UNIFIED BEAMING MODELS AND COMPACT RADIO SOURCES

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1. BASICS OF RELATIVISTIC BEAMING

Our interest in beaming models comes from the presumed existence of bulk relativistic flows in the nuclei of active galaxies. It is worth noting that this was in fact a theoretical prediction (Rees 1967), although (as we shall see) there is still some debate about precisely what is moving. We can begin with something uncontroversial: the relativistic transformation of specific intensity (or surface brightness).

$$I_\nu\ (\delta\nu_o) = \delta^3\ I_\nu\ (\nu_o) \tag{1}$$

where δ is the doppler factor caused by relative motion of source and observer. Equation (1) may be derived in an elementary way by transforming photon number densities and energies plus the relativistic aberration of solid angle elements. A more direct approach is to note that I_ν/ν^3 is proportional to the photon phase-space density, which is a relativistic invariant and is conserved along light rays (by Liouville's theorem). If we now consider an optically thin (spherical) blob moving with velocity β(c=1) at an angle $\cos^{-1}(\mu)$ to our line of sight then, _if_ the emission is isotropic in the blob's rest frame, the received flux density clearly also transforms as in (1). The doppler factor is $[\gamma(1-\beta\mu)]^{-1}$ and so, for a power-law spectrum with flux density $S_\nu \propto \nu^{-\alpha}$, we have

$$S = S_o\ (1-\beta\mu)^{-(3+\alpha)} \tag{2}$$

where S_o is the value at μ=0 (in the plane of the sky). For a quasi-continuous jet formed out of finite-lifetime blobs, the number of blobs observed at a given instant scales as δ^{-1} and hence the appropriate index in (2) becomes $(2+\alpha)$. The 'standard' model consists of a pair of such jets oppositely directed; however, life is simpler if we follow Lind and Blandford (1985) and neglect the receding component. We can then obtain a useful expression for the probability distribution of the beamed flux density. In general there will be an isotropic

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component in addition to the jet: we define R to be the ratio of one side of the jet to the isotropic component, at μ=0. The amplification relative to μ=0 is therefore $A = 1+R[(1-\beta\mu)^{-(2+\alpha)} - 1]$ and (since μ is uniformly distributed)

$$P(>A) = \frac{(1-\beta)}{\beta}\left[\left(\frac{(A_m+R-1)}{(A+R-1)}\right)^{1/(2+\alpha)} - 1\right] \qquad (3)$$

where the maximum amplification $A_m = 1+R[(1-\beta)^{-(2+\alpha)} - 1]$. This function is plotted in Figure 1 for various values of γ and R (α = 0 is taken): note that $A_m \gtrsim 100$ is required before the 'characteristic' $A^{1/(2+\alpha)}$ form becomes established.

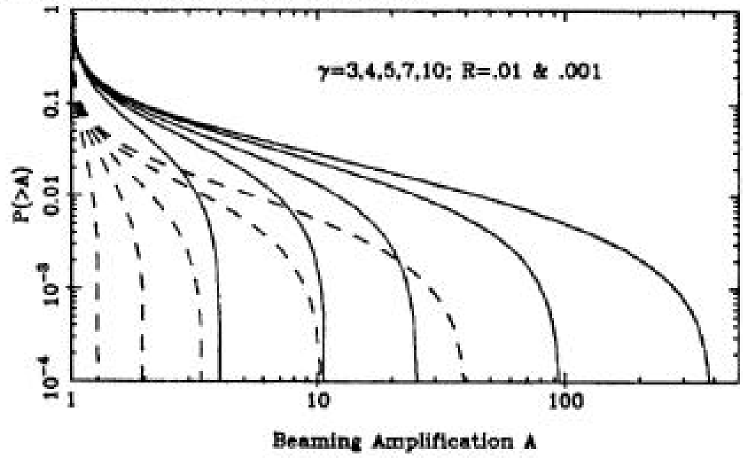

Figure 1

Equation (3) is a severe idealisation and some complications are discussed by Lind and Blandford (1985). The most natural of these is to recognise that if the jet is in any way non-steady, the observed emission will arise behind shocks. The effective beaming (post-shock) speed is then lower than the shock speed - which is the pattern speed observed with VLBI. If the jet consists of relativistically hot material ($P = \rho c^2/3$) then we have the exact relation between the Lorentz factors of the shock and the post-shock material:

$$\gamma_{post\text{-}shock} = \gamma_{shock}\, 2\, (9-\beta_{shock}^{-2})^{-1/2} \qquad (4)$$

(neglecting the velocity of the unshocked jet material). If we consider only strong shocks, then we have the approximate relation

$$\gamma_{post\text{-}shock} \simeq \gamma_{shock}\left(\frac{2}{\Gamma} - 1\right)^{\frac{1}{2}} + \frac{(\Gamma-1)}{\Gamma(2-\Gamma)} \qquad (5)$$

(valid to $\lesssim$ 10 percent for γshock $\gtrsim$ 5) where Γ is the quasi-specific-heat ratio; Γ = 5/3 for cold plasma, 4/3 in the ultrarelativistic limit. See Blandford and McKee (1976) for details of relativistic shocks. Equation (5) tells us that the effective Lorentz factor for beaming could easily be only ~ half that inferred from superluminal motion.

Further complications considered by Lind and Blandford include non-planar shocks and optical depth effects. The latter are especially important: for synchrotron emission, the optical depth scales as $\nu^{-(\alpha+5/2)}$ and the jet is likely to become optically thick when seen end-on. These effects thus tend to broaden the beaming cone considerably beyond the canonical $\theta \sim 1/\gamma$; we can probably still use a redistribution function of the form (3), but the relevant Lorentz factor is a parameter uncertain by a factor $\gtrsim 2$.

Less conventional explanations for superluminal motion include the 'light-signal' model and electron streaming models. In the former (e.g. Lynden-Bell 1977), the appearance of moving VLBI knots is generated by a pulse of radiation being scattered off a slowly-moving jet, in which case the emission is not strongly beamed. This model has fallen out of favour recently as it cannot explain why VLBI jets are one-sided (the cores are known to be stationary: Bartel et al. 1984). However, if current ideas about intrinsic one-sidedness persist (e.g. Bridle 1984), this model may revive, although there will still be difficulties explaining the lack of inverse-Compton X-rays in some sources (Marscher and Broderick 1981). Streaming models are perhaps even more speculative: here, bulk plasma flow is replaced by a highly anisotropic electron distribution with electrons following magnetic field lines at very low pitch angle. Such a configuration will indeed be generated by synchrotron losses, but scattering will tend to re-isotropise the distribution. Our knowledge of field configurations in active nuclei is too poor to be certain if such a model is possible, but it is certainly attractive in terms of its low energy requirements. Beaming in this model is again weak as the cone angle of visibility is set by the field geometry, not electron Lorentz factor (see e.g. Coleman 1986).

It should be clear, then, that beaming will be a difficult ghost to lay to rest, simply through our ignorance of the realistic $P(>A)$ function. In what follows, equation (3) will be assumed, in order to see if the simplest picture can be made consistent.

2. UNIFIED MODELS

The essence of all beaming theories is to ask what a compact radio source would look like when any putative beamed component is turned away from our line of sight: what is the unbeamed parent population? There have been three attempts to answer this question, which we now consider.

Note that, unless otherwise stated, $H_0 = 50$ kms^{-1} Mpc^{-1} and $\Omega_0 = 1$ are assumed throughout.

2.1 The Scheuer-Readhead Model

This unified model is almost certainly incorrect; nevertheless, it was such a classic paper that we can profit greatly from studying its downfall. Scheuer and Readhead (1979) suggested that compact radio quasars when unbeamed would appear as radio-quiet quasars. By assuming that all the radio emission was beamed - i.e. equation (3) with $R = 0$ - they were able to predict the radio flux-density distribution for an optically-selected sample: $P(>S) \propto S^{-1/(2+\alpha)}$, assuming a small dispersion in plane-of-sky flux densities. This prediction was not confirmed: the detection rate appeared to be a function of redshift (Smith and Wright 1980) and, more crucially, Condon et al. (1981) found that many quasars were not detected by the VLA at sub-mJy levels, implying a much slower variation of $P(>S)$ with S. In retrospect, these objections did not really refer to the main idea of the Scheuer-Readhead model. All the above authors were working in terms of a paradigm introduced by Schmidt (1970) whereby radio and optical luminosities of quasars correlated. The beaming model was therefore used to predict the distribution of radio-optical flux ratios. The results of Smith and Wright and Condon et al. can equally well be regarded simply as evidence against the Schmidt hypothesis and, indeed, Peacock, Miller and Longair (1986) have used similar arguments to show that radio and optical luminosities probably do not correlate.

The real objection to the Scheuer-Readhead model comes from more detailed observations of compact radio quasars. These turn out to have $\gtrsim 1$ percent of their total flux in the form of extended steep-spectrum emission (Perley et al. 1982; Schilizzi and de Bruyn 1983; Browne & Perley 1986). The morphology of this emission is such that it seems most unlikely to be beamed: the unbeamed counterparts of compact quasars would still be quite strong radio sources - much more luminous than the typical radio-quiet quasar.

2.2 The Orr-Browne Model

The steep-spectrum haloes discussed above led Orr and Browne (1982) to the idea that compact quasars were simply normal double radio sources seen end-on. In particular, they assumed that the unbeamed counterparts remained quasars, rather than appearing as radio galaxies (see Section 3 for discussion of the possibility that the optical quasar light may be anisotropic). Orr and Browne used this idea to predict the source counts for flat-spectrum quasars, given those for steep-spectrum quasars, with a fair degree of success. They did not check that their model also yielded the correct redshift distributions for flat-spectrum quasars, but this has been verified by Kapahi and Kulkarni (1986).

We can generalise these analyses to consider the full evolving luminosity function. Consider the integral luminosity function resulting from the application of beaming amplification to the plane-of-sky parent luminosity function N_o:

$$N(>L) = N_o(>L) + \int_{L/A_{max}}^{L/A_{min}} P(>A) \; dN_o \; . \qquad (6)$$

A_{max} and A_{min} are the beaming amplifications within which the source is classified as steep- or flat-spectrum. Orr and Browne give a complicated prescription for this division; we shall simply take $1 < A < 2$ to correspond to a steep-spectrum source, $2 < A < A_m$ for flat-spectrum. The results are highly insensitive to the exact division adopted. Since realistic values of A_m are $\lesssim 100$ (cf. Figure 1), we can take N_o to be locally a power law $N_o\,(>L) \propto L^{-\delta}$, in which case

$$\frac{N_{fs}}{N_o} = 1 + \int_2^{A_m} P(>A) \quad \delta A^{(\delta-1)} \quad dA \qquad (7)$$

and similarly for N_{ss}. Figure 2 plots the ratio N_{fs}/N_{ss} as a function of δ.

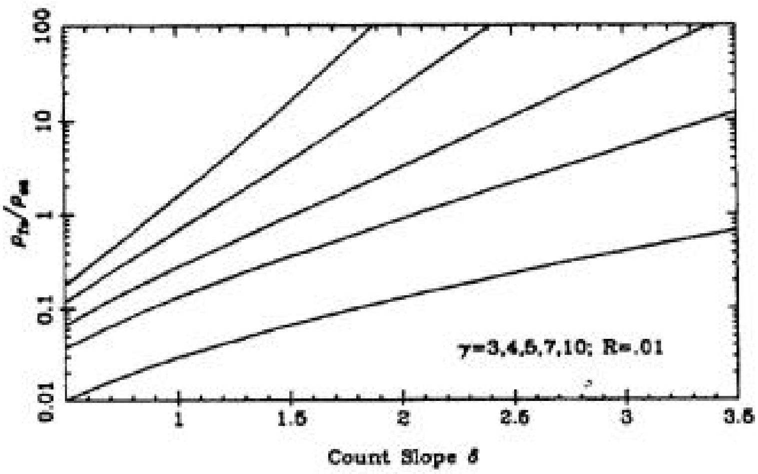

Figure 2

If $\delta > 1$ and $A_m > 5$ then the large - A_m result is accurate to a factor $\lesssim 1.5$:

$$\frac{N_{fs}}{N_{ss}} \simeq \frac{(1-\beta)}{\beta} \; \frac{A_m^{\delta}}{\delta(2+\alpha)} \simeq \frac{R^{\delta}(2\gamma^2)^{\delta(2+\alpha)-1}}{\delta(2+\alpha)} \quad . \qquad (8)$$

Orr and Browne argue that the appropriate value of R for steep-spectrum quasars is approximately $0.012\,((1+z)\nu_{obs}/5\mathrm{GHz})$ - allowing for a factor of 2 difference in their definition of R. This is probably not a good approximation for $(1+z)\nu \gtrsim 10$ GHz as the central components will then start to go optically thin and R will eventually cease to change with increasing frequency. Note that radio galaxies of the same total power as steep-spectrum quasars have by comparison very small observed values of R (~ 0.001): these objects can nevertheless generate substantial amplifications given high Lorentz factors ($A_m \simeq 40$ for $R = 0.001$, $\gamma = 10$ and $\alpha = 0$). We should therefore not be surprised at the existence of core-dominated radio galaxies with superluminal motion (e.g. 3C120: Walker 1984).

To test the predictions of Figure 2 most stringently we require the evolving radio luminosity function, since the unified scheme has to apply at all redshifts. The most recent determination of this is by Peacock (1985), but it is not precisely what we need as it does not distinguish radio galaxies from quasars. An RLF for quasars alone is given by Peacock (1987: this volume). The data for both steep- and flat-spectrum classes can be described by a luminosity evolution model with comparable degrees of evolution for each class. This latter point is slightly in conflict with the unified model, which predicts increasing dominance of flat-spectrum sources at high redshift. However, as mentioned above, the $R \propto (1+z)$ scaling on which this is based is probably unrealistic. It will therefore suffice to compare ρ_{ss} and ρ_{fs} at one redshift (we take $z = 1$, where most of the data lie). For $\Omega = 1$, Figure 3 plots firstly the two RLFs and secondly ρ_{fs}/ρ_{ss} versus slope of the steep-spectrum RLF.

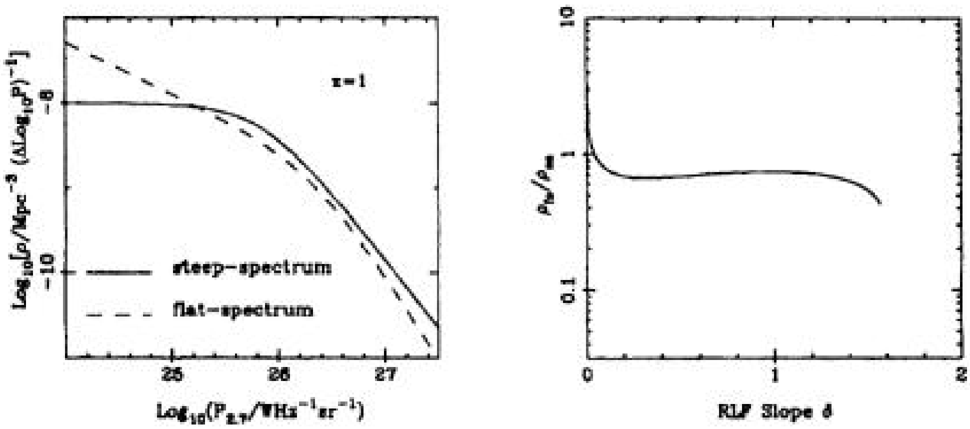

Figure 3

The interesting thing about this plot is that the two RLFs are virtually identical for $P > 10^{25}$ WHz^{-1} sr^{-1}. The flat-spectrum RLF does not decline for lower powers as would be predicted; it is not clear how much of a problem this is, as there are few objects in this region. Most of the data give us only one point: $\rho_{fs}/\rho_{ss} = 1$ at $\delta = 1.6$: this is as expected for a beaming model with $R = 0.01$, $\gamma = 5$, which is essentially the Orr-Browne conclusion. Any departures in detail from the model may not be too much of a problem: it is unrealistic to suppose that there is no spread of (R,γ) values or that these are totally uncorrelated with power. Orr and Browne suggested that the model γ value could be regarded as the mean of some distribution; we disagree. From (8), taking canonical figures of $\delta=2$, $\alpha=0$, we get $\rho_{fs}/\rho_{ss} \propto \gamma^6$: the model γ value will tend to be close to any upper cutoff in a distribution.

What further tests of the Orr-Browne model do we have? Some impressive arguments in favour were provided by Wills and Browne (1986), who found a strong correlation between broad emission-line velocity widths and radio core dominance, in the sense expected if the line-emitting clouds are confined to a disk: compact quasars have narrower lines. Wills and Browne also make the good point that any comparison of extended and compact sources which aims to test the unified scheme must be made at constant extended power. Thus, for example, the differences between the respective underlying nebulosities found by Boroson et al. (1985) may simply reflect a dependence on extended power.

Miller (1984) presented an argument against the Orr-Browne scheme, based on the fact that (for a given X-ray power) compact quasars have radio cores on average ~30 times stronger than extended quasars. If the X-ray emission is unbeamed, this rules out the beaming by a factor ~1000 required in the Orr-Browne model. This argument has been countered by Browne and Murphy (1987), who conclude that the X-ray emission in quasars does indeed contain a beamed component. They are able to come to this conclusion because radio maps of high dynamic range are now available for almost all the X-ray quasars studied by Miller (1984) and the correlation of X-ray power with core dominance at constant extended radio power can be studied directly: the core-dominated quasars are on average a factor ~10 more X-ray luminous.

A final potential test of the Orr-Browne model concerns the cluster environments of compact sources. This is probably the best test of all since it is about the only property which can be guaranteed to be isotropic (nuclear line and continuum emission can be obscured by dust lanes). We know the local galaxy density for the parent extended sources, and that this decreases with increasing extended luminosity (Longair and Seldner 1979; Prestage 1985; Prestage and Peacock 1987), so that there is a clear prediction for what should be found for compact sources. The problem at present is that studies have been limited to $z < 0.1$-0.2 by lack of deep galaxy counts and so only compact sources with $P_{2.7} \lesssim 10^{24}$ WHz^{-1} sr^{-1} have been studied. However, Prestage and Peacock find the cluster environments of these objects to be very sparse, possibly less dense than for FRII sources (classical doubles: see Fanaroff and Riley 1974) and certainly lower than FRI sources, which are the putative parents of such weak core-dominated sources (although the redshift limit means we are not yet able to compare many objects of the same extended luminosity). This result requires confirmation and extension to higher redshifts (and hence powers) using CCDs to generate faint galaxy samples. If rich environments continue not to be found, this will be a strong argument against both the Orr-Browne model and the unified picture for blazars discussed next.

2.3 Blazars

The least ambitious (and most plausible) unified scheme was suggested by Blandford and Rees (1978). The term 'blazar' covers objects with highly polarised ($\gtrsim$ 3 percent) rapidly variable (~ 1 day) optical nuclear emission (see Angel and Stockman 1980). These properties make a static isotropic model extremely hard to sustain: either there will be a compton catastrophe if the relativistic electrons and magnetic field are in equipartition or, if not, rapid synchrotron cooling will produce thermal electrons which wash out the polarisation. Blandford and Rees therefore concluded that the case for bulk relativistic flow was strong. In forming a unified scheme for blazars, we may need to recognise the original division of the Angel-Stockman term into two classes: BL Lac objects or OVV quasars according to the absence or presence of strong broad emission lines. Blandford and Rees suggested that the former category be regarded as beamed versions of ordinary radio galaxies.

This hypothesis became testable given measurements of the extended flux density of BL Lacs. Browne (1983) showed that the local density of BL Lacs with extended $P_{1.4\ \mathrm{GHz}} \gtrsim 10^{22.6}$ WHz^{-1}sr^{-1} was $\gtrsim 2 \times 10^{-8}$ Mpc^{-3}, which Browne claims to be about 0.017 times the density of elliptical radio galaxies with such luminosities. If correct, such a proportion of BL Lacs would be consistent with beaming into a cone of semi-angle γ^{-1} with $\gamma \simeq 5$ (although Browne's figure appears to be incorrect: see below). A more severe test (as in Section 2.2) would be to see if the overall luminosity function for BL Lacs behaves as predicted, but we have little idea how these objects evolve with cosmological epoch. Existing lists of Blazars (e.g. Angel and Stockman 1980) contain a surprisingly high proportion of bright low-redshift objects, and this has led some authors (e.g. Woltjer and Setti 1982) to ascribe a low degree of evolution to the blazar population. Existing blazar samples are of course grossly incomplete, but such a bias to low redshifts may be expected in beaming models. This is because it is well known that radio galaxies change their emission-line properties an an extended radio power threshold corresponding to the Fanaroff-Riley (1974) transition between classical double sources (FRII: $P_{1.4} \gtrsim 10^{24.5}$ WHz^{-1}sr^{-1}) and more diffuse objects: only FRII sources have strong nuclear emission lines (Hine and Longair 1979). At low redshifts, blazars will tend to have extended emission below the FR threshold - forming a classical line-less BL Lac. This argument is supported by the data of Antonucci and Ulvestad (1985), who give extended luminosities for all the Angel and Stockman objects. Figure 4 shows histograms of extended luminosity for objects with known redshift, distinguishing those objects which Angel and Stockman class as strong lined from those which are not.

There is a clear separation at about the FR borderline, in line with the above argument. The remaining objects of unknown redshift are presumably largely of the lineless class: if they have $z \lesssim 0.2$ almost all will fall into the FRI class.

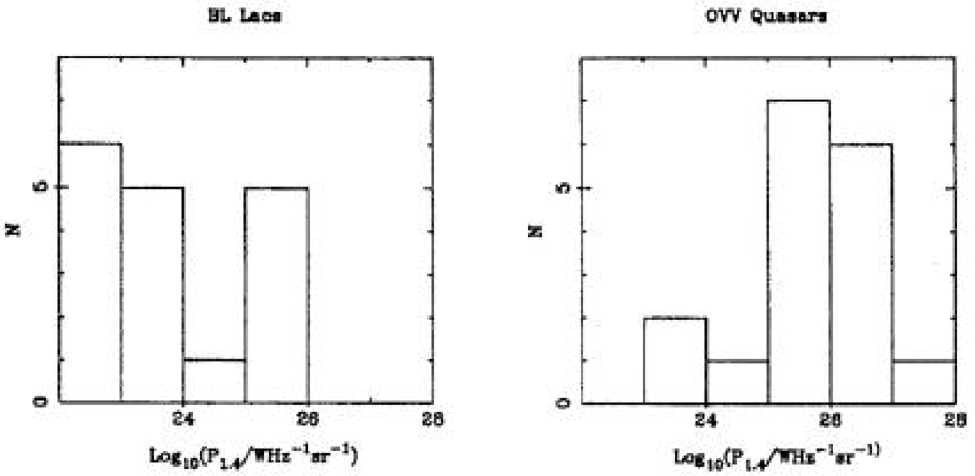

Figure 4

In addition to luminosity effects, the bias of BL Lacs to low redshift is assisted because FRI sources have relatively strong cores ($R \sim 0.01$) and beaming dominates more easily. Indeed, the 12 objects in Antonucci and Ulvestad's list that are core dominated by a factor > 50 all have extended $P_{1.4} < 10^{24.8}$ $WHz^{-1}sr^{-1}$. There is a problem here in that the most compact sources are core dominated by a factor ~ 1000, implying Lorentz factors $\gtrsim 10$ for $R = 0.01$, in conflict with the estimate from the space density. However, this calculation seems dubious: Browne adopts a space density of radio galaxies with $P_{1.4} > 10^{22.6}$ $WHz^{-1}sr^{-1}$ of 1.3×10^{-6} Mpc^{-3}, whereas the luminosity function of Windhorst (1984) yields 1.1×10^{-5}, so that in fact only 1 object in ~ 500 is a BL Lac. It is difficult to reconcile such a low fraction of BL Lacs with such high maximum amplifications: the formal solution of $\gamma = 90$, $R = 4 \times 10^{-6}$ is nonsensical. Probably we need to abandon the assumption of a universal Lorentz factor. Suppose we had $P(>\gamma) = \gamma^{-x}$ and let us seek limits to x. From (3) we have for $A_m \gg 1$ $P(A>2) \simeq R^{1/(2+\alpha)}$; since $A_m \simeq 4\gamma^4 R$, the total probability of $A>2$ is $\sim R^{x/4 + 1/(2+\alpha)}$. If we allow for a (likely) substantial incompleteness in the BL Lac samples and take $P(A>2) \simeq 10^{-2}$, then $R = 0.01$ and $\alpha = 0$ imply $x \simeq 2$. For an illustrative model, this is quite a sensible answer, as it allows ~ 10 percent of BL Lacs to be very highly beamed ($\gamma \gtrsim 10$) without producing vast numbers of core-dominated objects.

More direct support for the idea of elliptical radio galaxies as the parent population for blazars comes from the observation of low-level blazar activity in the nuclei of FRI sources like Cen A (Bailey et al. 1986): polarised nuclear continuum may be detectable in many FRI sources (at least in the infrared, where extinction is less important). This will probably be the best way of testing the unified blazar model in the future.

3. ALTERNATIVES

We have painted ourselves into something of a corner over the last two Sections. The arguments in favour of both the Orr-Browne and

Blandford-Rees unified schemes appear quite impressive, but they may be inconsistent. This is because one can regard essentially all flat-spectrum quasars as blazars: in the radio ($\nu \gtrsim 10$ GHz), they display the characteristic variable polarised emission that defines this class. In the optical/infrared, variable polarised continuum is seen in $\gtrsim 50\%$ of objects (Meisenheimer, private communication); the exceptions are generally those of high optical luminosity where the synchrotron component is washed out by the 'blue bump' (the presumed accretion-disk feature seen at ~ 2000Å in the rest frame). We therefore have two competing alternatives for the parent population of flat-spectrum quasars: either extended steep-spectrum quasars or extended radio galaxies. Deciding between these on the basis of statistics of number densities will be hard: the extended emission about flat-spectrum quasars is usually of FRII luminosity (Browne and Perley 1986; Section 2.3) and the numbers of FRII quasars and radio galaxies are comparable (Section 2.2). There is then no conflict between the Orr-Browne model and the idea of BL Lacs being beamed FRI galaxies: we are instead concerned with the class of parent object for luminous compact quasars such as 3C273.

In trying to answer this question, we are faced with another puzzle - what is the relation between the FRII sources which are galaxies and those which are quasars? A recent review of this problem was given by Owen (1986): the extended structures of both classes are tantalisingly similar and both appear to possess central cores and one-sided jets, but the latter are a factor ~10-100 weaker in radio galaxies. The similarity in appearance and number strongly argues for a connection between the two classes, and there are really only two natural alternatives: relation by a difference in time or a difference in orientation. In the first case, the nuclear quasar activity would be of shorter duration than the main radio outburst, with a radio galaxy spending ~50% of its time in an 'excited' quasar state. To explain why we always see the strong one-sided jet with the nucleus, we would require the flaring to last much longer than the travel time along the jet. If we use orientation to explain the difference, then the approximate equality of radio galaxies and extended quasars would imply $\mu > \frac{1}{2}$ in (2) for quasars. For the standard model, this implies beaming by a factor > 4 with respect to $\mu = 0$ (or a factor $\simeq 2$ lower if we include the counterjet), rising rapidly with μ. This could make quite an attractive picture, with galaxies for $\mu \lesssim 0.5$, extended quasars for $0.5 \lesssim \mu \lesssim 0.9$ and core-dominated quasars for $\mu \gtrsim 0.9$, were it not for one problem: how do we switch on the quasar light for $\mu \gtrsim 0.5$? We cannot do it by beaming: there is a beamed component in the light of compact quasars only (see above). Nevertheless, there is evidence for anisotropic light in radio galaxies (e.g. Cygnus A: Pierce and Stockton 1986) and the most natural way of making it visible over ~ 2π sr is by obscuration. Searches for obscured quasars in radio galaxies (e.g. Fabbiano et al. 1986) would seem highly worthwhile. It may seem contrived to have two mechanisms for anisotropy in the radio and optical, but we may have little alternative. Evidence is now arriving that superluminal motion may be found often in cores of quasars selected via their extended lobes (Zensus and Porcas 1986). On a conventional picture, this forces us to have beams pointing towards us, and something like obscuration is then the only obvious way to fix up the optical properties.

There are two ways of looking at the above discussion. We can be positive and note that beaming models come close to unifying a wide range of phenomena in an appealingly simple way; real life is messy enough that we shouldn't be surprised if one or two details don't appear to fit in at first sight. Alternatively, we can regard any sort of ad hoc tinkering with the model as a modern version of mediaeval epicycles - we may be working with a fundamentally unsound picture. Certainly, the number of tests of unified models is depressingly small and it is still possible that core-dominated quasars will have to be understood on their own terms as a distinct physical class. Indeed, we already know of one class of powerful radio source which we are happy not to fit into any unified picture: the compact steep-spectrum sources such as 3C48 (e.g. van Breugel et al. 1984). In the end, probably the best thing to do is to continue detailed studies of putative beamed objects. For example, the beautiful MERLIN maps of 3C273 (Davis 1986) with their >50:1 asymmetric structure may place stronger constraints on unified models than any study of the grand sweep of population statistics.

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