct populations of objects. In this section we will compare the data with the evolutionary models of DP90. DP90 do not treat the FR Is and FR IIs separately; instead they adopt a luminosity-dependent cosmological evolution for the total population of steep-spectrum sources, derived from source counts and redshift information. We will consider two of their models: the pure luminosity evolution model and the luminosity/density evolution model.

In both cases, the low-redshift luminosity function (LF) is fitted using two power-law slopes, with the LF being flatter below the break luminosity and steeper above. In the pure luminosity evolution model, the overall shape of this LF does not change with cosmological epoch, only the normalization in luminosity. Since the slope of the LF is flatter at low luminosities, it results in less cosmological evolution for the weaker objects. Since we only have to consider objects below the break luminosity, where the slope of the luminosity function is $\alpha = -0.69$, at a specific redshift the density is enhanced by a factor $10^{0.69}\times f$. The parameter f is the amount of luminosity evolution, which is determined by DP90 to be $f = 1.26z - 0.26z^2$. For the redshift ranges involved, the local

Table 2. Chance of finding two FR Is in the HDF and HFFs with $P_{178\,\mathrm{MHz}} > 24.8\,\mathrm{W\,Hz^{-1}\,sr^{-1}}$ for no evolution, and the pure luminosity and luminosity/density evolution models of Dunlop & Peacock (1990), using different redshift cut-offs.

		No Evolution		Pure Lum. Evolution			Lum/Dens Evolution		
z range	Volume ($\mathrm{Mpc^3}$)	Exp. nr	$P_{>2}$	Density enhance.	Exp. nr	$P_{>2}$	Density enhance.	Exp. nr	$P_{>2}$
< 1.5	2.4×10^5	0.048	0.1%	4.8	0.23	2%	4.1	0.20	2%
< 2.0	3.7×10^5	0.074	0.3%	6.4	0.47	8%	5.5	0.41	6%
< 2.5	4.9×10^5	0.098	0.4%	7.6	0.74	17%	6.6	0.65	14%
< 3.0	6.1×10^5	0.122	0.7%	8.2	1.00	26%	7.0	0.85	21%

space density of FR Is would on average be enhanced by a factor of 5–8, which corresponds to $P_{>2} = 2$–26 per cent. The data are presented in Table 2, with column 5 giving the mean density enhancement, column 6 giving the expected number of FR Is in the HDF and HFFs, and column 7 giving the chance of finding two or more FR Is in this area, for the pure luminosity evolution model of DP90.

The luminosity/density evolution model of DP90 is based on their pure luminosity evolution model, but modified to allow also the density normalization to vary with z. In a similar fashion as above, but with slightly different parameters, this model would result in an average space density enhancement of a factor of 4 to 7, which implies a chance of finding two or more FR Is in this area of 2–21 per cent, for the luminosity/density evolution model of DP90. This is given in columns 8–10 of Table 2.

Therefore, in contrast to the no-evolution models, the DP90 models, which do not treat FR I and FR II as distinct populations, predict surface densities of FR I radio sources which are only slightly lower than found in the HDF and HFFs.

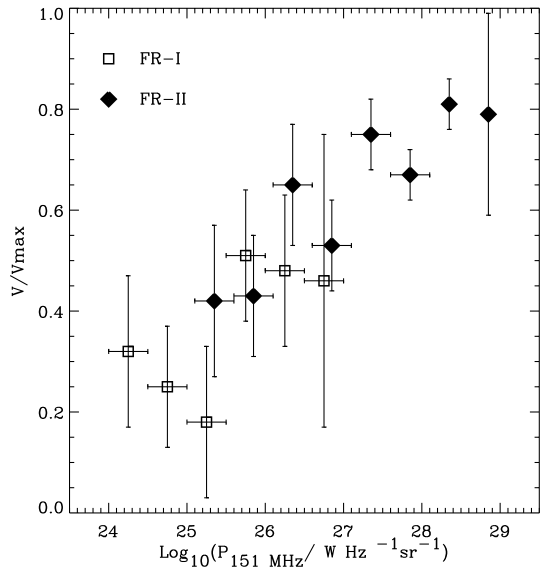

Figure 2. Average $V/V_{\max}$ values for FR Is (squares) and FR IIs (diamonds), for bins in $\Delta \log_{10}(P_{151\,\mathrm{MHz}}) = 0.5$. These values are taken from Jackson & Wall (1999). Note that no distinction can be made between FRIs and FRIIs.

4 DISCUSSION AND CONCLUSIONS

4.1 A single population scheme?

The deep optical/radio observations of the HDF and HFFs have allowed for the first time an estimate of the space density of FR I radio sources at high redshifts. The two FR I radio sources present in this area of sky indicate that it is unlikely that FR I radio sources undergo no cosmological evolution. We believe that this may undermine the reason for having a 'dual population' scheme, in which the FR I and FR II radio sources are treated as separate classes of objects, with little or no evolution and strong cosmological evolution respectively (e.g. Jackson & Wall 1999). We want to advocate a 'single-population' scheme, in which the cosmological evolution is a function of radio power, but not dependent on FR class. Since powerful radio sources undergo a stronger evolution than the less powerful ones, and FR Is are mainly radio sources of low power, FR Is undergo less evolution than FR IIs. However, the populations of FR I and FR IIs of similar radio power undergo similar cosmological evolution. Indeed, the evolution models of DP90, which make no distinction between FR classes, do fit number-count statistics and redshift distributions well. In addition, they predict number densities which are comparable to that found in the HDF and HFFs.

Basically, it is the coincidence of two observations which have led to a dual-population scheme: (1) the $V/V_{\max}$ test showing that high-power radio sources undergo strong space density enhancements and low-power sources do not, and (2) the morphological dichotomy between sources of high and low radio power. However, the $V/V_{\max}$ tests for FR Is and FR IIs are sensitive over very different redshift ranges. Jackson & Wall (1999) show in their figs 2 and 3 the mean $VV_{\max}$ values as a function of radio power for FR Is and FR IIs respectively, indicating an increase in $VV_{\max}$ as function of radio power. We reproduce these values in Fig. 2, using different symbols for the two FR classes. As can be seen, no distinction can be made between the mean $VV_{\max}$ values of FR I and FR II sources at a particular radio power. It is due to the fact that FR Is are of lower radio power, and therefore only found at the lowest redshifts, that they show a lower average $VV_{\max}$. We therefore believe that the results of the $VV_{\max}$ test actually do not make a dual-population scheme necessary, and perhaps even argue against one.

Willott et al. (2001) also introduced a dual-population scheme in their analysis of complete flux density-limited samples of 3C, 6C and 7C, which provided an unprecedented coverage of the redshift–luminosity plane. Their division between low-power radio sources with weak emission lines and high-power radio sources with strong emission lines (not by FR class), results in a space density enhancement of about an order of magnitude for the weak objects out to $z = 1$, and about 3 orders of magnitude for the powerful objects out to $z = 2$. Using the current data, it is difficult to make a distinction between this particular scheme and a single-population scheme as proposed here: although the two schemes have conceptually different viewpoints, they result quantitatively in a very similar cosmological evolution for the FR I galaxies. Note, however, that the evolution as proposed by Willott et al. results in a peculiar luminosity function at high redshift, with a prominent 'hump' at the location of the break-luminosity at low redshift.

Treating the population of powerful radio-loud AGN as a single class of object would have many benefits, since in this way the two FR classes are 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 FR I. This may also explain the dependence of the FR I/FR II 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.

If the dual-population scheme were to be correct, and FR Is and FR IIs undergo different cosmological evolutions, it would imply fundamental differences between these two classes of object, like the properties of their central engines such as black hole spin or jet composition. As has been argued by Gopal-Krishna & Wiita (2000), the existence of radio sources, in which the two lobes exhibit clearly different FR morphologies, is difficult to reconcile with such models, but supports explanations for the FR dichotomy based upon jet interaction with the medium external to the central engine.

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