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Radio Source Evolution and Unified Schemes

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Abstract: Powerful extragalactic radio sources are characterised by kpc-scale synchrotron emission associated with highly-collimated outflows of relativistic plasma. It is hypothesised that this outflowing plasma is powered by accretion processes concomitant with a central massive black hole. The radio morphologies of these sources comprise jets, lobes and for the most powerful sources, hotspots. At first sight, powerful extragalactic radio sources are a mixed group of objects, with the result that only some gross property delineates them further (e.g. steep-spectrum *or* flat-spectrum). However, there is accumulating observational evidence which suggests that it is the orientation of the radio axis to our line of sight that dictates their observed characteristics. This orientation dependence has been incorporated into 'unified schemes', which physically link apparently disparate radio source types via the random orientation of a 'parent' population on the plane of the sky. This paper summarises the 'dual-population unified scheme' paradigm investigated by Wall & Jackson (1997) and Jackson & Wall (1999) and discusses some of its implications with respect to radio source cosmology.

Keywords: galaxies: evolution — galaxies: jets — quasars: general — radio continuum: galaxies

1 Extragalactic Radio Sources: What are We Trying to Unify ?

A typical powerful extragalactic radio source harbours an active galactic nucleus (AGN) which, due to some process associated with the central massive black hole, produces powerful jets of highly collimated relativistic plasma (Scheuer 1974). The attendant radio emission is non-thermal, having an extent independent of that of the host galaxy. In these powerful sources the radio-emitting regions can extend out to hundreds of kpc or even Mpc beyond the host galaxy, although a notable exception is shown by the peaked-spectrum sources, which have galactic-size radio structures (tens of kpc). In contrast, very low radio power sources (normal and 'starburst' galaxies) have diffuse, thermal radio emission associated with stellar activity which is limited in extent by the optical host galaxy.

Extragalactic radio source morphologies vary enormously. Historically, a first-order classification describes them as *extended* or *compact* sources: extended sources are those with large-scale emission structures, whilst compact sources lack such features, usually being characterised by a dominant unresolved radio core. This division between extended and compact sources nearly correlates with that between steep- and flat-spectrum ones respectively, the latter terms describing the observed shape of the radio spectrum. However, it is now realised that both classifications (compact/extended and steep/flat) have major limitations in describing the known radio source types, namely that (i) hybrid sources exist, (ii) these characteristics are a function of observing frequency, (iii) peaked-spectrum sources (CSS and GPS) directly refute the compact=flat, extended=steep dogma, and (iv) that these classifications are affected by projection effects.

At low radio frequencies (i.e. $\nu < 400$ MHz) the radio morphologies of the double-lobed extended sources can be described by the scheme of Fanaroff & Riley (1974). This scheme measures the distance between the central maxima of a radio source compared to its overall size. When the regions of maximum brightness are separated by more than $0{\cdot}5$ times the overall source size, the source is classified as an FRII (as the source is edge-brightened). Where the regions of maximum brightness lie within this limit the source is an FRI (centrally concentrated). The FR class division very nearly correlates with radio power such that the highest-radio-power sources are predominantly FRII-type, whilst those of lower radio power are usually FRI-type. According to the FR classification *all* quasars[1] are FRIIs, whereas BL Lac sources have been observed with both FRI and FRII morphologies (Dallacasa et al. 1997).

Since the adoption of Fanaroff & Riley's morphological scheme, much effort has been expended on understanding the physical origin of the two FR classes. Fundamentally this origin is attributed to the following two factors:

[1] The term quasar is used throughout this paper to describe a radio-loud quasi-stellar object.

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(1) *'Nature': Differing Central Engines*

This hypothesis suggests that the two FR classes have different central accretion processes and that these, in turn account for the differences in large-scale radio structure associated with each FR type (Baum, Zirbel & O'Dea 1995). Whilst FRIIs have near-Eddington-luminosity accretion rates, it has been hypothesised that FRIs undergo sub-Eddington accretion due to an advection-dominated accretion flow (ADAF). A simple ADAF model is strongly supported by observations of the hard X-ray spectra from FRIs (Reynolds et al. 1996; Di Matteo & Fabian 1997), although not by their radio/sub-mm spectral characteristics (Di Matteo et al. 1998).

(2) *'Nurture': Environmental Differences*

This hypothesis suggests that the FRI/II division is a product of the effects of the environment in which the host galaxy exists. In this case both FRIs and FRIIs have similar accretion processes producing relativistic radio jets, with FRI radio jets decelerating over shorter distances than FRII radio jets due to entrainment of a dense surrounding medium (Bicknell 1996). This hypothesis requires that FRIs exist in regions of high IGM density, and indeed there is accumulated evidence that they do (Longair & Seldner 1979; Lilly & Prestage 1987; Prestage & Peacock 1988; Yates, Miller & Peacock 1989; Hill & Lilly 1991; Zirbel 1997). However, as 'classical' FRIIs are also found in clusters e.g. 3C 34; Best, Longair & Rottgering (1996) this cannot be the entire story.

It is almost certain that both factors contribute to the FRI/II division, although which is the dominant factor has yet to be determined. Further clues come from the observation that FRIs have optically brighter host galaxies (for the same intrinsic radio power) compared to FRIIs (Ledlow & Owen 1996).

Further complicating any simple classification of powerful radio sources are the peaked-spectrum radio sources — compact steep-spectrum (CSS) and gigahertz peaked-spectrum (GPS) sources. These are intrinisically powerful, yet galactic-sized, radio sources that exhibit a turnover in their radio spectrum around 1 GHz. Both CSS and GPS sources come in radio galaxy and quasar flavours. Their radio morphologies suggest that they are compact versions of the 'classical' FRIIs, although why they are so small has not yet been established: it is hypothesised that these are either young FRIIs or FRIIs trapped in a dense environment (Fanti & Fanti 1990; O'Dea, Baum & Stanghellini 1991; Fanti & Fanti 1994). Given their FRII morphologies, these peaked-spectrum sources are treated as part of the FRII population in the discussion that follows.

2 Dual-population Unification: Why Unify?

The central tenet of the current version of the unified scheme for radio-loud AGN is that the radio emission from the cores of powerful radio sources is highly anisotropic. Observationally, this manifests itself in two apparently exotic physical processes: (i) 'superluminal motion' of discrete blobs of radio plasma close to the radio core, and (ii) surface brightness temperatures that far exceed the limit set by inverse Compton processes. Both processes can be elegantly explained by a geometrical effect, relativistic Doppler boosting, which enhances the apparent speed and flux density of the approaching radio plasma (Rees 1967). As the radio jets are collimated, with opening angles $< 15°$, relativistic boosting only occurs for sources whose radio jet axes are in close alignment to our line of sight, so that most sources are observed 'unboosted' in a randomly oriented sample.

In addition to the radio jet orientation a second orientation-dependent feature is invoked to explain broad and narrow optical/UV emission-line features observed in powerful FRIIs. In these sources a dusty torus shields/reveals the central regions of the source, again depending upon the orientation of the source with respect to the observer. This is the same unification mechanism invoked to unify Seyfert I and II galaxies (Antonucci & Miller 1985). The torus opening angle has been determined to be $\sim 50°$ from the relative numbers of broad- and narrow-line FRIIs (Laing et al. 1994).

The 'dual-population' unified scheme adopted by Wall & Jackson (1997) is illustrated in Figure 1. In this scenario, FRII radio galaxies are the parent population of *all* quasars and *some* BL Lac-type sources, whilst FRI radio galaxies comprise the parent population of the remainder of the BL Lac-type sources. This differs from the more straightforward FRII–quasar, FRI–BL Lac unified scheme of Urry & Padovani (1995) in that we consider the two optical/UV spectral classes of FRIIs: in particular, low-excitation FRIIs show only weak, narrow optical/UV emission lines or none at all, and hence their beamed counterparts must appear as BL Lac-type sources rather than quasars. The known correlation between emission-line intensity and radio luminosity (Hine & Longair 1979) suggests that the split of the FRII population into low- and high-excitation types is a function of intrinsic radio power (Laing et al. 1994; Barthel 1994). There are about equal numbers of high- and low-excitation FRIIs at the low-power end of the FRII class ($P_{178\,\mathrm{MHz}} \sim 3\times10^{25}$ W Hz^{-1} sr^{-1}), rising to almost exclusively high-excitation FRIIs at the highest radio powers ($P_{178\,\mathrm{MHz}} \sim 10^{27}$ W Hz^{-1} sr^{-1}).

3. Space Density Evolution: When do These Sources Exist?

We have tested the dual-population unified scheme in a two-stage process: first we find a simple space-

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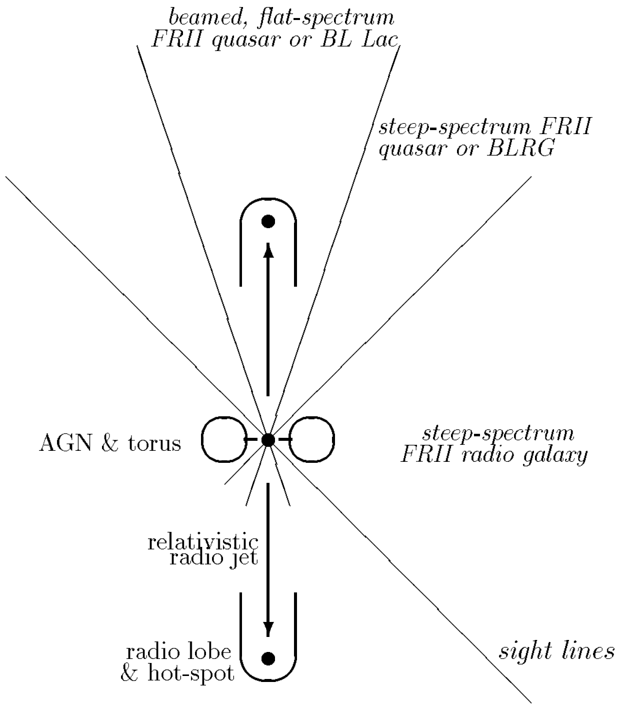

Figure 1a—Unified scheme for FRII radio sources.

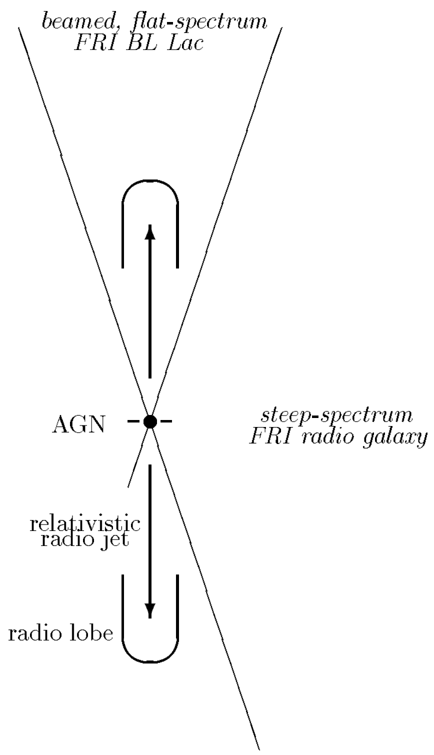

Figure 1b—Unified scheme for FRI radio sources.

density evolution model for the parent radio sources, and secondly we derive a set of beaming parameters that replicates the observed source counts at high frequencies. Full details of this analysis are given in Jackson & Wall (1999) so only a brief outline is presented in this section.

The first stage of our analysis adopts a simple parametric form for the evolution of the FRI and FRII populations. To describe the evolution, we adopt an evolution function, $F(P,z)$, which modifies the local radio luminosity function to give the radio luminosity function at any epoch, i.e. $\rho(P,z) = \rho_0(P)F(P,z)$. The function adopted describes exponential 'luminosity-dependent density evolution' (LDDE) $[F(P,z) = \exp M(P)\tau(z)]$, where $\tau(z)$ is the look-back time in units of the Hubble time. For Einstein–de Sitter ($\Omega = 1$) geometry this is given by $\tau(z) = [1 - (1+z)^{-1\cdot 5}]$. We also apply a redshift cutoff to the populations to mirror the observed behaviour of powerful radio sources (e.g. Shaver et al. 1996), modifying the evolution function so that it peaks at $z_c/2$, then declines to zero at the cutoff redshift z_c:

$$F = F(P,z) \qquad \text{for } z \le z_c/2\,,$$

$$F = F(P, z_c - z) \qquad \text{for } z_c/2 < z \le z_c, \text{ and}$$

$$F = 0 \qquad \text{for } z > z_c\,.$$

The evolution rate M is set between 0 and $M_{\rm max}$ as a function of radio power P:

$$M(P) = M_{\rm max}\frac{\log_{10}P - \log_{10}P_1}{\log_{10}P_2 - \log_{10}P_1} \quad \text{for } P_1 \le P \le P_2\,,$$

$$M(P) = 0 \qquad for P < P_1\,,$$

i.e. no evolution of radio sources of radio power less than P_1, and

$$M(P) = M_{\rm max} \text{ for } P > P_2\,,$$

i.e. sources of radio power greater than P_2 undergo maximal evolution.

The choice of this evolution function is constrained by (i) the evidence for differential evolution of radio sources, with the most powerful sources having undergone significantly more evolution than those of lower radio power (Longair 1966); (ii) the fact that an exponential form is required to fit the strong cosmic evolution to relatively modest redshifts (Doroshkevich, Longair & Zeldovich 1970); and (iii) the fact that there is a 'turnover' in the space density of powerful sources at high redshift, representing the epoch of peak AGN activity. Other simple forms of exponential evolution have been tested using the latest radio source count data and have been found to be less successful (Jackson 1997).

To determine an evolution model for the FRI and FRII parent populations, we use radio samples that are free from orientation bias. Low-frequency radio samples ($\nu < 400$ MHz) comprise sources whose radio emission is from extended, steep-spectrum regions. This extended emission swamps any emission from the (potentially boosted) core of the source. We use the source count from the 3CRR sample at 178 MHz (Laing, Riley & Longair 1983) and that from the

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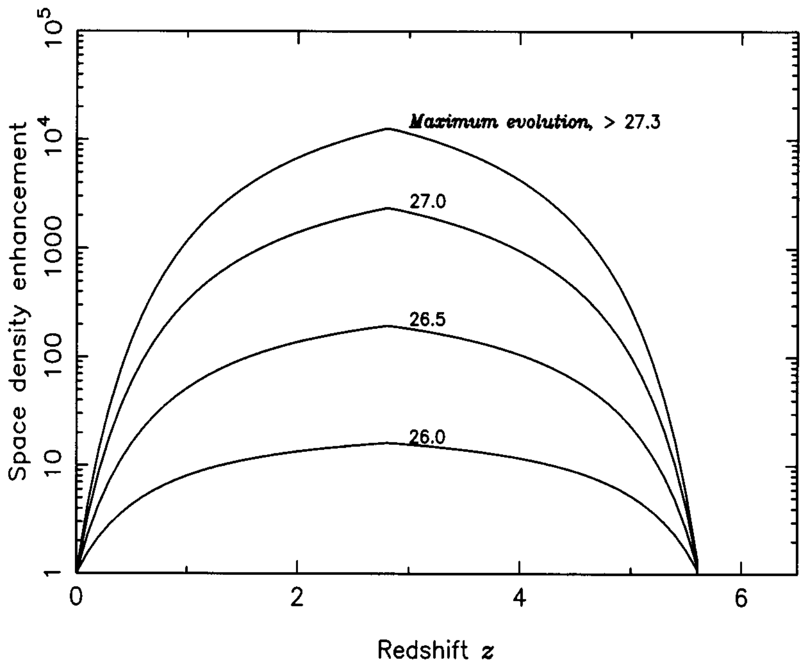

Figure 2—Comoving space density enhancements for a range of $\log_{10}$ FRII radio powers (in $\mathrm{W\,Hz^{-1}\,sr^{-1}}$ at 151 MHz), for $h = 0{\cdot}5$ and $\Omega = 1$.

6C survey at 151 MHz (Hales, Baldwin & Warner 1988) to fit a parametric model of space-density evolution that best reproduces the observed source count. The best-fit model is the parameter set that yields the χ^2-minimum between the observed and model source counts, where this minimum is found using the AMOEBA downhill simplex method in multi-dimensions (Press et al. 1992). The model fit has strong luminosity-dependent density evolution of the FRII population coupled with no evolution of the FRI population. The FRII population has its maximum space density at around $z \sim 2{\cdot}8$. The most powerful FRIIs have space density enhancement factors of $\sim 10^4$ (comoving) relative to their local space-density (Figure 2). Shaver et al. (1996) have found similar space density enhancement factors for a sample of flat-spectrum (i.e. beamed) radio sources of high radio power ($\log_{10} P_{2\cdot7\,\mathrm{GHz}} > 27$ W $\mathrm{Hz^{-1}\,sr^{-1}}$).

Testing the orientation dependence of the dual-population unified scheme involves using the derived evolution model to predict the radio source count at radio frequencies that characterise both parent sources and their beamed progeny. We describe the Doppler beaming of the radio core/jets in terms of a Lorentz factor γ, and the intrinsic core-to-extended flux ratio R_c, for each parent population, then randomly orient the sources to produce the total source count comprising beamed and unbeamed sources. A model fit to the observed 5 GHz count is determined by χ^2-minimisation using AMOEBA to search the beaming parameter space.

As discussed in Jackson & Wall (1999), the fitted beaming parameters are in agreement with those measured observationally. For example, the critical angle inferred for the FRII population is $\sim 7°$, concurring with 6–7° determined by Best et al. (1995) for a sample selected from 3CR, and a Lorentz factor γ of $8{\cdot}5$ is in accord with results from a large VLBI sample (Vermeulen 1995) and estimates of $\gamma \sim 10$ for highly beamed sources such as 3C 273 (Davis, Unwin & Muxlow 1991). Additional tests of the model predictions against observed radio source samples at intermediate frequencies have also been made, e.g. comparing the model and observed fraction of core-dominated sources at $2{\cdot}7$ GHz. The clear decline in the fraction of core-dominated sources found in a complete sample (totalling 3412 sources) towards lower flux densities is clearly predicted by the dual-population unified scheme (Figure 3). This decline arises due to the very strong cosmic evolution of the FRII population. That our model reproduces observational results such as this is a real strength of the dual-population unified scheme.

4 Physical Evolution: How do the Sources Evolve?

Our analysis has adopted a simple parametric form for the evolution of the source populations. However, whilst a parametric approach yields a model comprising only a limited number of free parameters, we must be careful in interpreting the overall results, as it is subject to the following limitations:

(1) *It cannot determine the type of evolution a population has undergone.* The successful evolution model requires that the FRII population undergoes density evolution with the magnitude of the evolution being luminosity-dependent.

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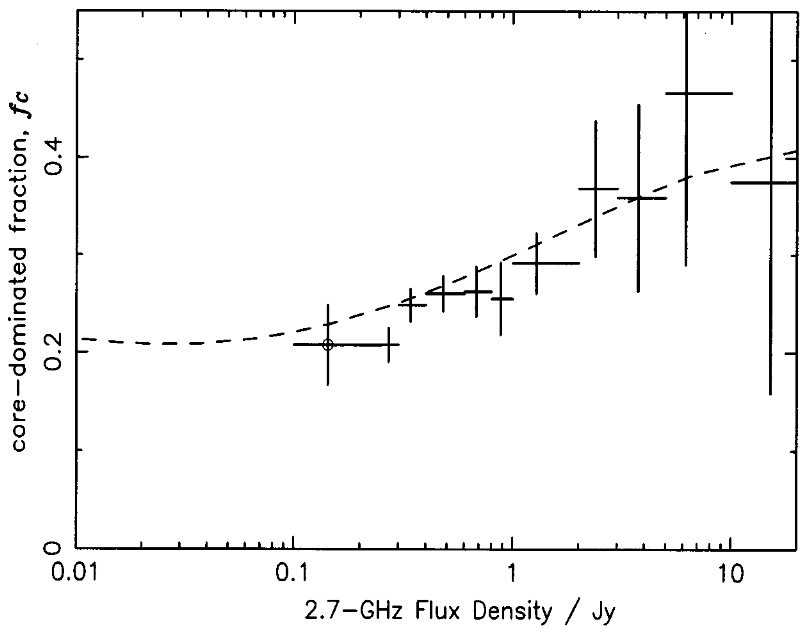

Figure 3—Fractions of core-dominated sources at 2·7 GHz. The dashed line is the model prediction for core-dominated sources (BL Lacs plus quasars). The data points are derived from two samples discussed in detail by Wall & Jackson (1997, Section 3·1: PKSCAT90 with $S_{2\cdot 7\mathrm{GHz}} \geq 0\cdot 25$ Jy) and one from the Parkes selected region (○) with $0\cdot 10 \leq S_{2\cdot 7\mathrm{GHz}} < 0\cdot 25$ Jy. The error in f_C is $\sqrt{N}$/(bin total).

However, due to the shape of the radio luminosity function, this evolution mimics pure luminosity evolution. Thus our model cannot discriminate between the different evolutionary scenarios of luminosity *or* density evolution *or* a combination of both.

(2) *It tells us nothing about the physical evolution of individual sources.* The model fits the behaviour of each population, so our evolution model tells us nothing about the physical evolution of a single source. All we can conclude is that FRIIs undergo significant cosmic evolution whilst the FRIs have a constant space density with epoch. Likewise, the derived beaming parameters cannot be applied to individual objects; instead they represent some 'average' values.

Moreover, a fundamental question remains unanswered: what has happened to the powerful radio sources from $z \sim$ 2–3 to the present epoch? From the form of the evolving radio luminosity function (RLF) we hypothesise that FRIIs have evolved to FRIs. This hypothesis rests on the result that the space density of FRIIs never exceeds that of the FRI population at any epoch. In this scenario FRIs are 'exhausted' FRIIs, with powerful FRIIs peaking in both space density and luminosity at $z \sim$ 2–3 and then declining towards the present epoch. In this scenario the 'quasar' (i.e. 'FRII') epoch coincides with, and is linked to, galaxy formation: powerful radio sources form from the largest mass fluctuations in the primaeval universe and evolve rapidly due to their central massive black holes (Silk & Rees 1998). Associated with this rapid evolution is the possibility of galactic mergers, which would have further boosted the fuel supply to the AGN, the end result being that sources that were very luminous at $z \sim 2$ have now exhausted their fuel.

5 Powerful Radio Sources as Cosmological Probes: Where are They?

Large-area radio surveys find that radio sources are relatively sparsely distributed on the sky. At $S_{1\,\mathrm{GHz}} >$ 3 mJy the surface density is of the order of 40 sources per square degree. However, it has been shown that mJy-level radio surveys trace large-scale structure on scales inaccessible to other wavelengths (Cress et al. 1996; Magliocchetti et al. 1998), falling between the scales probed by the CMB and optical/IR surveys such as 2dF and IRAS. In particular, radio surveys have two significant advantages over those at other wavelengths: (i) radio emission is unattenuated by the intervening medium, observations having established radio sources can be reliably traced to high redshift (Shaver et al. 1996); and (ii) the average redshift of radio sources in complete samples is high, typically $z \sim 1$ for $S_{1\cdot 4\,\mathrm{GHz}} > 50$ mJy.

The potential of the latest generation of large-area mJy-level radio surveys (e.g. NVSS, WENSS, SUMSS and FIRST) to reveal large-scale structure is now well recognised (Wall 1998). However, the primary

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constraint in using these surveys is that the redshift distribution $N(z)$ is undetermined. Analyses of spatial clustering require this distribution to convert 2D radio survey data to 3D using the 'cosmic Limber' equation (Loan, Wall & Lahav 1997). This is where evolution and beaming models of the total radio source sky can play a useful role. Unified-scheme-based evolution and beaming models predict $N(z)$, reducing the effort required in the spectroscopic follow-up of large samples of radio survey data, which is a long and difficult process.

6 Summary

We have discussed how a dual-population unification scheme successfully describes the evolution and Doppler beaming of powerful extragalactic radio sources. The evolution model is well supported by observational data and reflects the 'FRII/quasar epoch' at $z \sim 2$–3 attributable to very strong cosmic evolution of the FRII population. In contrast, FRIs have a constant space density with epoch; this is almost certainly due to the population being replaced at a rate which matches their radio-active lifetime.

Whilst a physical understanding of how individual radio-loud AGN evolve is not yet available, we hypothesise that luminosity evolution produces a transition from FRII- to FRI-type sources from $z \sim$ 2–3 to the present epoch. Even though we do not understand the nature of the physical process that caused this evolution, powerful radio sources are a reliable trace of large-scale structure, although further work is required to refine the redshift distribution of radio sources to mJy flux density limits.

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