Extragalactic radio-source evolution under the dual-population unification scheme

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Accepted 1998 November 13. Received 1998 October 26; in original form 1998 August 17

ABSTRACT
We show that a dual-population unification scheme provides a successful paradigm with which to describe the evolution and beaming of all bright extragalactic radio sources. The paradigm consists of two intrinsic radio-source populations, based on the two distinct radio-galaxy morphologies of Fanaroff–Riley (FR) classes I and II. These represent the ‘unbeamed’ or ‘side-on’ parent populations of steep radio spectra; the ‘beamed’ source types, including flat-spectrum quasars and BL Lac objects, arise through the random alignment of their radio axis to our line of sight where Doppler beaming of the relativistic radio jets produces highly anisotropic radio emission.

We develop the model in two stages. In the first stage the source space density as a function of cosmic epoch is determined for the two parent populations, and for this we use low-frequency source-count and identification data to avoid biases due to Doppler-enhanced radio emission. The second stage defines the beaming models for each population, using high-frequency survey data and in particular the 5-GHz source count in which at high flux densities the flat- and steep-spectrum sources contribute in similar measures. We assume that the flat-spectrum objects, quasars and BL Lac objects are ‘beamed’ versions of FR I and FR II objects in which the close alignment of the radio axis with the line of sight has changed the radio appearance into a core-dominated (flat-spectrum) object. We adopt a simple parametrization of the beaming, orient the parent populations at random with a Monte Carlo process, and use a minimization process to determine beaming parameters that yield a best fit to the 5-GHz source count. The best-fitting parameters are found to be in good agreement with those measured observationally for individual radio sources. In this, the model accurately reproduces the change in source-count form with frequency. Indeed the unified-scheme paradigm has great predictive power, and we show how the model successfully describes several additional and independent data sets.

Key words: galaxies: evolution – galaxies: jets – quasars: general – radio continuum: galaxies.

1 INTRODUCTION
The dramatic space-density evolution of radio-loud active galactic nuclei (AGNs) has been shown to mirror the cosmic star formation rate (Wall 1998; Boyle & Terlevich 1988; Shaver et al. 1998). Similar strong epoch dependence is seen in the faint-blue galaxy population (Metcalfe et al. 1995; Roche et al. 1996), IRAS galaxies (Saunders et al. 1990) and the radio-bright starbursting galaxies (Condon 1984; Rowan-Robinson et al. 1993). These correlated epoch dependencies provide enticing clues towards understanding AGN physics, in the context of triggers to activity such as coalescence of critical mass, merging, fuel supply, and the lobe confinement provided by an evolving intergalactic medium (IGM).

Our concept of the radio-source populations developed slowly. The work of Longair (1966) and collaborators (Doroshkevich, Longair & Zeldovich 1970) demonstrated conclusively the dependence of the radio-AGN evolution on radio luminosity: at redshifts \( z \) the most powerful radio sources showed space-density enhancements by factors of \( > 10^3 \) over present-day densities, whereas the less powerful sources showed little or no enhancement. Subsequently Fanaroff & Riley (1974) demonstrated a morphological dichotomy: double-lobe radio sources with regions of highest surface brightness close to the nucleus (Fanaroff–Riley type...
(FRI) have radio luminosities consistently lower than those with highest surface brightness at the extremities (FRII). The FR I–FR II division occurs approximately\(^1\) at a radio power of \(\log_{10}(P_{151 \text{ MHz}}) \sim 25\) W Hz\(^{-1}\) sr\(^{-1}\), close to the luminosity that separates strongly evolving radio sources from those showing little evolution. On the basis of this coincidence, Wall (1980) suggested that the FR I population showed near-constant space-density while the FR II objects evolved strongly with cosmic epoch.

The early surveys were at relatively low frequencies and catalogued predominantly steep-spectrum radio galaxies of extended double-lobed structures. During the late 1960s and the 1970s surveys at frequencies > 2 GHz found a large number of radio AGN, the spectra of which did not decrease monotonically with frequency – sources of hard radio spectra, described (unfortunately) as ‘flat-spectrum’ objects. In contrast to the host objects of steep radio spectra, predominantly giant ellipticals, the majority of the flat-spectrum objects were identified with quasi-stellar objects (quasars) or BL Lac objects and had compact radio structures, unresolved until mapped with very long baseline interferometry (VLBI). Schmidt (1976) and Masson & Wall (1977) claimed that despite the (quasars) apparent high radio luminosity of such objects, they showed little evolution. This result was disputed and eventually the comprehensive analysis of Dunlop & Peacock (1990) showed that qualitatively the flat-spectrum population showed a similar evolutionary behaviour to the steep-spectrum population: luminosity-dependent density evolution was required. However, at a particular radio luminosity, the space-density evolution of the flat-spectrum population is less than that of the steep-spectrum population. At the time, physical connections between the steep-spectrum and flat-spectrum populations were not considered in such analyses.

It was the discovery of relativistic expansion (Cohen et al. 1971; Moffat et al. 1972) through repeated VLBI measurements of the brighter ‘flat-spectrum’ sources that laid the foundation for unification paradigms. Whilst relativistic motion is the primary mechanism giving rise to anisotropic radio emission in radio-loud AGN, a second mechanism, the presence of a dusty molecular torus (Antonucci & Miller 1985) was invoked to explain the optical emission characteristics of some sources. From these two physical mechanisms the paradigm emerged in which the random orientation of a ‘parent’ population on the plane of the sky gave rise to radio sources of apparently diverse type. The unified schemes proposed for radio-loud AGN (Scheuer & Readhead 1979; Orr & Browne 1982; Scheuer 1987; Barthel & Spinelli 1989) have both radio and optical appearance governed by proximity of the line of sight to the radio (presumably rotation) axis. In the radio regime, close coincidence changes the morphology from an extended steep-spectrum source to a source with a dominant flat-spectrum ‘core’ from the Doppler-boosted base of the foreground jet. The optical appearance changes from a galaxy as viewed side-on to a quasar or BL Lac object when orientation permits a view into the torus opening angle and optical/UV radiation from the accretion disc system dominates stellar emission.

If we are to understand the physical significance of the evolution that originally suggested different populations, it is essential to delineate the populations on a physical basis. We cannot map the evolution meaningfully until we know the physically distinct populations for which we wish to derive it.

The primary purpose of this paper is to advance this chicken-and-egg situation in the following way. First, we consider the dual-population unified scheme, based on the premise that the two parent populations are FR I and FR II radio galaxies, which give rise to BL Lac objects and quasars as beamed progeny. Our basic assumption is that all radio sources detected above \(S_{\text{5 GHz}} \sim 3\) mJy are encompassed by this scheme. Using the best available data in terms of source counts and identifications at low frequencies, we estimate the space-densities of the parent populations. We then set up the unified models to define critical angles within which the line of sight turns these lobe-dominated sources into core-dominated sources. Using a Monte Carlo orienting process we allow free rein to the fitting process to reproduce a high-frequency radio source count. This process results in a model for the Doppler beaming of the radio jets with physical parameters that closely mirror those observed in VLBI monitoring surveys. The dual-population unified scheme makes numerous quantitative predictions that can be tested, and a number of these are described in this paper. Crucial further observations are delineated.

This is not the first attempt to incorporate a unification paradigm within space-density analyses. Before the discovery of dusty tori, Scheuer & Readhead (1979) proposed a model of superluminal expansion for quasars with a view to explaining the ratio of radio-quiet QSOs to radio-loud quasars. A second seminal study by Orr & Browne (1982) proposed that the core-dominated quasars were aligned versions of steep-spectrum quasars based on the twin relativistic-jet model of Blandford & Rees (1974). Using the observed redshift distribution of 3C quasars and a simple beaming model they calculated the Lorentz factor, \(\gamma\), from the observed core-to-lobe flux ratio distribution, \(R\), for a sample of quasars. They found that the flat-spectrum quasar fractions at 2.7 and 5 GHz could be reproduced by single values of \(R\) and \(\gamma\). These views of unification were limited, primarily in that the dusty torus did not form part of the modelling. More recently, Urry and Padovani (1995 and references therein) considered a simple two-population unified scheme, where FR II radio galaxies are the parent population of all quasars and FR Is are the parent population of all BL Lac-type objects. They fitted the observed luminosity function for the steep-spectrum, ‘misaligned’ objects to the flat-spectrum, ‘aligned’ luminosity function, using a pure luminosity evolution model coupled with the simple model of the Doppler beaming which required a large range of Lorentz factors.

In contrast, this paper starts with a definition of the two parent populations based on low-frequency data alone, and derives independent space-density descriptions for each. Using high-frequency data it then derives beaming models for each population. An embryonic version of the present model was described by Wall & Jackson (1997); the present paper adopts the same thesis and procedure, presents the data in detail, describes a refined version of evolution for the parent population and develops beaming models that provide a distribution of apparent jet velocities as well as core-to-lobe flux ratios. In addition, cosmological tests of the paradigm are presented.

Throughout this paper we use \(h = 0.5\) and \(\Omega_0 = 1.0\).

## 2 THE DUAL-POPULATION UNIFIED SCHEME

The current unification paradigm for radio-loud AGN is based on two ‘parent’ populations, namely (i) the high radio-power FR II galaxies and (ii) the moderate radio-power FR I galaxies. Both populations exhibit anisotropic radiation arising from superluminal motion (Doppler beaming) of the radio jets. In addition, obscuration by a dusty torus contributes to the orientation-dependent...
appearance of the high-power FR IIs; when the torus/rotation axis and the line of sight are approximately aligned, radiation from the accretion disc about the black hole dominates the galaxy emission. The orientation angle of the radio axis on the plane of the sky determines the observed characteristics and hence the classification of the object.

In the case of the FR II radio galaxy, a side-on view reveals a lobe-dominated steep-spectrum radio source hosted by a giant elliptical galaxy, possibly with narrow emission lines of high excitation. As the observer’s line of sight comes closer to the radio axis, the object appears as a ‘steep-spectrum quasar’, the line of sight bringing the blue light/broad-line region of the nuclear accretion disc into view to dominate the light of the host galaxy. At close coincidence, the radio emission is dominated by the Doppler-enhanced core or base of the forward jet; features may show superluminal velocities. In the case of the FR I radio galaxies, the side-on view shows a galaxy of weak-to-no narrow emission lines while the on-axis view reveals a BL Lac object of essentially featureless optical continuum and compact radio structure showing superluminal velocities.

The steep-spectrum side-on objects, FR I and FR II radio galaxies plus steep-spectrum quasars, dominate the results from low-frequency surveys, the complete samples and source counts. High-frequency radio surveys favour the radio sources of higher spectrum, i.e. beamed, core-dominated sources, BL Lac objects and core-dominated quasars. Raising the frequency of the survey selects samples and source counts dominated by objects with their radio axes close to our line of sight.

The hypothesis that lobe-dominated steep-spectrum and core-dominated flat-spectrum quasars are increasingly aligned versions of FR II radio galaxies was originally proposed by Scheuer (1987), Peacock (1987) and Barthel (1989). The corresponding scheme for FR I–BL Lac unification was put forward by Browne (1983) and Perez-Fournon & Biermann (1984). However, there is accumulated evidence that the unified scheme is not quite so straightforward. In particular the FR II sources are not a homogeneous population in terms of their optical/UV spectral characteristics: Hine & Longair (1979) showed that FR IIs can have strong narrow optical/UV emission lines (class ‘A’) or only weak, if any, lines, similar to FR I sources (class ‘B’). Laing et al. (1994) showed that in the 3CRR sample of Laing, Riley & Longair (1983), this dichotomy was reflected by a clean division between high-excitation/strong emission-line objects and low-excitation/weak-to-no emission-line objects. This dichotomy in the FR II population is reflected in the ‘dual population’ unified scheme which we propose. We suggest that only the class ‘A’ FR II sources appear as lobe-dominated broad-line quasars, or core-dominated broad-line quasars at small angles of their radio axes to our line of sight. Moreover, it is only for the class ‘A’ sources that the presence of an obscuring torus is invoked.

The role of the low-excitation FR IIs has not been considered in unified models or space-density analyses to date. However, the shape of the radio luminosity function for the FR II population shows that there must be many more low-excitation sources than high-excitation ones, given that excitation status correlates with radio power (Laing et al. 1994; Barthel 1994). If these objects have relativistically beamed radio jets then they must show a beamed subpopulation. There is strong evidence, both direct and circumstantial, that this subpopulation is seen as BL Lac objects. First, around some BL Lacs there are extended structures consistent in scale and power with the lobes of FR II sources (Browne et al. 1982; Kollgaard et al. 1992; Murphy, Browne & Perley 1993; Dallacasa et al. 1997). Secondly, there are too few FR Is for them to be the only class of host galaxy for BL Lacs

Figure 1. (a) Unified scheme for FR II radio sources. (b) Unified scheme for FR I radio sources.

(Owen, Ledlow & Keel 1996). Thirdly, the lack of observed narrow emission lines in the parent sources, in the class-B FR II galaxies, correlates with the optical spectral properties of BL Lacs; the majority of radio galaxies of intrinsic radio luminosities more powerful than the FRI/FRIII divide, show passive elliptical-galaxy spectra (Rixon, Wall & Benn 1991).

Thus our dual-population unified scheme, illustrated in Fig. 1, consists of two parent populations: (a) the high radio-power FR II radio galaxies, which are the parents of all radio quasars and some BL Lac-type objects, and (b) the moderate radio-power FR I radio galaxies, which are the parents of BL Lac-type objects.
Table 1. Extragalactic radio source classes.

| Population | UV/optical emission-line signature | Radio spectrum $\nu$–5 GHz | Class | Contribution to source count $\nu \leq 1$ GHz | $\nu \geq 1$ GHz |
|------------|-----------------------------------|-----------------------------|-------|---------------------------------------------|-----------------|
| FRII, class A\(^a\) | narrow | steep | RG | prominent | prominent |
| broad | | steep | RG\(^b\) | prominent | prominent |
| narrow | | ‘flat’ | quasar | <5 per cent | <10 per cent |
| FRII, class B\(^a\) | weak/none | narrow | steep | RG | prominent | prominent |
| none | | ‘flat’ | BL Lac | <5 per cent | <10 per cent |
| FR I | weak/none | narrow | ‘flat’ | RG | prominent | prominent |
| none | | | BL Lac | <5 per cent | <10 per cent |
| Starburst | narrow | steep | galaxy | <1 per cent | <1 per cent |
| GPS | narrow | ‘flat’ | RG | <1 per cent | ~5 per cent |
| broad | | ‘flat’ | quasar | <1 per cent | ~5 per cent |
| CSS | narrow | steep | RG | ~15 per cent | <1 per cent |
| broad | | steep | quasar | ~5 per cent | <1 per cent |

\(^a\)Hine & Longair (1979) emission-line class.
\(^b\)Alternatively a steep-spectrum quasar.

Whilst the identified classes of extragalactic radio sources are diverse (see e.g. Wall 1994 for a detailed discussion), we adopt the working hypothesis that all radio-source types found in surveys between 0.15 and 10 GHz down to $S_{1.4\,\text{GHz}} < 1$ mJy belong to one of the two parent populations or to one other population, the starburst galaxies (Condon 1984; Windhorst et al. 1985). Table 1 describes types of extragalactic radio sources commonly discussed in the literature; the only notable exclusion is cluster relic sources (Giovannini et al.1993), which are so few in number and so low in space-density as to have minimal impact on our analysis.

The *FR I* and *FR II* sources are the powerful radio sources explicitly described by the dual-population unified scheme of the previous section.

The *starburst* galaxies are late-type, in contrast to the other populations in the table. They have intrinsically weak radio emission, and dominate radio samples at low flux densities (Windhorst et al. 1985). There is no evidence of any Doppler beaming of their radio emission; they lie outside the dual-population unified scheme. The contribution of this population is included in our analysis using previously determined luminosity functions and evolution.

The *GPS* and *CSS* are ‘peaked-spectrum’ sources, objects with peaks in their radio spectra between 0.1 and 3 GHz. There is accumulating evidence that GHz-Peaked Spectrum and Compact Steep-Spectrum (GPS and CSS) sources represent young stages (< $10^8$ yr) of FR II radio sources (Readhead 1995; Fanti, Vigotti & Di Paolo 1996). Therefore these source types are encompassed in the dual-population unified scheme given that (i) the frequency of broad-line objects in these classes is in general agreement with the simple model of a broad-line region being obscured by a surrounding torus (Fanti & Fanti 1990) and (ii) superluminal motion has been observed in nearby GPS galaxies, with Lorentz factors similar to those inferred for classical FR IIs (Giovannini et al. 1995; Taylor, Vermeulen & Pearson 1995). Moreover the shortfall of peaked-spectrum quasars may due to Doppler-boosting of the forward radio jet flattening the characteristically peaked radio spectra with the result that GPS and CSS quasars are often categorized as ‘normal’ FR II quasars (Snellen 1997).

### 3 RADIO-SOURCE SPACE-DENSITIES WITHIN THE UNIFIED SCHEME

#### 3.1 Parametric models of radio-source evolution

The first stage in our analysis is to determine the space-density evolution of the two parent populations, allowing each to undergo quite separate evolutionary histories. For each of the two populations we determine its local radio luminosity function and adopt a simple parametric description of its evolution with epoch. Whilst the parametric approach has the disadvantage of applying a rigid form of evolutionary behaviour, it has the advantage of comprising only a limited set of parameters (e.g. Wall, Pearson & Longair 1980; Orr & Browne 1982; Morisawa & Takahara 1987; Rowan-Robinson et al. 1993). The alternative approach is a free-form fit (Robertson 1980; Peacock & Gull 1981; Dunlop & Peacock 1990), advantageous as there is no requirement to ‘guess’ the form of the evolution prior to determining an acceptable fit. However, the free-form method yields a large parameter set which is difficult to manage in subsequent analyses and does not necessarily lead to further physical understanding. A final consideration in our choice of approach is that in describing independent evolutionary histories for the FR I and FR II populations, we are limited to data sets that are simply too small to use in a free-form analysis.

There are two distinct types of parametrized evolution that may be applicable to extragalactic radio sources. In the case of *luminosity evolution* (LE) the radio luminosity of sources changes with epoch. If all sources undergo the same degree of LE it is described as ‘pure luminosity evolution’ (PLE). Alternatively in *density evolution* (DE) the comoving space-density of a population changes with epoch. If all sources undergo the same degree of density evolution it is described as ‘pure density evolution’ (PDE). A combination of luminosity and density evolution is of course possible. Previous analyses which attributed a single evolution history to *all* radio sources (i.e. combining the FR I and FR II populations into a single ‘steep-spectrum’ population) have concluded that neither PLE nor PDE are applicable (e.g. Wall, Pearson...
A suitable trial form for the evolution function can be determined from the \(<V/V_{\text{max}}\) statistic for a complete sample. The best sample available at low frequencies is the 3CRR sample at 178 MHz (Laing, Riley & Longair 1983 and more recently published data collated by R. Laing, private communication) as it is complete in terms of radio morphologies and redshifts.

(i) **FR II Evolution.** A plot of \(V/V_{\text{max}}\) (Fig. 2) for the 137 steep-spectrum FR II sources in 3CRR indicates that the highest radio power FR II sources have undergone far more evolution than the lower power ones. Whilst \(V/V_{\text{max}} = 0.664 (\sigma = 0.025)\) for the 137 FR II sources, this value rises from 0.415 (\(\sigma = 0.118\)) at \(\log_{10}(P_{151\text{MHz}}) = 24.25\) to 0.807 (\(\sigma = 0.052\)) at \(\log_{10}(P_{151\text{MHz}}) = 28.25\).

(ii) **FI Evolution.** The \(V/V_{\text{max}}\) statistic for the 26 FR I sources in 3CRR is shown in Fig. 3. In contrast to the strong evolution indicated for the FR II population, the FR Is show little evidence of evolution, with \(V/V_{\text{max}} = 0.314 (\sigma = 0.057)\) for all 26 sources possibly reflecting some negative evolution. The highest power FR I sources in 3CRR have a value of \(V/V_{\text{max}} = 0.507 (\sigma = 0.144)\) at \(\log_{10}(P_{151\text{MHz}}) = 25.75\).

To model the luminosity dependence of the parent-source evolution we adopt exponential luminosity-dependent density evolution (cf. ‘model 4b’ of Wall et al. 1980) such that the evolution function \(F(P, z)\) has the form

\[
F(P, z) = \exp(M(P)\tau(z)),
\]

where \(\tau(z)\) is the look-back time in units of the Hubble time. For Einstein–de Sitter (Ω=1) geometry this is given by

\[
\tau(z) = [1 - (1 + z)^{-1.5}].
\]
Additionally we apply a redshift cut-off to the populations mirroring the observed behaviour of the powerful radio sources at high redshift (Shaver et al. 1996). The evolution function is modified such that the evolution peaks at \( z_c / 2 \) and declines to zero at the cut-off redshift \( z_c \):

\[
F = F(P,z) \text{ for } z \leq z_c / 2, \\
F = F(P, z_c - z) \text{ for } z_c / 2 < z \leq z_c \text{ and} \\
F = 0 \text{ for } z > z_c. 
\]

The evolution rate \( M \) is set between 0 and \( M_{\text{max}} \) dependent on radio power \( P \):

\[
M(P) = M_{\text{max}} \frac{\log_{10} P - \log_{10} P_1}{\log_{10} P_2 - \log_{10} P_1} \text{ for } P_1 \leq P \leq P_2, \\
M(P) = 0 \text{ for } P < P_1, \text{ i.e. no evolution of radio sources of radio power less than } P_1, \\
\text{and } M(P) = M_{\text{max}} \text{ for } P > P_2, \text{ i.e. sources of radio power greater than } P_2 \text{ undergo maximal evolution.}
\]

### 3.4 Determining the evolution

#### 3.4.1 Deriving the local radio luminosity function (LRLF)

Luminosity distributions were compiled for the powerful radio sources from the complete 3CRR sample, comprising 173 sources with \( S_{\text{178 MHz}} \geq 10.9 \text{ Jy} \). In this analysis the 10 flat-spectrum sources \( (\alpha_{\text{178 MHz}} > -0.5, \text{ where } S \propto \nu^\alpha) \) are excluded so the remainder are steep-spectrum sources, ‘uncontaminated’ by the effects of Doppler beaming.

The 178-MHz flux densities were translated to 151 MHz using a single spectral index \( \alpha_{\text{178 MHz}} = -0.75 \), the mean value for the 3CRR steep-spectrum sample. Separate luminosity distributions were compiled for the FR I and FR II steep-spectrum parent populations using the morphological classifications compiled by Laing et al. (1983) and by R. Laing (private communication). The total sample comprises 26 FR I and 137 FR II sources. The unbinned data were smoothed to give a master luminosity distribution for each population by convolving each of the unbinned luminosities with a Gaussian curve of unit area, varying \( \sigma \) until the sum of all contributions was smooth whilst preserving the ‘real’ features of the distribution. The binned and master luminosity distributions for the two populations are shown in Fig. 4.

The local radio luminosity functions for the FR I and FR II populations are then determined from equation (1), using the evolution function described by equation (3). However, the scarcity of radio sources in the 3CRR sample with radio powers below \( \log_{10} P_{\text{151 MHz}} = 23.5 \text{ W Hz}^{-1} \text{ sr}^{-1} \) yields an incomplete LRLF at these radio powers. This incompleteness is resolved by incorporation of the LRLFs determined for (i) the ‘local’ ES0 galaxies (Condon 1984) considering them as part of the FR I population, and (ii) the starburst galaxies, with the LRLF as derived by Rowan-Robinson (1993) and the evolution function of Saunders et al. (1990). These starburst sources were folded into the space-density analysis with the set evolution function

\[
F_{\text{star}}(z) = \exp(Q\tau(z)),
\]

with \( \tau(z) \), the look-back time, as given in equation (4). The evolution function \( F_{\text{star}} \) describes pure luminosity evolution as follows:

\[
Q = 3.1 \text{ for } 0 \leq z \leq 2, \\
F_{\text{star}}(z) = F_{\text{star}}(z = 2) \text{ for } 2 < z \leq 5, \\
\text{and } F_{\text{star}}(z) = 0 \text{ for } z > 5.
\]

The total local radio luminosity function is then the sum of the LRLFs for each of the three populations (FR I, FR II and starburst galaxies). The derived LRLF (Fig. 5) shows that the transition between the FR I and FR II populations is gradual and is not a simple transition at some radio power. This is also illustrated in Fig. 4 where there are a number of FR IIs in the 3CRR sample with \( P_{\text{151 MHz}} > 10^{25} \text{ W Hz}^{-1} \text{ sr}^{-1} \). The luminosity functions were tapered to avoid discontinuities, with the result that the space-densities for low-power FR IIs \( (\log_{10} P_{\text{151 MHz}} < 23.5) \) and high-power FR IIs \( (\log_{10} P_{\text{151 MHz}} > 27.5) \) are insignificant. We find good agreement with other LRLFs determined independently. At the low-power end the total LRLF agrees well with those determined by Dunlop & Peacock (1990), Sadler, Jenkins & Kotanyi (1989) and Auricemma et al. (1977). This agreement suggests that our FR I LRLF is reasonably well defined. This definition is important as low-power FR I sources are far more numerous locally than the higher radio-power FR I found in the 3CRR sample, and at low flux densities their contribution is substantial.

![Figure 4](https://academic.oup.com/mnras/article-abstract/304/1/160/971926)

**Figure 4.** Luminosity distributions for the 26 FR I (cross-hatched) and 137 FR II (hatched) radio sources in 3CRR. The smoothed master luminosity distributions are overplotted and were derived with \( \sigma = 0.35 \) in \( \log_{10}(P_{\text{151 MHz}}) \) as discussed in the text.

![Figure 5](https://academic.oup.com/mnras/article-abstract/304/1/160/971926)

**Figure 5.** Derived LRLF at 151 MHz. The solid line is the total LRLF with constituent populations FR I (dotted), FR II (dashed) and starburst galaxies (dot–dashed).
The model FR I and FR II LRLFs from the Milne ($\Omega = 0$) version of our successful model fit are in agreement with the results of Urry & Padovani (1995), expected as both analyses find little or no evolution of the FR I population. However, there is a major discrepancy between the two FR II LRLFs. Urry and Padovani adopted pure luminosity evolution for the FR II population, which predicts a high local space-density of low-power FR II. The parameters in the evolution functions for FR II were optimized by performing a $\chi^2$-minimization between the two FR II LRLFs. Urry and Padovani’s LRLF there should be similar local space-density of low-power FR II sources. According to Urry and Padovani’s LRLF there should be similar local space-densities of FR Is and FR II. Much smaller local space-densities for FR Is are observed; Ledlow & Owen (1996) find only 6 per cent of FR II sources in a local survey of Abell clusters ($z < 0.09$). However, overestimation of the LRLF for low-power FR II does not affect the analysis performed by Urry and Padovani which concentrates on fitting the RLF for the high-power quasar population.

3.4.2 Fitting the 151-MHz source count

The parameters in the evolution functions for FR I and FR II sources were optimized by performing a $\chi^2$-minimization between the observed source count at 151 MHz and the total count predicted by the differentially evolving RLF. The minimization was achieved using the amoeba downhill simplex method in multi-dimensions (Press et al. 1992). The unique set of evolution parameters thus derived for each parent population is shown in Table 2.

The 151-MHz source count used in this comparison (Fig. 6) consists of the count from the 6C survey (Hales, Baldwin & Warner 1988) and the count from the 3CR survey from the 3CRR catalogue at 178 MHz (Laing, Riley & Longair 1983), transposed to 151 MHz using a single spectral index of $-0.75$.

The set of parameters given in Table 3 provides a good fit to the observed source count. This fit has strong cosmic evolution of the FR II population coupled with no evolution of the FR I population. The fit to the differential count is shown in Fig. 6. For the most powerful FR II sources this model predicts a space-density enhancement at $z=2.8$ of $>10^5$ times that of the local space-density (Fig. 7). That the FR I population undergoes little or no evolution is a requirement of the 151-MHz source count fit: any significant evolution produces an excess of faint sources, in disagreement with the decline of the differential source count towards lower flux densities. The successful fit also indicates a redshift cut-off in the FR II population, with the fit with $z_c = 5.62$ superior to that with $z_c = \infty$ at the 99.9 per cent level of significance. As a result the model reproduces the ‘quasar epoch’, reflected as a peak in the FR II space-density (Fig. 7) around $z = 2-3$, as seen for powerful flat-spectrum quasars (Shaver et al. 1996).

4 RADIO-SOURCE BEAMING IN THE UNIFIED SCHEME

According to the dual-population unified scheme, flat-spectrum quasars and BL Lac-type sources are the steep-spectrum FR II and FR I sources aligned so that the radio axes are close to our line of sight. The result is that the flat-spectrum emission from the approaching radio jet is Doppler-boosted or ‘beamed’. This

Figure 6. Source-count fit at 151 MHz. Data points represent the observed differential source count at 151 MHz constructed as described in the text. The model produces contributions from the three populations, the FR II sources (dashed), the FR I sources (dotted) and the starburst galaxies (•). The total model count is shown as a solid line. All counts are shown in relative differential form with $N_0 = 2400S_{151\,\text{MHz}}^{-1.5} \, \text{sf}^{-1}$.

Figure 7. Space density enhancements as determined from optimized model parameters for a range of $\log_{10}(P_{151\,\text{MHz}})$ values as shown.

$^3$It is the base of the approaching jet that is flat-spectrum. Alternative scenarios are that the relativistic emission is from (i) the stationary core of the radio source which is optically thick at the observing frequency or (ii) synchrotron plasma emanating from the central object. All three scenarios are in agreement with the results here.
Doppler boosting can result in the jet emission dominating the extended lobe emission.

Having derived the space-density and its epoch dependence for the parent populations, the low-frequency counts and identification statistics are satisfied. Translating the count of these steep-spectrum objects to 5 GHz reveals the shortfall at high flux densities in particular which must be there: no flat-spectrum sources have yet been included and such sources constitute more than half of those found in cm-wavelength surveys. To provide this contribution we ‘beam’ the parent populations, orienting objects randomly to mimic the effects of the Doppler-enhanced radiation when lines of sight and ejection axes come into close coincidence. The parameters required to describe the beamed emission for any source are the spectral index of the core/jet emission, the Lorentz factor required to describe the beamed emission for any source are the intrinsic ratio \( R_c \) of core-to-lobe radio luminosity. We adopt a simple model of the Doppler beaming for each of the two populations, with the beaming parameters varied to produce the best statistical fit to the 5-GHz source count.

### 4.1 The Doppler beaming parameters

We chose to model the Doppler beaming of the FR I and FR II populations with a range of intrinsic core-to-extended flux ratios (distributed normally about a median value) together with a single Lorentz factor for each parent population. There is an additional complication for the FR I population, in that the intrinsic ratio is a function of radio power with significant scatter about a median value (de Ruiter, Parma & Fanti 1990). In contrast, there is little evidence that the ratio correlates with radio power for the FR II population. Fig. 8 shows the observed ratio for 47 high-excitation FR II galaxies from the 3CRR sample. The median ratio appears uncorrelated to total radio power, with a significant scatter around the median values. The same result has been seen (Morganti et al. 1997) in narrow-line radio galaxies from the 2-Jy sample (Wall & Peacock 1985).

For the FR I population we adopt the following function from the observed ratio for B2 galaxies (de Ruiter et al. 1990):

\[
\log_{10} R_{\text{med}} = -0.55 \log_{10}(P_{151\text{ MHz}}) + 10.78,
\]

where \( R_{\text{med}} \) is the median ratio for FR Is of radio power \( P_{151\text{ MHz}} \). The intrinsic core-to-extended flux ratio \( R_c \) is then determined as a normal distribution about \( R_{\text{med}} \) with \( \sigma = 0.45 R_{\text{med}} \) (Laing et al. 1999). For the FR II population we reflect the observed scatter in the intrinsic ratio \( R_c \) by simply distributing it normally about a single median value \( R_{\text{med}} \), with \( \sigma = 0.45 R_{\text{med}} \). The derived intrinsic ratio, \( R_c \), is frequency-independent, apportioning the total source flux density between the extended and core emission.

### 4.2 Modelling the beamed products

The FR I and FR II populations give rise to beamed and unbeamed sources with the observed core-to-extended flux ratio, \( R_{\text{obs}} \), determining whether a particular source is observed as flat- or steep-spectrum. The procedure is illustrated in Fig. 9 and described in detail below. Throughout all flux densities are K-corrected to observed-frame values using \( \alpha = -0.75 \).

(i) A single spectral index, \( \alpha_{5\text{GHz}} = -0.75 \) is applied to the 151-MHz flux density to determine the flux density of the steep-spectrum contribution at 5 GHz. This represents the emission from the extended lobes of the source. The value of –0.75 is adopted as it is the mean spectral index of the steep-spectrum 3CRR sources between 178 MHz and 750 MHz (Laing & Peacock 1980). We extrapolate this index to 5 GHz as there is no evidence that the spectrum of the steep-spectrum components in 3CRR steepens significantly between 178 MHz and 2.7 GHz (Laing & Peacock 1980).

This steep-spectrum component flux density, \( S_{5\text{GHz, steep}} \), is

\[
S_{5\text{GHz, steep}} = S_{151\text{MHz}} \left( \frac{5000}{151} \right)^{-0.75},
\]

shown as line A to B in Fig. 9.

(ii) The emission from the flat-spectrum core of the source is calculated assuming that the source comprises a pair of oppositely directed relativistic jets of bulk plasma velocity \( \beta c \). The ejection axis of these jets is aligned at some random angle \( \theta \) (\( 0^\circ \leq \theta \leq 90^\circ \)) to our line of sight. The observed core-to-extended flux ratio, \( R_{\text{obs}} \), determines the degree of beaming observed as follows:

\[
R_{\text{obs}} = R_c \Delta,
\]

where \( \Delta \) is the sum of the Doppler enhancement from the forward- and counter-jets of the source:

\[
\Delta = \delta_f + \delta_c
\]

with the Doppler factor for the forward-jet, \( \delta_f \), as

\[
\delta_f = \left[ \gamma (1 - \beta \cos \theta) \right]^{-1}
\]

and for the counter-jet, \( \delta_c \), as

\[
\delta_c = \left[ \gamma (1 + \beta \cos \theta) \right]^{-1},
\]

where \( \beta = \nu c = (1 - \gamma^{-2})^{1/2} \).

For radio emission comprising continuously ejected plasma, \( \rho = 2 - \alpha_{\text{flat}} \). We adopt a value for the spectral index of the core emission, \( \alpha_{\text{flat}} \), of 0.0 as this is the mean spectral index \( \alpha_{\text{flat}} = 1.0 \) of the core components of the B2 sources (de Ruiter et al. 1990).

Therefore the observed core-to-extended flux ratio is given by

\[
R_{\text{obs}} = R_c \left[ \gamma (1 - \beta \cos \theta) \right]^{-2} + \left[ \gamma (1 + \beta \cos \theta) \right]^{-2}.
\]

The flux density of the beamed contribution, \( S_{5\text{GHz, flat}} \), is represented by line B to C in Fig. 9 and is simply related to the steep-spectrum flux density by

\[
S_{5\text{GHz}} = R_{\text{obs}} S_{5\text{GHz, steep}}.
\]
A source is counted as ‘flat-spectrum’ for values of $R_{\text{obs}}$ large enough such that $\alpha_{5\text{GHz}} = -0.75$ (solid line). If the radio axis lies close to the line of sight ($\theta \approx \theta_c$) the core emission (dotted) dominates and the source appears ‘flat-spectrum’; the total flux density of the source is $S_{5\text{GHz}} = S_{5\text{GHz};\text{flat}} + S_{5\text{GHz};\text{steep}}$.

The spectral index between 2.7 and 5 GHz is given by

$$\alpha_{5\text{GHz}} = \frac{\log_{10}(S_{5\text{GHz};\text{total}}/S_{2.7\text{GHz};\text{total}})}{\log_{10}(P_{5\text{GHz}}/P_{2.7\text{GHz}})}.$$ 

For $\alpha_{\text{flat}} = 0.0$ the flat-spectrum components have the same flux density at 2.7 and 5 GHz, i.e. $S_{2.7\text{GHz};\text{flat}} = S_{5\text{GHz};\text{flat}}$ and for $\alpha_{\text{steep}} = -0.75$ the steep-spectrum components at 2.7 and 5 GHz are related as $S_{2.7\text{GHz};\text{steep}} = 1.6 S_{5\text{GHz};\text{steep}}$. Thus we determine $R_{\text{min}}$ as having the value of 0.66.

The largest angle between the jet and the line of sight for the source to appear flat-spectrum occurs at the critical angle $\theta_c$ when $R_{\text{obs}} = R_{\text{min}}$. Thus $\theta_c = \theta_{\text{min}} = \delta(\theta_c)$ so that $\theta_c$ is determinable from

$$\cos(\theta_c) = \frac{1}{\beta} \left( \frac{R_{\text{obs}}}{R_{\text{min}}} \right)^{\frac{1}{\beta - 1}},$$

assuming that the beaming due to the counter-jet is negligible. In fact our successful model finds that $\theta_c < 10^\circ$ and the assumption is justified.

Thus the only unknown parameters in the 5-GHz source-count fit are values for $\gamma$ and $R_{\text{med}}$ for each of the FR I and FR II populations.

### 4.3 Fitting the 5-GHz source count

The 5-GHz source count is constructed from survey data as detailed in Table 4 and is well defined across a wide flux-density range. At 5 GHz, the beamed products of the FR I and FR II sources make a highly significant contribution to the source count; for flux densities above 0.5 Jy, some 55 per cent of sources are ‘flat-spectrum’ (Pauliny-Toth et al. 1978).

To define the populations in accordance with our earlier discussion of the FR II beamed products, we split the FR II parent sources into high- and low-excitation types using a simple linear function of $\log_{10}(P_{151\text{MHz}})$ as suggested by Laing et al. (1994) and Barthel (1994). The fraction of low-excitation FR IIs was set at 50 per cent at $\log_{10}(P_{151\text{MHz}}) = 25.0$, declining to zero at $\log_{10}(P_{151\text{MHz}}) = 27.0$.

The source-count fit was carried out as for the 151-MHz count, this time incorporating the beamed products of the FR I and FR II sources by randomly aligning the sources with respect to our line of sight. The source alignment angle, $\theta$, for each of the FR I and FR II contributions was generated using $\text{nag}$ pseudo-random number routines. The best-fitting beaming parameters were determined

| Flux density range $S_{5\text{GHz}}$ | Survey instrument(s) | Survey name | Reference |
|-------------------------------------|----------------------|-------------|-----------|
| 10–100 Jy                           | NRAO + MPIfR         | strong sources | Kühr, Pauliny-Toth & Nauber (1981) |
| 1.5–10 Jy                           | Green Bank 91m       | 87 GB       | Gregory & Condon (1991) |
| 0.5–1.3 Jy                          | NRAO + MPIfR         | S4          | Pauliny-Toth et al. (1978) |
| 67 mJy–0.5 Jy                       | NRAO 300h            | 6cm survey  | Davis (1971) |
| 10–55 mJy                           | MPIfR                | deep selected regions | Pauliny-Toth, Steppe & Witzel (1980) |
| 1.5–8.5 mJy                         | VLA                  | E/S0 galaxy | Wrobel & Krause (1990) |
| 1.36–6.00 mJy                       | VLA                  | Lynx-2 area | Donnelly, Partridge & Windhorst (1987) |
| 16–60 $\mu$Jy                      | VLA                  | DEEPS2      | Fomalont et al. (1991) |
again using the amoeba downhill simplex method, minimizing $\chi^2$ evaluated between the observed and model source counts at 5 GHz.

A good fit to the 5-GHz source count was found for the parameter values given in Table 5.

The observed source count and the count calculated for the optimum fit are shown in Fig. 10. Here the subpopulations contributing to the count are split into their beamed and unbeamed products as detailed in Table 6. The contribution from the beamed sources peaks at high flux densities ($0.1 < S_{5 \text{GHz}} < 10 \text{ Jy}$), broadening the ‘evolution bulge’ of the count. Thus the unification scheme provides a straightforward explanation of why the source-count ‘plateau’ widens with survey frequency. It is the Doppler-beaming of the FR II population that has the primary impact in this

Table 5. Fitted beaming parameter values.

| Population | Parameter values | Chi-square test $\chi^2$ | $\nu^a$ |
|------------|------------------|--------------------------|--------|
| FR II      | $\gamma = 8.5, R_{\text{med}} = 0.01$ |  |  |
| FR I       | $\gamma = 15.0, \theta_{\text{med}} = 7.1$ |  |  |

Best fit 32.98 25

$^a$Degrees of freedom.

Table 6. Radio source types at 5 GHz.

| Ref$^a$ | Source population/evolution/ beamed & unbeamed products | Beamed at 5 GHz? | Radio spectrum $5\text{GHz}$ |
|---------|----------------------------------------------------------|-----------------|----------------------------|
| FR II sources | tapered exp LDDE, $F(\nu, z) = \exp M(\nu)r(z)$ evolution parameters as determined in Section 3 | | |
| 1 | High-excitation radio galaxies & quasars (class A) | no | steep |
| 2 | Quasars | yes | ‘flat’ |
| 3 | Low-excitation radio galaxies (class B) | no | steep |
| 4 | BL-Lac type objects | yes | ‘flat’ |
| FR I sources | non-evolving as determined in Section 3 | | |
| 5 | FR I radio galaxies (class B) | no | steep |
| 6 | BL-Lac type objects | yes | ‘flat’ |
| Low power | exp PLE, $F(z) = \exp Q(z)$ PLE as described in Section 3 | | |
| 7 | starburst galaxies | no | steep |

$^a$These numbers are used to reference the source types in Figs 10–17.

Figure 10. Source count fit at 5 GHz. Data points represent the differential source count at 5 GHz from data given in Table 4. The model produces contributions from seven source types as described in Table 6. All counts are shown in relative differential form with $N_0 = 60(S_{5 \text{GHz}})^{-1.5} \text{ sr}^{-1}$. 

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The single most successful aspect of the model is that values of the Lorentz factor \( \gamma \) determined from the optimization process agree with those determined from estimates made from (i) VLBI observations of superluminal sources and (ii) synchrotron self-Compton models for the observed and predicted X-ray flux.

### 5.1 The beaming models

#### 5.1.1 Jet speeds; values of the Lorentz factor \( \gamma \)

The substantial predictive power of the model provides direct tests of the dual-population unified scheme.

#### 5.1.2 The observed core flux:extended flux ratio

The observed core-to-extended flux ratios, \( R_{\text{obs}} \), span a wide range of values. The most lobe-dominated sources, those unaffected by Doppler beaming, have ratios as low as \( R_{\text{obs}} \sim 10^{-5} \) \( (\text{e.g.} \ OD-159 \text{ from the 2-Jy sample; Morganti, Killeen & Tadhunter 1993}) \). In contrast, the most core-dominated sources are heavily Doppler-beamed and can have \( R_{\text{obs}} \sim 10^3 \) \( (\text{e.g.} \ PKS \text{ B0400+258; Murphy, Browne & Perley 1993}) \).

Our assumption of a normal distribution for \( R_{\text{obs}} \) about \( R_{\text{med}} \) results in a wide range of \( R_{\text{obs}} \) for both FR I and FR II beamed products (Figs 11 and 12), and provides a smooth transition between the parent objects and their beamed sources. The \( R_{\text{obs}} \) values for BL Lac-type sources are predicted to extend to higher values due to the large range of intrinsic \( R_{\text{c}} \) values. The limited data in complete samples appropriate for comparison are in approximate agreement.

#### 5.2 Multi-frequency source counts

Figure 13 shows the observed differential source counts at a wide range of radio frequencies together with the predictions of counts from the model. The model successfully reproduces these source counts, qualitatively at least. There are quantitative differences, most notably the excess in the prediction at low flux densities for 1.4 GHz. The most probable explanation is that our simple model of the local luminosity function overestimates the space-density for powers below \( \log_{10}(P_{151 \text{MHz}}) \sim 24.0 \).

#### 5.3 Core-dominated and broad-line fractions

Figure 14 shows the population mix as predicted by the model as a function of 5-GHz flux density. The striking feature is the change in dominant population moving from high flux densities (high-excitation FR II radio galaxies and quasars) to low flux densities (FR I radio galaxies, BL Lac-type sources and, eventually, starburst galaxies). The domination of the high-excitation FR II sources at high flux densities produces a pronounced peak in the quasar population between 0.5 and 10 Jy; the decline in quasar fraction towards lower flux densities is in close agreement with observation (Fig. 15), as discussed by Wall & Jackson (1997).

The change in fraction of broad-line sources as a function of flux density agrees with the best available determinations at 408 MHz [fig. 5 of Wall & Jackson (1997)]. Such a change is evidence for the unified scheme rather than evidence against it as was suggested by Singal (1996). Despite its relative simplicity, the dual-population scheme shows that tests of unification dealing with broad-brush
Radio-source unification and evolution

Figure 13. Observed source counts at six frequencies with data points from surveys as given in Wall (1994) and the addition of the VLA FIRST survey source-count points $1 \text{mJy} \lesssim S_{14\text{GHz}} \lesssim 1 \text{Jy}$ (Becker, White & Helfand 1995). The predicted model counts are shown as dashed lines. All counts are in relative differential form $\Delta N / \Delta N_0$, where $\Delta N$ is the number of sources per sr with flux density $S_2$ between $S_2$ and $S_1$ and $N_0 = K_2 S_2^{-15}$, the number of sources expected in a uniformly filled Euclidean universe. The values of $K_2$ are 2400, 2730, 3618, 4247, 5677 and 3738, respectively, for the six frequencies shown. The horizontal range bars show the flux-density bin width $S_2$ to $S_1$, and the error bars represent $\sqrt{N}$ uncertainties. Polygons show the count estimates from $P(D)$ (background-deflection) analyses.

Figure 14. The predicted population mix at 5 GHz, with populations as given in Table 6.

Figure 15. Core-dominated fractions at 2.7 GHz. The dashed line is the model prediction of core-dominated sources (BL.Lacs plus quasars). The data points are derived from two samples discussed in detail by Wall & Jackson (1997), Section 3.1: PKSCAT90 (+) with $S_{2.7\text{GHz}} \geqslant 0.25 \text{Jy}$ and PSR (open circle) with $0.10 \leqslant S_{2.7\text{GHz}} < 0.25 \text{Jy}$. The error in $f_C$ is $\sqrt{(N_x)} / (\text{bin total})$. 

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proportions of broad-line objects or flat-spectrum objects are far too simplistic; the mix of subpopulations selected in each sample must be considered. There must be similar reservations over elementary tests based on size discrimination (e.g. Kapahi et al. 1996).

5.4 The redshift distribution of flat-spectrum quasars

A single subpopulation redshift distribution, \( N(z) \), provides a potent test of the model. The flat-spectrum sample of Shaver et al. (1996) comprises 442 sources, all of which are identified. Of these, 358 quasar redshifts were available to us. The sample is moderately complete to \( S_{2.7 \text{ GHz}} > 0.25 \text{ Jy} \), although a substantial proportion of the sample is limited to \( S_{2.7 \text{ GHz}} = 0.6 \text{ Jy} \). All sources were selected as flat-spectrum, with \( \alpha_{2.7 \text{ GHz}} \approx -0.4 \) (\( S \propto r^\alpha \)). The redshift distribution for the observed sample of 358 quasars is shown in Fig. 16, along with the model prediction for an equivalent complete flux-limited sample \( \left(S_{2.7 \text{ GHz}} \leq 0.5 \text{ Jy}\right) \). The model successfully replicates the observed \( N(z) \) for the largest sample of spectroscopically identified quasars available. It should be emphasized that these data are completely independent of the (low-frequency) data used to construct the model.

5.5 Radio surveys to mJy flux-density levels

The new, large-area radio surveys (i.e. FIRST, NVSS, WENSS & SUMSS) reach mJy flux-density levels and will yield samples forming the basis of future direct tests of the dual-population model.

Figure 17 shows a comparison between \( N(z) \) distributions for a flux density range \( 1 \leq S_{1.4 \text{ GHz}} < 100 \text{ mJy} \). The striking differences between our model prediction and the average \( N(z) \) model of Dunlop & Peacock (1990) are (i) the sharp spike at \( z \sim 0.1 \) due to the starburst galaxies in our model, a population not included in the Dunlop & Peacock analysis, (ii) the lower median redshift distribution of sources in the prediction of the current model, as a result of the dominance of the unevolving FR I sources within this flux density range, and (iii) the greater prominence of flat-spectrum sources in our model, the beamed products of the low-power FR I sources.

Although the model predicts unequivocal \( N(z) \) and population mix, e.g. for flux densities in the range \( 1 < S_{1.4 \text{ GHz}} < 100 \text{ mJy} \), it has been developed from consideration of total source counts at high and low frequencies, but population mix only at low frequencies and high flux densities, \( S_{1.4 \text{ GHz}} > 10 \text{ Jy} \). Complete samples (with redshifts) at the mJy level offer substantial scope for improvement or refinement of the parameters. For example, the sample at \( S_{2.7 \text{ GHz}} \approx 0.3 \text{ mJy} \) of Gruppioni et al. (1997) contains more broad-line objects than predicted. If confirmed, this suggests that we have overestimated the FR I LRLF at low powers, a possibility already suggested in Section 5.2. Tapering off the FR I LRLF more rapidly at its higher radio powers would require a

Table 7. Population mix at 1.4 GHz.

| Flux density range | FR II high-excitation | FR II low-excitation | — FR I — | Starburst galaxies |
|-------------------|----------------------|----------------------|----------|-------------------|
| \( S_{1.4 \text{ GHz}} > 100 \text{ mJy} \) | 59 per cent | 15 per cent | 10 per cent | 4 per cent | 7 per cent | 4 per cent | 1 per cent |
| \( 1 \leq S_{1.4 \text{ GHz}} \leq 100 \text{ mJy} \) | 7 per cent | 1 per cent | 4 per cent | — | 38 per cent | 30 per cent | 20 per cent |

Figure 16. The redshift distribution for 358 flat-spectrum quasars from Shaver et al. (1996), shown with the model prediction for 358 quasars selected with \( \alpha_{2.7 \text{ GHz}} \approx -0.4 \) and \( S_{2.7 \text{ GHz}} \approx 0.5 \text{ Jy} \).

Figure 17. The predicted (integral) population mix at 1.4 GHz with the populations as described in Table 6.
compensatory broadening of the FR II LRLF, resulting in an increased proportion of FR II objects at sub-mJy levels.

6 CONCLUSIONS

We have described a paradigm in which evolution of extragalactic radio sources is delineated for populations that are physically related through orientation-dependent effects. The dual-population scheme is based on the premise that the two parent populations are radio galaxies of FR I and FR II morphologies, with distinctly different evolutions which we have determined from analysis of counts and identification data at low frequencies. The fundamental assumption is that all FR II and FR I radio galaxies have radio lobes fed with relativistic beams. The beaming models by which these parent objects appear as the quasars or BL Lac objects when lines of sight coincide closely with the radio axes were then developed by considering the high-frequency counts and identifications, dominated by these beamed products.

The model provides agreement with source counts and with identification and redshift data at high flux densities and at both high and low frequencies. It provides a natural explanation of the change in shape of source counts with frequency. Furthermore, such a unified scheme provides a natural explanation of why steep-spectrum sources show more pronounced cosmological evolution than do beamed (flat-spectrum) sources of the same (apparent) power (Dunlop & Peacock 1990), a result anticipated by Scheuer & Readhead (1979).

One of the clearest successes of the model is that the beam speeds derived from statistics of counts and identifications are in reasonable agreement with those determined for individual sources from VLBI measurements. Further, it predicts a core-dominated fraction of sources as a function of flux density in excellent agreement with observation.

Four further remarks are important with respect to the current model:

(i) Although we chose luminosity-dependent density evolution (LDDE) to describe the evolution, it can be shown that due to the shape of the RLF some models of LDDE are exactly equivalent to pure luminosity evolution (PLE). Obviously a simple solution of PLE would be very interesting with regard to physical models for all AGN evolution (radio-loud and radio-quiet).

(ii) The model fit of LDDE has the lower radio power FR IIIs undergoing little or no evolution. By virtue of the correlation between line-strength and radio luminosity, these are inevitably of weak emission-line type. This suggests that the weak-lined FR IIIs underwent a similar evolutionary history as FR Is; it is only the powerful strong emission-line FR IIIs that evolved strongly with cosmic epoch. It might then be possible to define the two populations in terms of optical emission-line strength rather than radio morphology, the two emission types perhaps representing different accretion types. Such a view has important ramifications for the process of physical evolution, and it may be that development of such a variant of the model could result in a single-source function describing the entirety of the radio-source population.

(iii) Although the simple beaming models adopted provide a good description of the count data, there are other combinations of the Doppler beaming parameters that work. For example, a very wide distribution of Lorentz factors also fits the GHz-frequency source counts and this variant was adopted by Urry and Padovani (1995). Ultimately our selection of parameters was made on the basis that the intrinsic core-to-extended flux ratio is an observed quantity and that the model distribution of $R_{\text{obs}}$ values produced has the observed shape. In addition, the single $\gamma$ value fitted in our model can be interpreted as modelling the mean value for the fastest material in the jets. The critical angles inferred from the successful models are $\sim 8^\circ$ and $\sim 5^\circ$ for the FR I and FR II populations, respectively.

(iv) It must be borne in mind that the current model has been developed fundamentally with only three data sets: a source count at 151 MHz, a source count at 5 GHz, and a complete set of identifications and redshifts at 178 MHz. It is clear that the model can be improved. For example it predicts a low flux-density end of the 1.4-GHz count that is too high, and it predicts too few broad-line objects at low flux densities. Both deficiencies could be rectified with a local radio luminosity function for which the FR I component rolls off at somewhat lower powers than the current one, compensated by extending the FR II component to these lower powers.

However, in view of the limited data from which the scheme was developed, its general success in describing much of the remaining data provides an indication that the concept is substantially correct.

ACKNOWLEDGMENT

We are very grateful to Robert Laing for many constructive comments towards the development of this paper.

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Figure 18. The predicted $N(z)$ (per 0.01z per sr) for sources with $1 \lesssim \Delta L_{1480} < 100$ mJy. Models are from Dunlop & Peacock (1990) (average of their models 1–7), shown as thin lines, and this paper, shown as thick lines. Dotted lines are flat-spectrum sources, dashed lines are steep-spectrum sources and solid lines are total of all sources.
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