VLBI MAPPING OF THE NUCLEI OF RADIO GALAXIES AND QUASARS

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It is now possible, by means of VLBI hybrid mapping, to make maps of radio sources with a resolution of ∿ 1 milliarcsecond. This enables us for the first time to compare the morphologies of the small- and large-scale structures of extragalactic radio sources, and they are strikingly different.

1. INTRODUCTION

There are two major classes of extragalactic radio sources namely the extended (> 1 arc sec) and compact (< 1 arc second) objects. These are fairly well delineated by their radio spectra. In Figure 1 is

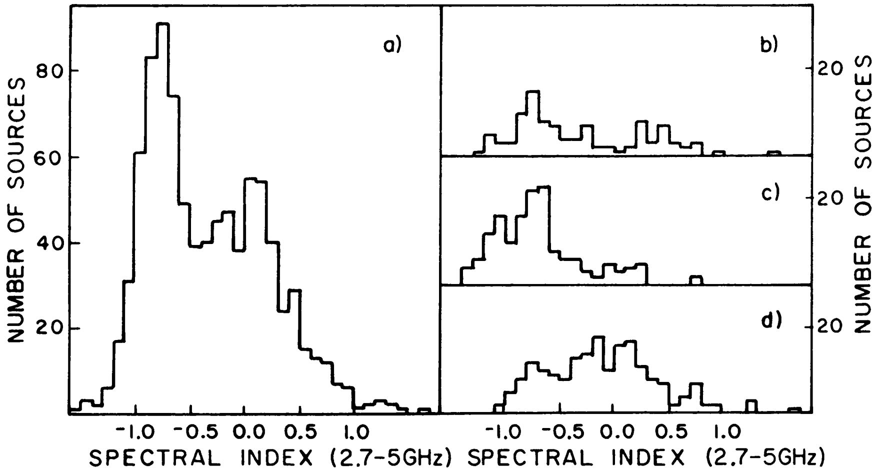

Figure 1. The spectral index distribution of sources in the SIV survey: a) complete sample, b) empty fields, c) radio galaxies, d) quasars (from Pauliny-Toth et al. 1978). Most objects with $\alpha > -0.5$ are compact.

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shown the distribution of radio spectral indices from the SIV survey (Pauliny-Toth et al. 1978), and we see immediately that over 60% of these objects have flat spectra (i.e. they are compact), and only about 40% have steep spectra (i.e. they are probably extended). Many hundreds of these extended objects have been mapped by aperture synthesis at Cambridge, Westerbork, Greenbank and recently the VLA. Only ∿ a dozen compact objects have been mapped thus far. Nevertheless the results of mapping this small sample have been illuminating, and it is these objects which I will discuss here.

The spectral index classification is not a completely reliable guide to angular size, since there are some steep spectrum objects which are compact (e.g. 3C147, 3C380) and which look quite different to the "classical double" extended sources. A more useful classification is given by the radio morphology at a given frequency and the disposition of the radio structure relative to the optical objects. It is useful to define "symmetric" objects as those in which the dominant radio emission at 5 GHz comes from two regions on opposite sides of, and roughly equi-distant from the optical object; and to define "core" objects as those in which the dominant emission at 5 GHz comes from a component coincident with the optical object, and in which the extended radio emission region, if any, is asymmetric.

2. THE NEED FOR HIGH RESOLUTION (<< 1 ARC SECOND) MAPS

In order to understand the physical processes responsible for the creation and evolution of extragalactic radio sources we need to map these on the angular scales $10^{-4} \rightarrow 1$ arc second, i.e. on VLBI scales, for the following reasons:

1) As we have just seen, the compact objects comprise more than half the total population of radio sources at high frequencies and they are too small (<< 1") to be mapped by conventional methods.

2) Many compact objects vary on time-scales of days → decades. Thus the study of variation in structure adds another dimension to the conventional mapping of extragalactic objects, and it enables us to study the physics of these objects in a completely different way.

3) It is now commonly believed that the energy of the extended objects originates in the nucleus of the galaxy or quasar. VLBI observations enable us to map these centres of activity with a resolution ∿ 1 pc at the Hubble radius.

4) Searches for interstellar scintillation in extragalactic objects (Condon & Backer (1975), Condon & Dennison (1978), Readhead et al. (1980b))have shown that the angular sizes of the most compact regions are >> 10^{-5} arc seconds. Thus it is possible with high frequency VLBI to study the smallest detectable features in these objects.

3. HYBRID MAPPING

The hybrid mapping technique which we have used has been described in detail by Readhead & Wilkinson (1978). It is superior to the old model fitting methods for three reasons:

1) The visibility phases are derived from the closure phase (Jennison 1958) and amplitude data. The inclusion of the phase data is essential for making reliable maps, and removes the 180° ambiguity inherent in amplitude only reconstructions. This is particularly important when comparing maps at different epochs of a strongly varying source. In addition, with limited data it is sometimes possible to have quite different models which fit the amplitude data equally well. In our experience the closure phase data is a powerful discriminant in such cases.

2) Four or more telescopes are used for making hybrid maps. The CIT/JPL processor can now correlate all pairs of a five station network simultaneously, thus making observations on large networks more tractable.

3) Continuous tracking of the source for 9 to 12 hours, depending on the declination, ensures that we get all the possible visibility information on a given network.

In Figure 2 are shown three maps of 3C 147 at different frequencies. In the cases of 609 and 1671 MHz maps it was possible to use the core as an internal phase reference, so that the closure phase relations do give the visibility phases directly. The agreement of the three maps is excellent and gives confidence in the hybrid mapping procedure, especially when you consider that the maps were made on different networks at the three frequencies. In addition the fits to the data are very good in each case. Figure 3 shows the fit at 1671 MHz. This is typical of the fits obtained by hybrid mapping

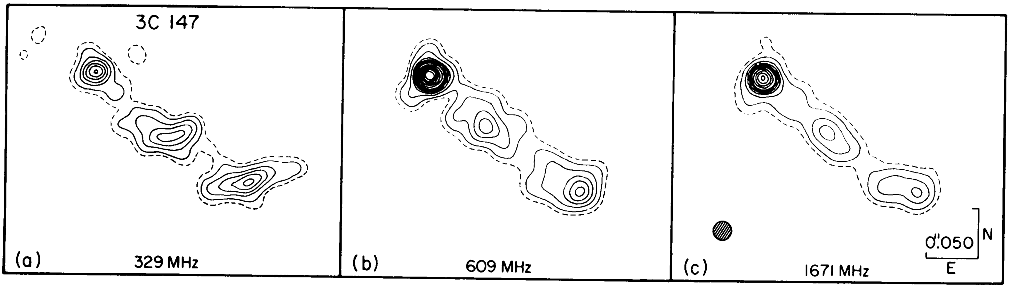


Figure 2. Hybrid maps of 3C 147: a) Simon et al. (1980), b) Wilkinson et al. (1977), c) Readhead and Wilkinson (1980).

The morphology of 3C 147 is typical of core objects. The most striking characteristics are:

1) It is a one-sided jet,

2) There is a very compact, flat spectrum core at the end of an extended steep spectrum jet,

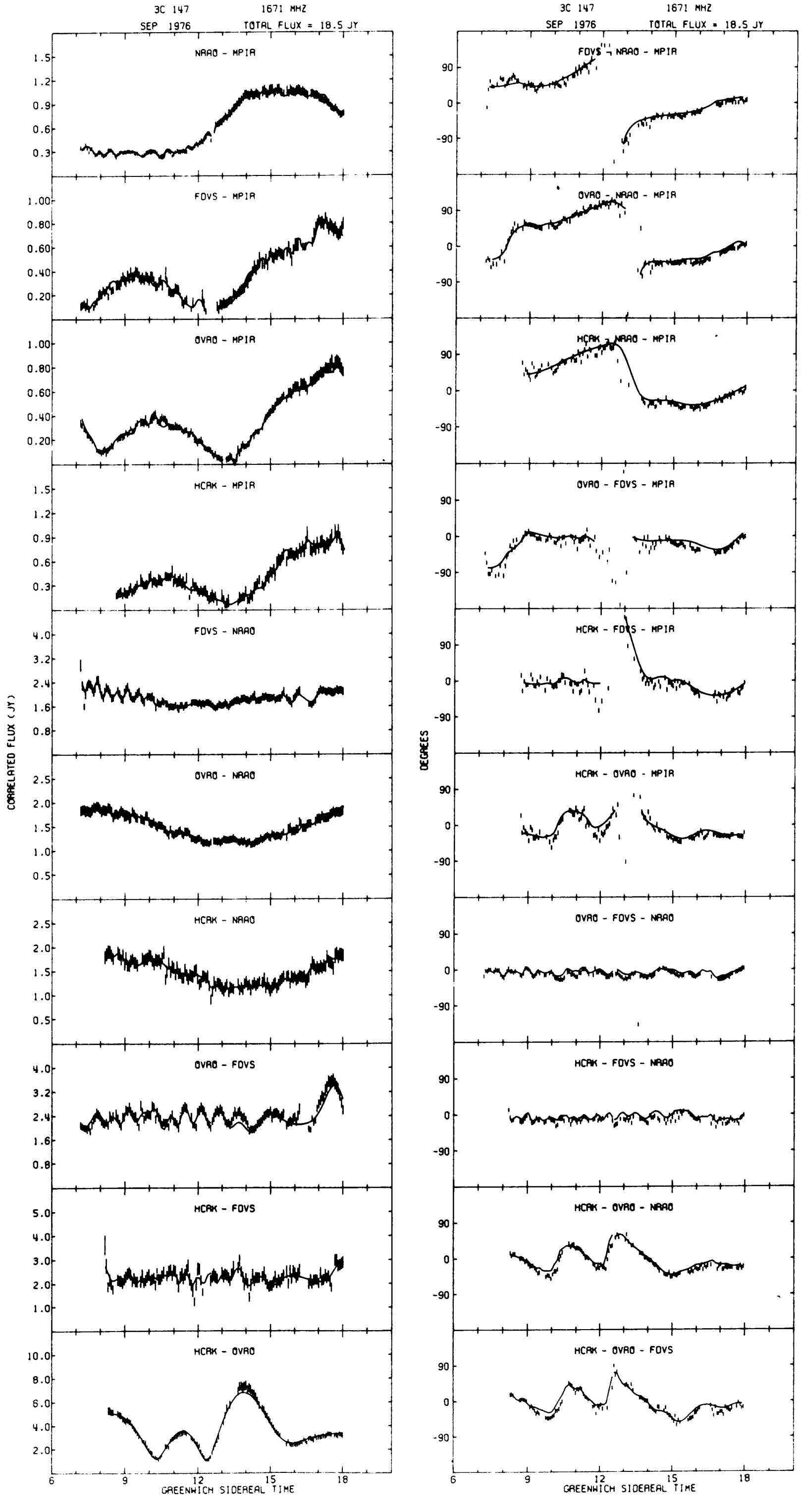


Figure 3. The fit to the amplitudes and closure phases of the delta functions which constitute the map shown in Figure 2c. (Readhead and Wilkinson, 1980). The fit is excellent, and gives confidence in the hybrid mapping procedure. At times of very deep minima in the correlated fluxes the closure phase flips through ~180°. In successive iterations the direction of the phase flip varied, on some baselines, and we have not tried to fit the closure phases at these times. This has a negligible affect on the hybrid map.

3) The position angle of the jet is different to that of the larger scale (∿ 1") structure.

The objects which we have mapped thus far by this technique are shown in Table I. Apart from 3C 84, nearly all of these objects are one-sided jets with a flat spectrum core and a steep spectrum jet. The only objects which are not clearly asymmetric are CTA 21 and 3C 119, which have only been observed at one frequency. We have found that it is often necessary to have maps at two frequencies before asymmetry is clearly shown, because of the different spectral indices of the core and jet.

TABLE I
Objects Which have been Mapped by VLBI

Object	Mapped at Frequencies (GHz)	Asymmetric	Flat Spectrum Core Steep Spectrum Jet	References
CTA 21	.609	?	?	43
3C 84	.609, 5.011, 10.650	Complex	Complex	19, 22, 28, 43
3C 111	10.650	√	?	15
3C 119	1.671	?	?	21
3C 120	5.011, 10.650	√	√	29
3C 147	.327, .609, 1.671, 4.885, 15.035	√	√	27, 32, 40, 42
3C 273	.609, 5.011, 10.650	√	√	24, 43
3C 286	.327, .609, 1.671	√	√	21, 40, 43
3C 345	.609. 5.011, 10.650	√	√	29, 43
3C 380	1.671, 5.011	√	√	22, 28, 32
3C 454.3	.609, 1.671	√	√	21, 43
CTA102	.609, 1.671	√	√	21, 43
NGC6251	10.650	√	√	5

4. THE MORPHOLOGY OF THE NUCLEAR COMPONENTS

Among the objects mapped thus far there are symmetric objects, steep spectrum core objects and flat spectrum core objects. Taken in this order, the relative dominance of the central component is increasing, and I have chosen one example from each group to illustrate their major characteristics

4.1 Symmetric Objects

A hybrid map, and a model of NGC 6251 are shown (Cohen & Readhead

1979) in Figure 4. It is a one-sided jet with a flat spectrum core and steep spectrum jet, and the jet is well aligned with the large scale (>> 1") structure (Readhead et. al. 1978a).

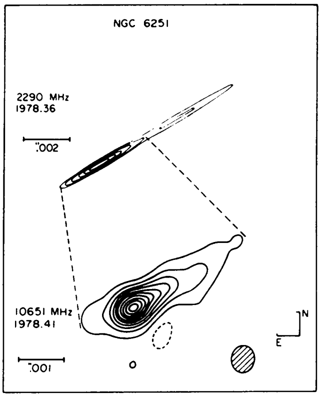


Figure 4. Hybrid map (10,651 MHz) and model (2290 MHz) of the nucleus of the symmetric radio galaxy NGC 6251 (Cohen and Readhead, 1979).

Thus far such good alignment has always been found in symmetric objects (Readhead et. al. 1978b). No significant structural variations have been seen, (i.e. over a period of 1 year).

4.2 Core Objects with Steep Spectra (at 5 GHz)

In Figure 5 is shown a hybrid map of 3C 380 (Readhead & Wilkinson 1980).

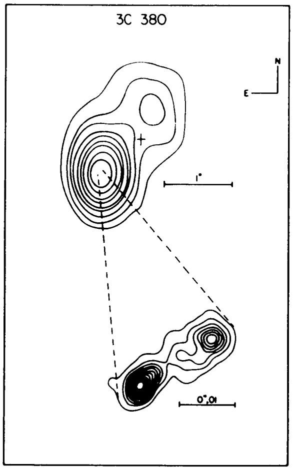


Figure 5. Top: Map of 3C 380 at 15 GHz made with Cambridge 5 km telescope (Scott, 1977). Bottom: Hybrid map at 1671 MHz (Readhead & Wilkinson 1980). The cross marks the position of a compact component The optical object coincides with the SE component of the 15 GHz map.

In many respects this source is very like 3C 147. The object is curved, i.e. the smallest and largest features are not aligned. This is typical of core objects (see §5). No significant structural variations have been seen in objects of this type.

4.3 Core Objects with Flat Spectra (at 5 GHz)

A hybrid map of 3C 273 (Readhead et al. (1979)) is shown in Figure 6. Objects in this class often show significant structural variations on time-scales $\lesssim$ 1 year.

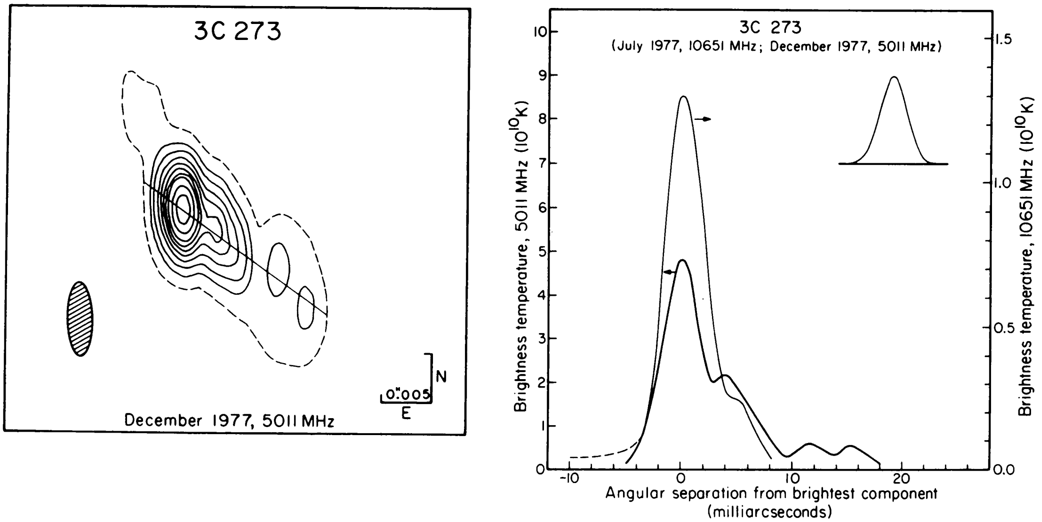


Figure 6. Left: Hybrid map of 3C 273 at 5011 MHz. Right: Sections through the 5011 MHz and 10,651 MHz maps of 3C 273, showing that the core has a flat spectrum and the jet a steep spectrum (Readhead et al. 1979).

An important point which emerges from this comparison is that the morphology of central components of symmetric objects is very similar to that of the core objects. R. Linfield (private communication) has recently made a hybrid map of the central component of 3C 111 and finds that, like NGC 6251, it is a one-sided jet.

5. SYMMETRIC AND/OR ASYMMETRIC JETS?

One of the most interesting questions in extragalactic radio astronomy is whether there are two mechanisms for producing jets - one symmetric and one asymmetric, or whether there is only one, symmetric mechanism.

Most extended (>1 arc sec) objects are symmetric, and until recently it appeared that asymmetric objects were rare, the best examples being 3C 273 and M87, and a few D2 quasars (Miley, 1971). It now appears that asymmetry might be as ubiquitous as symmetry in extragalactic objects. In particular, even in the symmetric objects 3C 111 and NGC 6251 the radio nuclei are asymmetric. These are the only nuclei of symmetric objects mapped thus far, but it is unlikely that the first two objects mapped will be entirely atypical. These jets could be instantaneously one-sided, but alternating between one side and the other. In that case, if the typical switching time were longer than $\sim 10^4$ years, the morphology of the objects in any complete sample of steep spectrum radio sources would change from asymmetric to symmetric at an overall size of a few tens of kiloparsecs - which is not observed. However NGC 6251 has an asymmetric jet 200 kpc long (Waggett et. al. 1978), implying a switching time $>10^5$ years. Thus either both jets are on quasi-continuously, and we just do not see the counter-jet, or NGC 6251 is atypical.

The occurence of asymmetric nuclei in symmetric objects strongly suggests that objects such as 3C 273 and M87 may not be as different from typical symmetric objects as they appear, and that the fundamental mechanism is symmetric but it only appears asymmetric to us. There is other evidence that this may be the case: In Table II are summarized some of the major differences between core and symmetric objects. There are three striking correlations between morphological class and other important physical characteristics:

(i) Alignment between small scale and extended structure (ΔPA) - symmetric objects are well aligned whereas core objects are often curved.

(ii) Overall Size - the core objects are consistently smaller than symmetric objects.

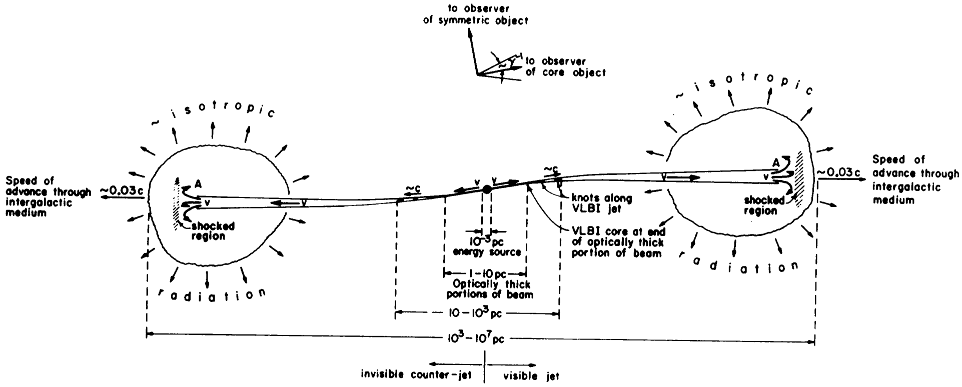
(iii) Distance Class - core objects are on average more distant than symmetric objects.

TABLE II

Objects in which both very compact (<<1") and extended (>1") Structure have been mapped. (H_o = 50 km/s/Mpc, q_o = 0.5)

Name	z	Size (kpc)	Type	Change in p.a. (deg)	References
NGC315	0.0167	1500	Symm	< 4	2, 15
NGC6251	0.023	2900	Symm	4.5	5, 25, 41
3C111	0.0485	270	Symm	< 4	14, 15
3C371	0.050	4	Core	30	22, 23, 28
3C390.3	0.0561	320	Symm	< 5	14, 15, 24
3C405	0.0565	190	Symm	< 4	11, 13
3C236	0.0989	5700	Symm	< 3.5	36, 44
3C273	0.158	70	Core	40	18, 26, 29, 35, 39
3C279	0.54	87	Core	~60	8, 16, 18
3C147	0.545	5	Core	25	10, 27, 32, 40, 62
3C345	0.594	25	Core	45	26, 29, 37, 38
3C380	0.691	40	Core	20	22, 28, 32, 34
4C39.25	0.698	25	Core	~40	22, 28, 37, 38, 39
3C454.3	0.860	50	Core	34	9, 21, 37, 39, 43

These effects can all be explained in terms of the simple model shown in Figure 7 (Readhead et. al. (1978b)). On this model both core and symmetric objects are produced by twin beams along which the particles travel with relativistic bulk velocity v. In core objects the angle, θ, between the line of sight and the beam is small ($\theta < \frac{1}{\gamma}$, where $\gamma = (1 - (v/c)^2)^{-1/2}$). In symmetric objects this angle is large. The observed asymmetry in the nuclei of both core and symmetric objects is due to relativistic beaming of the radiation from the jets. If the intrinsic bending of the beams is small (≲ 5°) this would account for the good alignment observed in symmetric objects, while projection and beaming effects in core objects would account for both the large apparent curvature and the small overall size. In addition, one has to observe a large number of objects, and hence a large volume of space in order to find a significant number of objects pointing almost along the line of sight. This helps to explain the larger average distance of the core objects.



Particle bulk velocity along jets = v(~c). At positions "A", at heads of jets, there may be some beaming of radiation in directions almost parallel to the beam, but most of the radiation from the head regions is ~ isotropic.

Figure 7. Simple model which accounts for the most obvious differences between core and symmetric objects (Readhead et. al. (1978b), Scheuer & Readhead (1979), and Blandford & Konigl (1979)).

This model also accounts naturally for
iv) the superluminal velocities observed in some core objects (e.g. Cohen et. al. 1977, Cohen et. al. 1979), and
v) the ratio of radio-quiet to radio quasars (Scheuer & Readhead, 1979).

A detailed physical discussion of this model has been given by Blandford & Konigl (1979). I must emphasize that this is not the only plausible hypothesis which can account for some of these effects (Readhead et. al. 1978), but it is the only one which gives a natural explanation for all of them.

Regardless of whether or not this simple model is either wholly or partially correct, the fact that the first VLBI maps are nearly all asymmetric is of great significance and seems destined to play as crucial a role in our understanding of these objects as the symmetry of the "classical double" sources.

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DISCUSSION

A.S. Wilson: Preliminary results from new 610 MHz observations at Westerbrook by R.G. Strom, A.G. Willis and me show the probable existence of a very faint counterjet (i.e., to the SE) in NGC 6251. This result supports the idea that both beams do exist simultaneously.

Readhead: I am delighted to hear it. The ratio of the surface brightnesses in the two jets will place useful limits on γ in our model.

Penston: I thought I noticed that the optically violently variable objects fell among the compact sources. Could your model accommodate such a difference in the optical properties?

Readhead: Yes, given that the intrinsic liminosities of core and symmetric sources are probably very different, I would not be surprised if other physical properties, such as optical and X-ray flux, showed some differences between the two classes.

Schmidt: Is your hypothesis concerning the ratio of radio-quiet to radio-noisy quasars compatible with a different evolution of the two types of quasar?

Readhead: Taken in its simplest form, with a single value of γ, the hypothesis is probably not compatible with a different evolution of the two types of quasar. However, as Peter Scheuer and I have pointed out (Scheuer and Readhead, 1979), it is clear that a range of values of γ is needed, and it may be that the symmetric objects have predominantly low values of γ, while the core objects have predominantly high values of γ. Moreover, if relativistic beaming is important in core objects, the intrinsic luminosities of these objects are much lower than they appear. Thus, the power of the core objects is probably much less than the symmetric objects, and it may well be that there is a different cosmological evolution for weak and powerful quasars.

As Martin Rees has pointed out, even without the model it might be difficult to reconcile the different evolution of the two quasar types with the strong evolution of the parent population of optically selected quasars. However, I would agree that the model seems at first sight to aggravate the problem.

We need to know much more about the radio emission from complete samples of optically selected quasars, and hence limits on the values of γ for the two quasar types, before we can decide if there is a serious confict.