UNIFIED SCHEMES FOR EXTRAGALACTIC RADIO SOURCES

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1. Introduction

The most widely discussed class of unified schemes for radio-loud extragalactic sources attempts to interpret their seemingly disparate types as the same objects seen from different directions. The orientation dependence is attributed to relativistic beaming of the nonthermal jet and, possibly, anisotropic obscuration/re-radiation of the nuclear emission by a circum-nuclear distribution of dusty material with polar openings, possibly a torus [1]. Although alternative approaches have been mooted for unifying radio galaxies (RGs) and quasars (QSRs) by incorporating a strong jet-environment interaction [2], or temporally decaying nuclear prominence [3], the orientation based unified scheme, thanks to its rich predictive potential, has been subjected to a multitude of observational tests and its pros and cons have been discussed extensively in recent reviews [1] [4–7]. Here we briefly address some recent developments, including the claim that the radio size measurements of powerful RGs and QSRs are incompatible with orientation being the primary distinction between them. On balance, it seems that while the basic orientation picture can broadly explain the bulk of the observations, its viability could be much enhanced by taking into consideration the (inevitable) temporal evolution of radio sources.

2. Unification of low–luminosity sources (BL Lacs & FR I RGs)

Due to the statistical similarity in isotropic attributes, such as extended radio emission and the host galaxy, and based on the analyses of radio/X-ray luminosity functions, FR I galaxies have long been favoured as the parent (misaligned) population of BL Lac objects [e.g., 7-9]. The needed evidence for radiation anisotropy in the bases of radio jets of FR I galaxies is furnished by the recent detection/inference of (i) relativistic motion

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within the cores of several FR-I galaxies (e.g., [10, 11]), and (ii) polarization asymmetry between their radio lobe pairs [12]. The RG(FR I) – BL Lac unification is further supported by the growing evidence that both lie in moderately clustered environments (Abell richness class 0)[13,14], though BL Lacs appear to avoid very rich clusters [15,16] (see, however, [7, 13]).

Taking a clue from their matching X-ray luminosity but distinctly lower optical polarization, radio/optical luminosities and variability, it has been argued that the X-ray selected BL Lacs (XBLs) are viewed at intermediate orientation between the apparently more active radio-selected BL Lacs (RBLs) and the parent FR I galaxies (e.g., [16–18]). However, the implication that XBLs are much more numerous than RBLs is challenged by the proposal that the XBLs may in fact be the small minority of cases where the peak of the synchrotron spectrum extends up to soft X-ray energies [19, 7]. This controversy remains to be settled, leaving open the question of a 'transitional' population within the FR I unified scheme (Sect.5).

3. Unification of high–luminosity (FR II) radio sources

In this version of the unified scheme, the lobe–dominated QSRs (LDQs) and core-dominated QSRs (CDQs/blazars) are increasingly aligned versions of powerful radio galaxies (PRGs). Recent reviews [5, 7] summarize and update the evidence for this hypothesis, employing orientation independent properties, such as extended radio emission, [O II] 3727 emission, environmental clustering, near-IR (stellar) emission of the host galaxy [20] and far-IR emission (even at $\lambda_{rest} \sim 50\ \mu$, the nuclear continuum is either beamed, or re-radiated anisotropically by the torus, though at longer wavelengths it becomes increasingly isotropic [21, 22]). Further support to the unified scheme comes from the recent detection of scattered Mg II broad emission line in the UV spectrum of the nearest PRG Cygnus A [23], though this object may still pose potential concerns to the unified scheme [24].

Additional supporting evidences emerging from recent radio data are: (i) The increasing 'apparent' brightness temperature along the orientation sequence NLRG–LDQ–CDQ, as deduced from radio flux variability [25]; (ii) growing evidence from VLBI for the apparent motion to be usually faster in the nuclei of more core-dominated sources [26]; (iii) peaking of the radio spectra of the *cores* of LDQs at a few times smaller rest-frame frequency, on average, than the spectra of CDQs [27-29]; (iv) the greater lobe depolarization asymmetry observed in QSRs, compared to PRGs [30]; (v) the large-scale radio structure of QSRs appearing more bent than that of PRGs, which is shown to be consistent with the critical misalignment angle $\theta_c \sim 45^o$ being the dividing line between PRGs and QSRs [31, 32]; (this is also consistent with the statistics of jet opening angle in PRGs and

QSRs; [33]). Note that structural asymmetries consistent with such a value of θ_c are noticeable also among compact–steep–spectrum radio sources [34].

4. The radio size 'anomaly'. Does it spell doom for unification?

An important clue to the orientation based unification came from the result that in the metre-wavelength selected 3CRR sample, where the axes of the radio sources should be randomly oriented, the ratio, R, of the median radio sizes of broad–line objects (QSRs) and narrow–line objects (PRGs) is smaller than unity (R $\sim$ 0.5, for z $>$ 0.5) [35]. However, the lack of such a trend at z $<$ 0.5, bolstered by a similar behaviour reported for some other metre-wavelength samples a few times deeper than the 3CRR sample, has evoked serious doubts about the unified scheme [6, 36-38]. We suggest that even the result R $\sim$ 1 can be explained, despite PRGs being oriented closer to the sky plane than QSRs, provided the following simple, empirically deduced temporal evolution of FR II sources is taken into account [5].

Firstly, recall that a typical powerful radio source during its lifetime T $\simeq 10^7 - 10^8$ yr grows to a size L $\approx 10^2$ kpc such that the expansion velocity V $\propto$ P$^\alpha$, with $\alpha \approx 0.3$ [39], and the (nearly uniform) expansion to L $\approx 10^2$ kpc is accompanied by roughly an order–of–magnitude decrease in the radio luminosity P [40,41]. Secondly, the apparent increase in the QSR–to–PRG number ratio (f_q) with flux density, suggests that intrinsically more powerful radio sources have larger torus openings angles (2 ψ) [5, 6, 42,43].

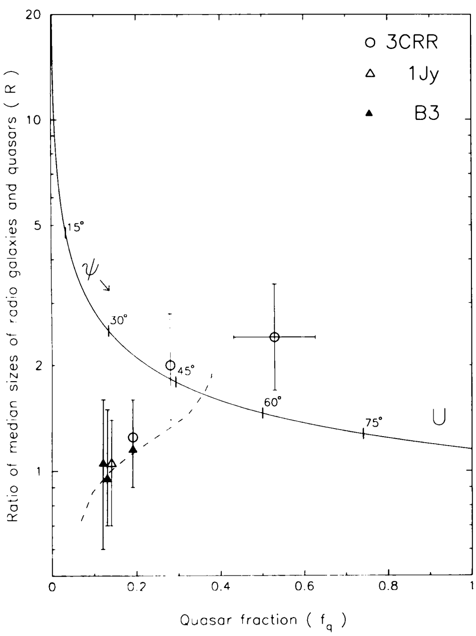

Fig. 1: A plot of R *versus* f_q for the 3 metre-wavelength samples; the data points are from ref.[6], so also the prediction of the orientation unified scheme for a range of ψ (curve "U"). The dashed curve shows a prediction of our model incorporating temporal evolution into the unified scheme [Sect. 4]. The adopted values for the input parameters, consistent with the observations (Sect. 4, ref.[44]), are: (i) an e-folding time of 10^7 yr for the decay of P, (ii) a radio source 'injection' spectrum: n(P$_0$) $\propto$ P$_0{}^{-2}$; (iii) radio size L $\propto P_0^{0.3} \times t^{0.8}$, and (iv) $\psi = 0.4 \log (P_0/10^{26}\ \mathrm{WHz}^{-1})$ where $0.2 \leq \psi \leq \psi_{max} = 1$ rad. The dashed curve spans 2 orders-of-magnitude in P increasing to the right (just as the data points). Details are in ref.[44].

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Now, consider the sources observed near a radio luminosity P below that of the most powerful born sources. At any given time, such sources would include young (hence small) sources freshly born with that level of luminosity, as well as ageing sources that were born with higher luminosity in the past, but have since then faded to P and, concurrently, expanded to larger sizes. Since these older, expanded sources with larger sizes should have a higher quasar–fraction (f_q) owing to their higher initial luminosities, P_o (and correspondingly larger ψ), the median size of the QSRs in a sample taken near the luminosity P may well approach, or even exceed that of the PRGs [5]. A quantitative prediction based on this simple picture matches the radio size data quite well (Fig. 1 & ref. [44]) and, moreover, explains simultaneously the difference reported, e.g., in refs. [6] & [37], between the radio size — luminosity correlations for PRGs and QSRs. Furthermore, in this picture, except in the metre-wavelength samples selected at the highest radio luminosities, QSRs would, on average, be *older* (hence, intrinsically larger) than PRGs. This is opposite to the pattern envisioned in some alternative unification scenarios (e.g., [3]).

5. Towards a single unified scheme for FR I and FR II sources?

Unlike the FR II unification wherein the LDQs appear at intermediate orientation between the CDQs and the (misaligned) PRGs, the FR I unified scheme lacks a well established 'transitional' population between the BL Lacs and the FR I galaxies (Sect.2). To bridge this conceptual gap and thus devise a common framework for the two unified schemes, a few possibilities have been proposed (see refs. [7, 5] for comments), as noted below.

A link between the two schemes is hinted, firstly by the near absence of QSRs among low–luminosity (FR I) sources, plus the evidence for wider torus openings in more powerful sources (Sect. 4). Since, plausibly, the decreasing ψ at lower P could approach near the FR I / FR II break, the typical relativistic beaming angle of the nonthermal jet, a direct view of the nuclear region in FR I sources (a pre–requisite for QSR classification) would be unavoidably accompanied by a Doppler–boosted nuclear continuum jet. Due to this and the obscuration of the nuclear region by the material stripped by the jet from the narrow torus funnels, the aligned FR I sources would mostly be classified as BL Lacs. The lack of a transitional, LDQ type population among FR I sources could thus be understood without invoking a conceptual dichotomy between the FR I and FR II unified schemes [45, 42]. (For evidence for dust in the torus funnels, see ref. [46]).

On the other hand, an analysis of the radio and X–ray luminosity functions has led Maraschi & Rovetti [47] to propose a 'generalized' unified scheme, based on an expanded 'parent' population including all steep-spectrum sources (FR I, FR II & LDQs), whose beamed population would include all flat–spectrum sources (BL Lacs & CDQs). Vagnetti & Spera [48], instead, posit that the canonical BL Lacs are the remnants of (distant) CDQs, by postulating an increase in the jet's Lorenz factor with cosmic time, which leads to an increased beaming of the continuum (The superluminal velocities and jet/counter–jet ratios are predicted in ref. [49]).

6. Potential problems and some outstanding issues

The reported disparity between the asymmetry properties of the CIV λ 1549 line from LDQs and CDQs remain to be understood within the orientation scenario [50, 51]. Another intriguing recent finding is that the broad–line radio galaxies (BLRGs) have flatter mid–IR spectra compared to *both* QSRs and PRGs [22], weakening the general notion that BLRGs are intermediate to PRGs and QSRs in orientation. Other outstanding questions include:
(i) Is an important subset of FR I galaxies devoid of a BL Lac nucleus, as argued in ref. [16] for galaxies in rich clusters (also, [15] see, however [7]).
(ii) Are the low–excitation FR II galaxies parents of some high–luminosity BL Lacs [52,53]? Note that their nuclear 'dullness' could be transitory, making their exclusion from the statistics of FR II sources potentially unsafe.
(iii) Is alignment the key difference between XLBs and RBLs (Sect.2)?
(iv) Does a jet's Lorentz factor correlate with its power (e.g., [54,25,26])?
(v) Do FR I sources, too, possess a broad–line–region? Or, their central engines are basically different from those of the FR II sources (e.g., [55])?

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