# VLBI SURVEY OF A COMPLETE SAMPLE OF ACTIVE NUCLEI AND QUASARS [+]

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ABSTRACT

We have conducted a VLBI survey of a complete, flux-density limited
sample of 65 extragalactic radio sources, selected at 5 GHz. We have
made hybrid maps at 5 GHz of all of the sources accessible to the
Mark-II system. The sources can be divided provisionally into a number
of classes with different properties: central components of extended
double sources, steep-spectrum compact sources, very compact (almost
unresolved) sources, asymmetric sources (sometimes called "core-jet"
sources), and "compact double" sources. It is not yet clear whether
any of these classes is physically distinct from the others, or whether
there is a continuous range of properties.

## 1. INTRODUCTION

Since 1977 we have been engaged on a project to determine the structure
of a complete, unbiased sample of VLBI sources, and to measure changes
in the sources. The sample consists of 65 sources, of which 45 have
VLBI structure. Mapping 45 sources with our present instrumentation is
a very large project, but even so, 45 is a small number for statistical
studies. Thus, although statistical trends may become apparent, our
purpose is more to provide an overview of the range of morphologies
exhibited by the sources.

We cannot overemphasize the importance of studying a complete
sample of this type. There has been a tendency in VLBI to concentrate
on a small number of sources of special interest, such as the
superluminal sources, simply because VLBI is still very time-consuming;
although things are getting easier these days with the establishment of
the U.S. and European VLBI Networks. Studies of individual sources
can, of course, be very rewarding, but they leave many questions
unanswered, and may even bias our view of the VLBI universe. In
addition to exploring the menagerie of source morphologies, we can
address a number of specific questions by way of a complete survey, all

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aimed ultimately at elucidating the fundamental cause of galactic
nuclear activity.  For example, we may expect to find more superluminal
sources, and find out just how common they are - an important parameter
for the relativistic-beaming theories;  and we can look for
correlations between VLBI and optical and X-ray properties of the
sources which may indicate physical connections and constrain
theoretical models.

## 2.  THE COMPLETE SAMPLE

The sample we have chosen to study contains 65 sources, selected from
the NRAO-MPIfR 6-cm Strong Source Surveys S4 and S5 (Pauliny-Toth et
al. 1978, Kühr et al. 1981a).  The selection criteria were:  (a)
declination (1950) > 35 deg, for good u,v-coverage with existing
telescopes;  (b) galactic latitude |b| > 10 deg;  and (c) total flux
density at 5 GHz $\geq$ 1.3 Jy (at the epoch of the original surveys).  The
flux density limit was chosen to include a moderately large number of
sources strong enough to be mapped with the Mark-II system.

     The sample thus defined contains 20 classical double radio sources
and 45 core-dominated sources (having > 95% of their flux density
arising in a region smaller than about 1 arcsec).  Most of the
classical double sources were known from VLA and other observations to
contain no compact component strong enough to map with current Mark-II
VLB systems (i.e., > 0.25 Jy).  All 65 sources are listed in Table 1,
which gives the source names, optical type (galaxy, quasar, BL Lac
object, or empty field), redshift where available, and large scale
radio structure (I or II indicates a classical double source of
Fanaroff-Riley class I or II;  U indicates a core-dominated or
unresolved source);  the remaining columns of Table 1 will be explained
below.

## 3.  OBSERVATIONS

We made observations in three stages.  All the observations were made
at 5 GHz.  First, we made brief ("snapshot") observations to determine
which sources in the complete sample could be adequately mapped.  A
detection is indicated by "Y" in the column headed "VLB?" in Table 1.
Then we made first-epoch maps of the sources detected in the finding
survey from full-track (10-11 hour) observations with three or four
antennas of the U.S. VLBI Network together with the 100-m antenna of
the MPIfR at Effelsberg (in most cases).  The observations were
completed in seven sessions scheduled by the U.S. VLBI Network between
1978 and 1982, as indicated in Table 1, in which the antennas used are
shown by their conventional abbreviations.  Finally, we have begun the
third stage:  second-epoch maps of all the sources.  We shall present
preliminary results of some of the second-epoch observations later in
this Symposium (Readhead et al. 1984).

TABLE 1
The Complete Sample

| Source | | Opt | z | Radio | VLB? | First Epoch Mapped | First Epoch Antennas | Second Epoch Mapped | Second Epoch Antennas | Classification |
|--------|--|-----|---|-------|------|--------|----------|--------|----------|----------------|
| 0016+731 |        | Q  | -      | U  | Y | 1982 Apr | BKGPO | | | Very compact |
| 0040+517 |        | G  | 0.350  | II | N | ---- | | | | ---- |
| 0108+388 | OC314  | EF | -      | U  | Y | 1979 Jul | GFOH | 1982 Dec | BKGPO | Double |
| 0133+476 | OC457  | Q  | 0.86?  | U  | Y | 1978 Dec | GFOH | | | Compact |
| 0153+744 |        | Q  | -      | U  | Y | 1982 Apr | B GFO | | | Double |
| 0210+860 | 3C61.1 | Q  | 0.184  | II | N | ---- | | | | ---- |
| 0212+735 |        | BL?| -      | U  | Y | 1980 Sep | BK PO | | | Asymmetric |
| 0220+427 | 3C66B  | G  | 0.0215 | I  | N | ---- | | | | ---- |
| 0314+416 | 3C83.1B| G  | 0.0181 | I  | N | ---- | | | | ---- |
| 0316+413 | 3C84   | G  | 0.0172 | U  | Y | 1978 Dec | GFOH | | | Unclassified |
| 0404+768 | 4C76.03| G  | -      | U  | N | ---- | | | | ---- |
| 0454+844 |        | BL | -      | U  | Y | 1981 Aug | BKGFO | | | Compact |
| 0538+498 | 3C147  | Q  | 0.545  | U  | Y | (see Simon et al.) | | | | Steep-spect |
| 0605+480 | 3C153  | G  | 0.2769 | II | N | ---- | | | | ---- |
| 0710+439 | OI417  | G  | -      | U  | Y | 1980 Jul | BKGFO | 1982 Dec | BKGFO | Double |
| 0711+356 | OI318  | Q  | 1.620  | U  | Y | 1980 Jul | BKGFO | 1982 Dec | BKGFO | Double |
| 0723+679 | 3C179  | Q  | 0.846  | II | Y | (see Porcas et al.) | | | | Central cmpt |
| 0804+499 | OJ508  | Q? | -      | U  | Y | 1979 Dec | BKGFO | | | Very compact |
| 0809+483 | 3C196  | Q  | 0.871  | II | N | ---- | | | | ---- |
| 0814+425 | OJ425  | Q  | -      | U  | Y | 1979 Jul | GFOH | | | Compact |
| 0831+557 | 4C55.16| G  | 0.2420 | U  | Y | 1979 Dec | KGFO | | | Steep-spect |
| 0836+710 | 4C71.07| Q  | 2.17   | U  | Y | 1980 Sep | BK PO | | | Asymmetric |
| 0850+581 | 4C58.17| Q  | 1.322  | U  | Y | 1980 Jul | BK PO | | | Unclassified |
| 0859+470 | 4C47.29| Q  | 1.462  | U  | Y | 1978 Dec | GFOH | | | Compact |
| 0906+430 | 3C216  | Q  | 0.670  | U  | Y | 1979 Dec | BKGFO | | | Steep-spect |
| 0917+458 | 3C219  | G  | 0.1744 | II | N | ---- | | | | ---- |
| 0923+392 | 4C39.25| Q  | 0.699  | U  | Y | 1978 Dec | GFOH | | | Unclassified |
| 0945+408 | 4C40.24| Q  | 1.252  | U  | Y | 1979 Jul | GFOH | | | Steep-spect |
| 0951+699 | M82    | G  | 0.0009 | ?  | N | ---- | | | | ---- |
| 0954+556 | 4C55.17| Q  | 0.909  | U  | Y | ---- | | | | Unclassified |
| 0954+658 |        | BL?| -      | U  | Y | ---- | | | | Unclassified |
| 1003+351 | 3C236  | G  | 0.0989 | II | Y | (see Schilizzi et al.) | | | | Central cmpt |
| 1031+567 | OL553  | G? | -      | U  | Y | ---- | | | | Unclassified |
| 1157+732 | 3C268.1| G  | -      | II | N | ---- | | | | ---- |
| 1254+476 | 3C280  | G  | 0.994  | II | N | ---- | | | | ---- |
| 1358+624 | 4C62.22| G  | -      | U  | Y | ---- | | | | Unclassified |
| 1409+524 | 3C295  | G  | 0.4614 | II | N | ---- | | | | ---- |
| 1458+718 | 3C309.1| Q  | 0.905  | U  | Y | 1981 Aug | BKGFO | 1982 Dec | BKGFO | Steep-spect |
| 1609+660 | 3C330  | G  | 0.549  | II | N | ---- | | | | ---- |
| 1624+416 | 4C41.32| G? | -      | U  | Y | 1980 Jul | BKGFO | | | Asymmetric |
| 1633+382 | 4C38.41| Q  | 1.814  | U  | Y | 1979 Apr | BKGFO | | | Asymmetric |
| 1634+628 | 3C343  | Q  | 0.988  | U  | N | ---- | | | | ---- |
| 1637+574 | OS562  | Q  | 0.745  | U  | Y | 1979 Jul | GFOH | | | Compact |
| 1641+399 | 3C345  | Q  | 0.595  | U  | Y | (see Cohen et al.) | | | | Asymmetric |
| 1642+690 | 4C69.21| Q  | -      | U  | Y | 1980 Jul | BKGFO | | | Asymmetric |
| 1652+398 | 4C39.49| BL | 0.0337 | U  | Y | 1980 Jul | BKGFO | | | Unclassified |
| 1739+522 | 4C51.37| Q  | 1.375  | U  | Y | 1982 Apr | B GFO | | | Very compact |
| 1749+701 |        | BL | -      | U  | Y | 1982 Apr | BKGFO | | | Asymmetric |
| 1803+784 |        | BL?| -      | U  | Y | 1982 Apr | BKGFO | | | Asymmetric |
| 1807+698 | 3C371  | G  | 0.05   | U  | Y | 1978 Dec | GFOH | 1982 Dec | BKGFO | Asymmetric |
| 1823+568 | 4C56.27| BL?| -      | U  | Y | 1979 Dec | BKGFO | | | Asymmetric |
| 1828+487 | 3C380  | Q  | 0.692  | U  | Y | 1978 Dec | GFOH | | | Steep-spect |
| 1842+455 | 3C388  | G  | 0.0908 | II | N | ---- | | | | ---- |
| 1845+797 | 3C390.3| G  | 0.0569 | II | Y | 1982 Apr | BKGFO | | | Central cmpt |
| 1928+738 | 4C73.18| Q  | 0.36   | U  | Y | 1980 Sep | BK PO | | | Asymmetric |
| 1939+605 | 3C401  | G  | 0.201  | II | N | ---- | | | | ---- |
| 1954+513 | OV591  | Q  | 1.230  | U  | Y | 1979 Jul | GFOH | | | Compact |
| 2021+614 | OW637  | G  | 0.2266 | U  | Y | 1979 Dec | KGFO | 1982 Dec | BKGFO | Double |
| 2153+377 | 3C438  | G  | 0.292  | II | N | ---- | | | | ---- |
| 2200+420 | BL Lac | BL | 0.07   | U  | Y | 1978 Dec | GFOH | | | Asymmetric |
| 2229+391 | 3C449  | G  | 0.171  | I  | N | ---- | | | | ---- |
| 2243+394 | 3C452  | G  | 0.0811 | II | N | ---- | | | | ---- |
| 2342+821 |        | EF | -      | U  | N | ---- | | | | ---- |
| 2351+456 | 4C45.51| G  | -      | U  | Y | 1980 Jul | BKGFO | | | Asymmetric |
| 2352+495 | OZ488  | G  | 0.237  | U  | Y | 1979 Dec | BKGFO | | | Double |

Space allows us to present only a few of the maps here. They have
a resolution of about 1 mas (or 2 mas when Effelsberg was not
available). The dynamic range of the maps has improved considerably
since we presented the first results from this program (Pearson and
Readhead 1981): we can now usually achieve a dynamic range of between
100:1 and 200:1. The improvement over earlier results (which had a
dynamic range of about 20:1) is due primarily to the use of an
amplitude self-calibration scheme (based on CORTEL by Cornwell and
Wilkinson 1981). Even so, the reader should be aware that the quality
of the maps varies considerably from source to source, depending on the
exact u,v-coverage, the source structure, and the accuracy of the
calibration. The field of view of the maps is limited: we are likely
to have missed weak components more than about 25 mas from the
brightness peak, and the arrays are insensitive to structure on a scale
larger than about 10 mas.


## 4.  RESULTS

In the initial finding survey, we detected 45 of the 65 sources. Of
the 20 undetected sources, 17 are classical double sources with central
components weaker than 0.25 Jy, and the other three are supposedly
"compact" sources (these should be studied at intermediate resolutions
$\sim$ 10-100 mas).

We have made first-epoch maps of 37 of the 45 detected sources.
The remainder include four sources which have been extensively studied
by other people (3C147, 3C179, 3C236, and 3C345, all described in other
contributions to this Symposium), and four which were too weak for
satisfactory mapping with Mark-II; we hope to map these later with
Mark-III.

The sample of 45 detected sources includes 30 quasars or BL Lac
objects, 14 galaxies, and one empty field. Unfortunately, only 27 have
measured redshifts. The redshifts range from 0.05 for the galaxy 3C371
to over 2 for some of the quasars. There is a correspondingly wide
range in the linear scales and luminosities of the sources.


## 5.  CLASSIFICATION

In order to impose some order on the diversity of structures found in
the VLBI maps, we have attempted to separate the sources into a number
of groups with similar characteristics, based on the VLBI maps, the
radio spectra (obtained from the literature, primarily Kühr et al.
1981b), and the radio variability of the sources (monitored at 10.8 GHz
by Seielstad et al. 1983). The classification is necessarily somewhat
subjective and provisional, as there appears to be a wide range of
source types, with several sources showing characteristics of two or
more of the groups. Further observations may either clarify our
classification or show that the attempt is misguided. Essentially, we

have chosen a number of well-studied, "archetypal" sources, and looked for similar characteristics amongst the others. Our assignment of sources to classes is indicated in Table 1 and summarized in Table 2. We have not attempted to classify eight of the sources in the sample: four (0316+413 = 3C84, 0850+581, 0923+392 = 4C39.25, and 1652+398) do not clearly belong in any of the classes we have described, and the remainder are the four sources which we were unable to map with Mark-II. We shall now discuss each class in turn.

### TABLE 2 - Classification

| | |
|---|---|
| Central components of classical double sources: | 3 |
| Steep-spectrum compact sources: | 6 |
| Very compact sources: | 9 |
| Asymmetric sources ("core-jets"): | 13 |
| "Compact double" sources: | 6 |
| Unclassified: | 8 |
| | -- |
| Total: | 45 |

## 6. CENTRAL COMPONENTS OF CLASSICAL DOUBLE SOURCES

This class is very easy to identify. We detected central components in three of the 20 sources in the complete sample which are dominated by extended emission. The results are clearly biased towards sources with unusually strong central components. Two of the three sources (3C179 and 3C236) will be discussed by other participants in this Symposium; the third is 3C390.3 which has also been mapped by Preuss et al. (1980) and Linfield (1981). All three sources show good alignment between the nuclear structure and the outer lobes. One (3C179) is definitely superluminal (Porcas 1981), and one (3C390.3) is apparently not (v/c < 0.5: Preuss et al.). It is of interest that 3C390.3 shows evidence for two-sided ejection: Linfield's 10.7-GHz map shows a "core-jet" structure directed towards the bright, compact SE lobe, while both our 5-GHz map and that of Preuss et al. show another component 5 mas away on the NW side of the "core".

## 7. STEEP-SPECTRUM COMPACT SOURCES

This class of source is the subject of several contributions to this Symposium. The sources are characterized by a steep, straight spectrum, usually with a low-frequency turnover near 100 MHz, and sometimes flattening at high frequencies. They show structure on all angular scales from 1 mas to 1 arcsec. The VLBI maps of three of these sources are shown in Figure 1, together with VLA maps (Pearson, Perley, and Readhead, in preparation). The VLBI structure is complex, showing a compact, flat-spectrum core, and in some cases a central "jet" which may be misaligned by as much as 90 deg from the large-scale structure. All the sources, except 0831+557 which has a peculiar structure, are
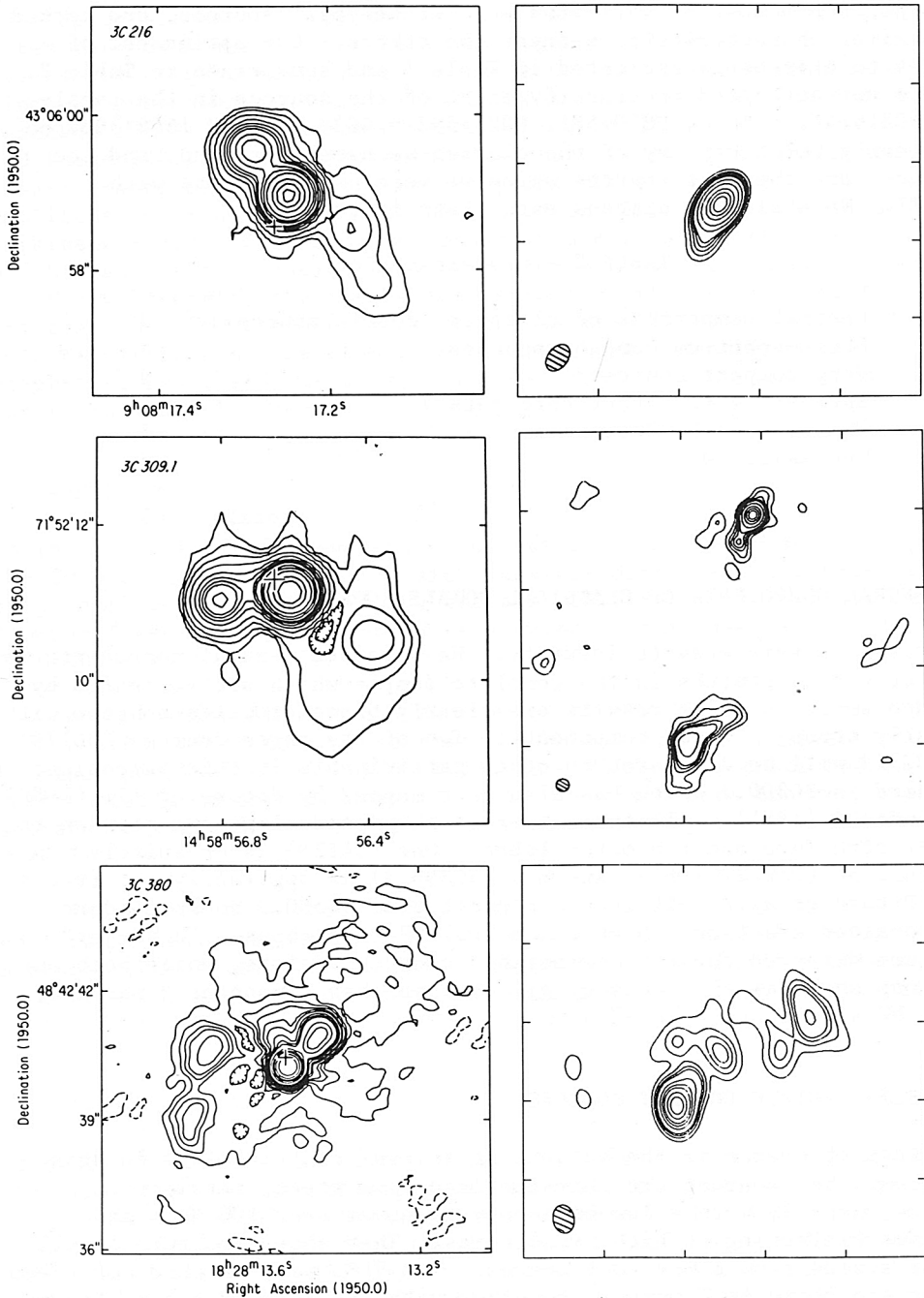
Fig. 1.   5 GHz VLA maps (left) and VLBI survey maps (right) of three "steep-spectrum compact" sources.   The VLBI map of 3C216 is 20 mas square;   the VLBI maps of 3C309.1 and 3C380 are 40 mas square.

quasars.  These sources can perhaps be understood as normal extended double sources seen "end-on", but if this is the case, then relativistic beaming is required to account for the large number of these sources in the sample.  There is some evidence from inverse-Compton arguments that relativistic bulk motion is occurring in two of these sources (3C147 and 3C390.3;  Simon 1982).


## 8.  VERY COMPACT SOURCES

A number of the sources were only barely resolved in our observations; for example, in 0016+731, 0804+499, and 1739+522, the visibility is > 95% even on transatlantic baselines.  All the sources in this class are highly variable, changing by 50% or more in 4 yr or less (at 10.8 GHz). All are fairly strongly polarized (> 1%) and all are quasars or BL Lac objects.  The hybrid maps show some evidence for low-brightness structure at a level of < 1% of the peak.


## 9.  ASYMMETRIC SOURCES

A large number of the sources appear to be asymmetric sources like 3C345.  The term "core-jet" is frequently used to describe these sources, although in only a few is there sufficient evidence to justify the word "jet".  They are characterized by a strong, compact component at one end of a lower-brightness linear feature.  When observations at a second frequency are available, the core is found to have a flat (self-absorbed) spectrum while the jet has a steeper, transparent spectrum.  Two examples are shown in Figure 2.  All these sources are variable, though not as violently so as the very compact sources.  Two of the sources in this class are known to be superluminal (3C345 and BL Lac) and others may very possibly be (e.g., 3C371:  Readhead et al. 1984).  In some cases the VLBI structure is well aligned with outer arcsecond-scale structure (e.g., 3C371, 1642+690).  Lack of alignment does not imply that there is no connection, however, as 3C345 illustrates (Browne et al. 1982).


## 10.  COMPACT DOUBLE SOURCES

The existence of a distinct class of symmetric, compact double VLBI sources was first pointed out by Phillips and Mutel (1982).  These objects are dominated by two components of almost equal brightness, separated by 5 - 20 mas.  It turns out that several of them have additional weaker components, so the term "compact double" is a misnomer, although we shall continue to use it here.  These sources appear to be distinctly different from the others in several respects: they have radio spectra with a single smooth "hump" peaking around 1 - 5 GHz, and no steep spectrum component;  they have no structure on arcsecond scales brighter than 0.2% of the peak;  they are only slightly variable (< 10% in 4 yr);  and they have very low radio
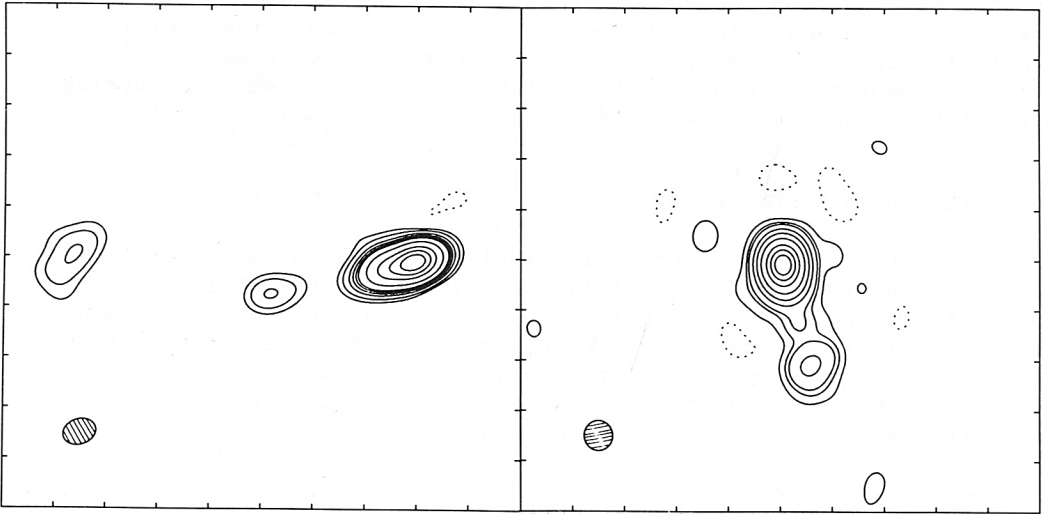
Fig. 2.  5 GHz VLBI survey maps of two "asymmetric" sources.  Left: 0212+735;  right:  1642+690.  Both maps are 20 mas square;  the restoring beams are indicated by the hatched ellipses.
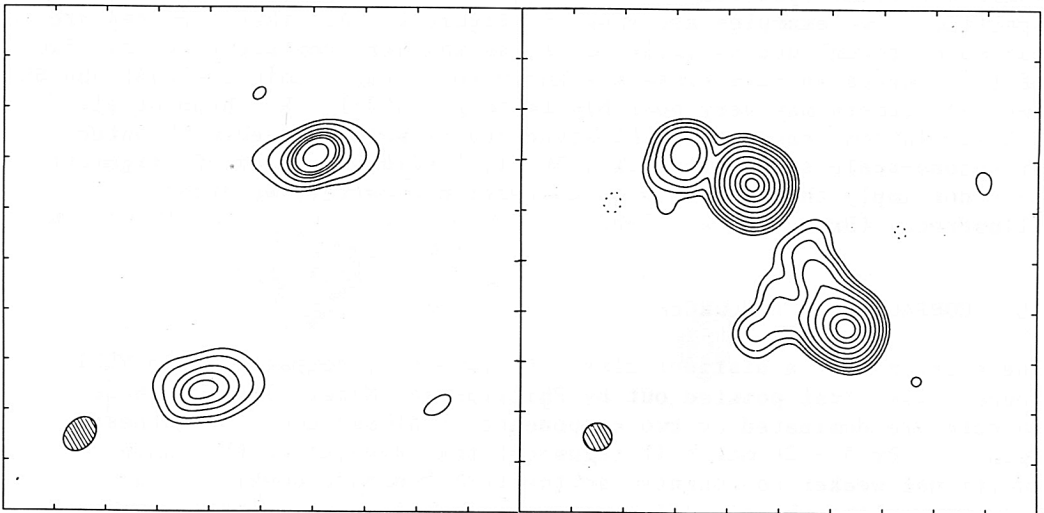


Fig. 3.  5 GHz VLBI survey maps of two "compact double" sources.  Left: 0153+744;  right:  2021+614.  Both maps are 20 mas square;  the restoring beams are indicated by the hatched ellipses.

polarization (< 0.2% in all except 0711+356).  The correlation of
double structure with humped spectrum was noticed in an independent
sample by Phillips and Mutel (although not all sources with such
spectra are compact doubles), and the correlation between humped
spectrum, low variability, and low polarization was noticed by Rudnick
and Jones (1982).  Figure 3 shows VLBI maps of two of the sources in
this class;  further examples can be found in the contribution by
Readhead et al. (1984).  In some cases, observations at another
frequency show that the sources are not as symmetric as they appear at
5 GHz, and some should perhaps be allocated to our "asymmetric" class
instead (see Readhead et al. 1984).  In particular 0711+356 looks out
of place in the "compact double" class, and fits better into the
"asymmetric" class.


## 11.  TRENDS AND CORRELATIONS

Finally, we should like to summarize some of the trends which have
already emerged from our work.

### 11.1.  Radio spectrum

Most of the compact double sources have a distinctive "humped"
spectrum.  By contrast, most of the compact and very asymmetric sources
have a flat or complex spectrum over a wide frequency range.
Unfortunately, variability may corrupt the published spectra, and more
single-epoch spectral measurements (like those of Owen et al. 1980) are
needed to see if there is a real difference in spectrum between the
classes.

### 11.2.  Large-scale radio structure

A considerable body of information on the arcsec-scale structure of the
sources is available from work with the VLA by Perley (1982).  It is
notable that none of the six "compact doubles" has any extended
structure, while several of the very compact and asymmetric sources do
(as do all the steep-spectrum compact sources).  Of the seven
asymmetric sources with large-scale structure, only three show a good
agreement between mas and arcsec position angle, presumably owing to
curvature in the sources.

### 11.3.  Radio polarization

Perley (1982) and Rudnick and Jones (1982, 1983) have measured the
integrated polarization of most of the sources at 5 GHz.  The compact
double sources all have low polarization (< 0.5%), while the very
compact and asymmetric sources usually have high polarization (1 - 8%).
Asymmetric sources generally have higher polarization than the very
compact sources.  There is no clear correlation of polarization
position angle with structural position angle, perhaps because the
former is corrupted by Faraday rotation.

## 11.4.   Optical identification and spectrum

The optical data on the objects are very inhomogeneous, and in
particular, there has been no systematic attempt to distinguish between
quasars and BL Lac objects.  We have begun a program to obtain
high-quality spectra of all the objects using the Palomar 5-m
telescope, which we hope will improve the situation.  But with such
information as is available, we can again see a difference between the
compact double sources and the others:  while only 12 of the 45 VLBI
sources are identified with galaxies, three of the six compact double
sources are galaxies (and thus fairly low-redshift objects).

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