THE MILLIARCSECOND STRUCTURE OF RADIO GALAXIES AND QUASARS

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Hybrid maps of the nuclei of radio galaxies and quasars show a variety of morphologies. Among compact sources, two structures are common: an asymmetric, "core-jet" morphology (eg, 3C 273), and an "equal double" morphology with two separated, similar components (eg, CTD 93). The nuclei of extended, double radio galaxies generally have a core-jet morphology with the jet directed toward one of the outer components.

1. INTRODUCTION

It is now generally accepted that one can make reliable maps with milliarcsecond resolution in VLBI by means of various hybrid mapping algorithms using closure phases and closure amplitudes [4,27,28]. Our experience with hybrid mapping and model fitting has shown that in cases where there is only a small sample of amplitudes and closure phases, or no closure phases at all, there may be significant errors in the derived structure. For this reason, we shall discuss only those objects which have been properly mapped according to the following criteria. The observations must (1) be long, continuous tracks, for reliable calibration and good (u,v)-coverage; (2) be made at four or more telescopes, for good (u,v)-coverage; and (3) include closure phases.

At the time of the IAU Symposium on Objects of High Redshift, two years ago, only a dozen objects had been mapped by VLBI [22]. The number is now about 50 (Table I). All of these objects vary, and some have now been mapped at six epochs and six frequencies, so the total number of hybrid maps is about 200. In this review, we shall discuss the morphology of these very compact objects. Table I lists the name of each object, its optical type (Quasar, Galaxy, or Unidentified), and a brief description of the milliarcsecond structure, with references to the original observations. We have been making a VLBI survey of the structure of northern sources stronger than 1.3 Jy at 5 GHz [15,16], and a number of the results we shall present are from this work. Unfortunately, as the survey is not yet complete, we do not have a

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TABLE I : SOURCES MAPPED BY VLBI

0055+300	NGC315	G	0.0167	Core-jet	[8]
0133+476	OC457	Q		Slightly resolved	[15]
0212+735		Q		Core-jet?	[16]
0316+162	CTA21	U		Slightly resolved	[35]
0316+413	3C84	G	0.0177	Complex	[14,15,34]
0333+320	NRAO140	Q	1.258	Core-jet/superlum?	[10]
0355+508	NRAO150	U		Core-jet	[12]
0415+379	3C111	G	0.0485	Core-jet	[8]
0428+205		G	0.219	Slightly resolved	[20]
0429+415	3C119	Q	0.408	Core-jet?	[17]
0430+052	3C120	G	0.032	Core-jet/superlum	[2,26]
0538+498	3C147	Q	0.545	Core-jet	[33,36]
0710+439	OI417	G		Triple	[16]
0711+356	OI318	Q	1.620	Double,Core-jet?	[16]
0804+499	OJ508	Q		Slightly resolved	[16]
0814+425	OJ425	Q		Slightly resolved	[16]
0836+710		Q		Double,Core-jet?	[6,16]
0850+581	4C58.17	Q	1.322	Slightly resolved	[16]
0859+470	4C47.29	Q	1.462	Slightly resolved	[15]
0906+430	3C216	Q	0.670	Slightly resolved	[16]
0923+392	4C39.25	Q	0.698	Equal double	[15]
0945+408	4C40.24	Q	1.252	Slightly resolved	[16]
1003+351	3C236	G	0.099	Core-jet	[32]
1226+023	3C273	Q	0.158	Core-jet/superlum	[2,18,26]
1228+126	3C274	G	0.004	Core-jet	[30]
1323+321	DA344	U		Equal double	[13]
1328+307	3C286	Q	0.846	Core-jet	[17,33,35]
1518+047		U		Equal double	[20]
1607+268	CTD93	G?		Equal double	[19]
1624+416	4C41.32	U		Slightly resolved	[16]
1633+382	4C38.41	Q	1.814	Double,Core-jet?	[16]
1637+574	OS562	Q	0.745	Slightly resolved	[16]
1637+826	NGC6251	G	0.023	Core-jet	[3,23]
1641+399	3C345	Q	0.594	Core-jet/superlum	[2,26]
1642+690	4C69.21	Q		Slightly resolved	[16]
1652+398	4C39.49	G	0.0337	Slightly resolved	[16]
1807+698	3C371	G	0.050?	Core-jet	[15]
1823+568	4C56.27	Q?		Slightly resolved	[16]
1828+487	3C380	Q	0.691	Core-jet?	[15]
1845+797	3C390.3	G	0.0561	Core-jet	[8]
1901+319	3C395	G	0.635	Double,Core-jet?	[6,19]
1928+738	4C73.18	Q		Core-jet	[16]
1954+513	OV591	Q	1.230	Slightly resolved	[16]
1957+405	Cyg A	G	0.0565	Core-jet	[8]
2021+614		Q		Double,Core-jet?	[16]
2050+364		U		Equal double	[20]
2200+420	BL Lac	Q	0.069	Core-jet/superlum?	[11,15]
2251+158	3C454.3	Q	0.860	Core-jet	[5,17,35]
2351+456	4C45.51	G		Slightly resolved	[16]

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well-defined, complete sample of objects, and selection effects must bias the data to some degree. Nevertheless, there are already some clear trends of great astrophysical interest.

It is well to remember that, as these objects are varying, it is in principle possible for their morphology to change quite dramatically on a time-scale of months. The rapid structural changes of the objects enable us to study the dynamical evolution. These variations have been described in detail at this Symposium by Marshall Cohen, Art Wolfe, and others, and we shall not consider them further here.

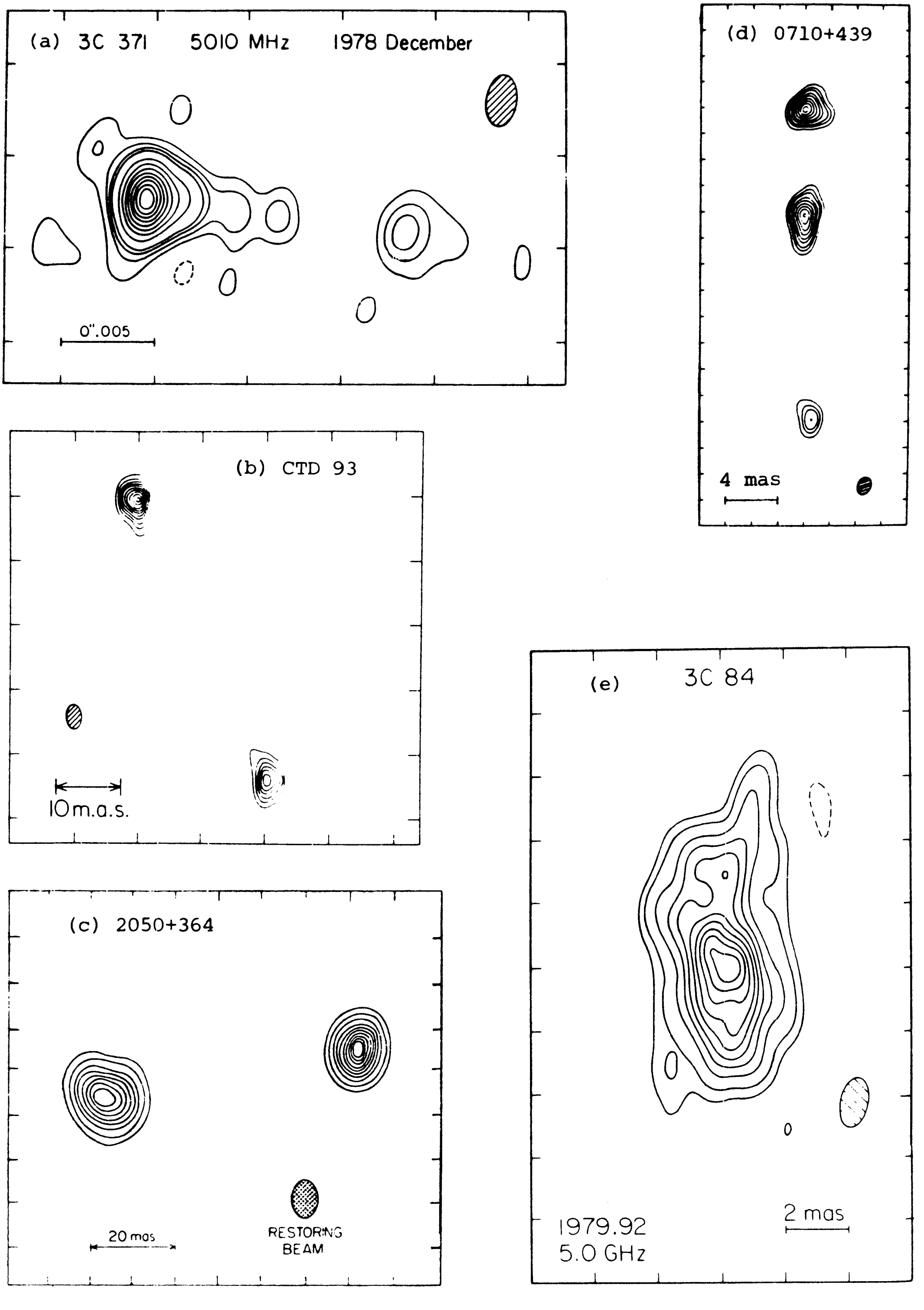
2. COMPACT RADIO SOURCES

One of the most interesting facts to emerge from the maps is that a significant fraction (perhaps as many as 50%) of the objects are one-sided jets, with a flat-spectrum core at one end of a steep-spectrum jet. Good examples are 3C 371 (Figure 1), 3C 273 and 3C 345 (Cohen and Unwin, this volume). It is perhaps misleading to use the term "jet" in this context, as the VLBI maps rarely have sufficient dynamic range to detect low-brightness structure, but the term is justified in cases like 3C 345 and NGC 6251 where the milli-arcsecond jet appears to be continuous with the larger-scale jet detected by conventional interferometry.

Observations of these one-sided jets over a range of frequencies show that the cores observed at lower frequencies can themselves be resolved into one-sided jets at higher frequencies, again with an optically thick core at one end (eg, 3C 273 [24]). Thus it appears that we are seeing continuous jets in which the core at a particular frequency is simply the region where the jet becomes optically thick at that frequency. It is therefore generally assumed that the center of activity - the "central engine" - coincides approximately with the core. The asymmetric structure itself may well be the result of relativistic beaming. This has been discussed in a number of papers [1,7,24,31], and in several contributions to this Symposium.

In some cases, objects appear at first sight to be equal doubles. However, observations at other frequencies often show that the two components have different spectra, so that the source is really asymmetric. For example, at 1.7 GHz 3C 380 looks like an equal double, but at higher frequencies it looks more like a one-sided jet [15]. Two further examples of objects that look like equal doubles at 5 GHz, but which may well turn out to be one-sided jets, because their high-frequency spectra are flat, are 0836+710 [6,16] and 2021+614 [16].

It is now clear, however, that there is a class of objects which have two equal components with very similar spectra. Phillips and Mutel [21] have observed a number of objects with spectra that peak near 1 GHz (see Figure 2) and have found that five out of six such objects are equal doubles at 1.7 GHz. Two of these (CTD 93 and


(a) 3C 371 5010 MHz 1978 December
0".005
(b) CTD 93
10m.a.s.
(c) 2050+364
20 mas
RESTORING BEAM
(d) 0710+439
4 mas
(e) 3C 84
1979.92
5.0 GHz
2 mas

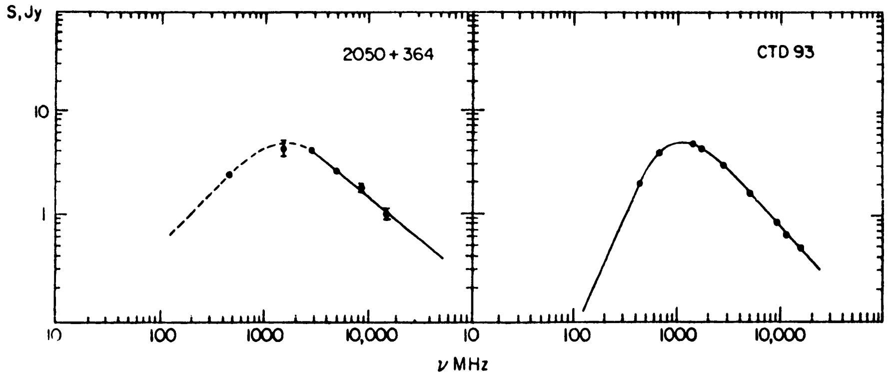


Figure 2. Radio spectra of CTD 93 [19] and 2050+364 [20].

2050+364) are shown in Figure 1. 3C 395 is rather similar to 3C 380 in that the two components have very different spectra; but the spectra of the other four objects are consistent with two very similar homogeneous synchrotron components (unlike the core-jet sources), suggesting that the components are probably nearly equal in flux density over a wide frequency range. In all four cases, at least one of the components is elongated along the source axis. In these equal double sources, there is no obvious candidate for the center of activity. Phillips and Mutel have suggested that the components straddle an invisible nucleus. They point out that the high-frequency spectra of these objects are similar to those in "classical double" sources, and they suggest that these compact doubles represent an early phase in the evolution of this class of object. A difficulty with this interpretation is that the proportion of objects showing this morphology is higher than expected: it could be as high as 15%, whereas the typical double source is expected to spend less than 1% of its lifetime at separations < 1 kpc.

A problem with present-day VLBI observations is the poor dynamic range. This is illustrated by 0710+439 (Figure 1). Here again the source is dominated by two components of almost equal brightness, one of which is extended along the source axis; but in this case there is a third component with one-tenth the flux density of the other two. If this third component had been a factor of two weaker we should not have detected it.

Some objects are much more complex. A unique example is NGC 1275 (3C 84), described at this Symposium by Jon Romney. A 5-GHz map made by Unwin et al. [34] is shown in Figure 1. It consists of a number of compact regions separated by less than a beam-width and embedded in more extended structure. The structure is difficult to interpret, especially at low frequencies where the resolution is poor and where

Figure 1 (opposite). VLBI maps of (a) 3C 371, 5 GHz [15]; (b) CTD 93, 1.7 GHz [19]; (c) 2050+364, 1.7 GHz [20]; (d) 0710+439, 5 GHz [16]; (e) 3C 84 (NGC 1275), 5 GHz [34].

the extended emission is dominant. It seems that observations at high frequencies, where the extended structure is insignificant, are needed to make sense of the structure of NGC 1275 and to determine whether there is a single center of activity or multiple centers.

There is a general tendency for the milliarcsecond structure in the compact sources to be aligned with the low-brightness outer structure when outer structure is present. The alignment is rarely perfect, however, and the objects show considerable curvature on small scales. This has been attributed to projection effects [24]. There are some cases of large misalignment: recent 23-GHz maps of 3C 345 show that the jet curves through 100 deg in the central few milliarcseconds to join on to the arcsecond-scale jet; and in three objects (3C 147 [25], 3C 395 [6], and 3C 454.3 [5]) the steep-spectrum component or jet is on the opposite side of the core from the arcsecond-scale structure.

Table II gives the numbers of objects in each morphological class, subdivided by optical identification.

3. CENTRAL COMPONENTS OF EXTENDED SYMMETRIC RADIO SOURCES

The extended symmetric double radio sources found in low-frequency surveys, like the 3C survey, are presumably selected without bias as to orientation, unlike the compact sources for which this may not be true. Most of the central components are too weak to be mapped with present VLBI networks, but a few are strong enough. So far seven central components have been mapped (those of 3C 111, 3C 236, 3C 274, 3C 390.3, NGC 315, NGC 6251, and Cyg A); they are all identified with galaxies. The VLBI maps show that the parsec-scale nuclear radio source is asymmetric in all seven cases, in spite of the high degree of overall symmetry of the outer components. In 3C 390.3, a milliarcsecond component has been detected on the side opposite the jet [9]; but the poor dynamic range of the VLBI maps is such that the presence of a "counter-jet" of one-tenth the brightness of the detected jet cannot be ruled out in the other sources. In all cases, the nuclear jet is aligned within a few degrees of the axis of the source, defined by a

TABLE II : STATISTICS OF OBJECTS MAPPED BY VLBI

	Q	G	U	Total	Fraction
Slightly resolved	10	4	2	16	33%
Core-jet	11	9	1	21	43%
Equal double	1	1	3	5	10%
Double or core-jet?	4	1	0	5	10%
Complex	0	2	0	2	4%
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TOTAL	26	17	6	49	

large-scale jet or outer hot-spot. This is in marked contrast to the compact sources.

The asymmetric structure observed in these nuclei is probably not due to switching of the beam from one side to the other on a short time-scale (< 1000 years), because in all three cases where there is a large-scale jet (3C 274, NGC 315, and NGC 6251), the nuclear jet is pointing in the same direction; and the detection of weak counter-jets in NGC 315 and NGC 6251 rules out the possibility that the larger jets are switching on time-scales > 1000 years. A plausible explanation is that the material in both small-scale and large-scale jets is moving relativistically, since this allows us to reconcile the asymmetry seen in 70% of radio nuclei with the superluminal motion detected in several of them.

In a complete sample of double radio galaxies, selected without bias as to orientation, we would not expect to detect highly superluminal motion in many objects. The sources which have been mapped so far, however, are exceptional in that they have unusually strong central components. Velocities of the order of the speed of light are in principle easy to detect with VLBI observations spanning a few years. Detection of superluminal expansion in these objects would provide strong evidence that the strength of the central components is due to relativistic beaming. The detection of superluminal expansion in the quasar 3C 179, reported by Richard Porcas at this Symposium, supports this picture, as 3C 179 is a classical double source with an exceptionally strong central component.

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DISCUSSION

EKERS: There are other classes of extragalactic radio sources which are asymmetric but which are not jets; e.g., the tail sources, and most of Perley's sample of sources dominated by a compact component. I do not think you should call any asymmetric VLBI source a jet until you have maps which demonstrate that it is jet-like.

READHEAD: There are some sources, such as NGC 6251 and 3C 273, where there is no doubt that there is a connection between the milliarcsecond "jet" and the larger scale jet. In all these sources there is a flat-spectrum core, and the "jet" component has a steeper spectrum. We have used the term "core-jet" for other sources with this morphology, though in some cases, like 3C 380, it is not clear that the description is correct, and we should perhaps simply describe these sources as asymmetric. They are marked "core-jet?" in Table I.

SCHILIZZI: The nucleus of 3C 236 is not well aligned with the outer lobes. There is a variation in position angle of about 20 degrees between the milliarcsecond and the kiloparsec scales.

READHEAD: This is a small misalignment compared with the core-dominated sources, most of which have a variation greater than 20 degrees.

LAING: The dust lane in Cyg A, which is perpendicular to the VLB jet, is seen close to edge on, suggesting that the jet is approximately in the plane of the sky. Is this consistent with the jet's asymmetry being due to Doppler beaming?

READHEAD: Owing to the poor dynamic range of VLBI maps, it is not possible to rule out a counter-jet of 1/5 of the strength of the jet. This asymmetry can be explained by relativistic beaming with $\gamma = 7$ at an inclination of 70°.

KONIGL: The two components of the compact double sources could be identified with the inner core and a detached knot in a relativistic jet, like those seen in superluminal sources. If the jet is only moderately relativistic, it could be seen at a sufficiently large angle to the axis for the core and the knot to be separately resolved and have relatively simple synchrotron spectra. This interpretation is consistent with the high measured fluxes and with the elongation of one of the components along the axis. Superluminal motions might be seen in this case. Alternatively, the emission could be from shocks behind dense clouds accelerated by the jet. The flow behind the shocks is directed sideways, so the emission is not beamed strictly along the axis of the jet, and the clouds could be seen at a large angle to the jet axis. Superluminal motions would not be expected in this case.

SHAPIRO: The existence of compact symmetric doubles is not entirely inconsistent with the presence of relativistic jets. If the jets are not purely radial outflows confined to a narrow cone, but instead represent a relativistic expansion, the surface of which is the radio source and moves outward from the center of activity in all directions, then the surface elements which move perpendicular to the collimation axis will relativistically beam their radiation at the observer, who will see only these surface elements since the rest is beamed away from the observer. An example is the relativistic blast wave model (Shapiro, P. R.: 1979, Astrophys. J., 233, 831-850).