COMPACT RADIO STRUCTURE OF QUASARS

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ABSTRACT. Recent results concerning the compact radio structure of quasars are reviewed. Emphasis is placed on VLBI results from statistical studies, from detailed mapping and from multi-epoch monitoring of variable sources.

1. INTRODUCTION

The description of radio source structures as either "compact" or "extended" is primarily the result of the resolution capabilities of different instruments. Connected element arrays such as the VLA and MERLIN have limiting resolutions of somewhat better than 0.5 arcsecond and hence are ideal for mapping structures with angular extents greater than $\sim$ 1 arcsecond. Frazer Owen describes such extended radio structures of quasars in his review (these proceedings). In this review I will concentrate on the sub-arcsecond structure of quasars, basing my descriptions on the results of VLBI measurements. These range in resolution from $\sim$ 10 mas for the European VLBI network (EVN) down to $\sim$ 0.2 mas achieved on transatlantic baselines at the highest observing frequencies.

For this review, I have excluded discussions of objects normally classified as Seyfert galaxies, radio galaxies etc., and concentrate only on observational material relating to quasars. The reader is referred to the review of Phinney (1985) for a more theoretical viewpoint, and to Porcas (1985) and the Proceedings of IAU Symposium 110 "VLBI and Compact Radio Sources" (1984) for more extensive treatments of compact radio structure.

2. STATISTICS AND SURVEYS

A division can be made between compact steep spectrum (CSS) sources (spectral index, $\alpha \simeq -0.7$, $S \propto \nu^{\alpha}$) and compact flat spectrum sources. The latter class, which are largely identified with quasars and BL Lac objects, have been extensively observed using VLBI techniques. Zensus et al. (1984) observed a sample of 57 such sources, with flux densities

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greater than 1 Jy, using a 3-element VLBI array with resolutions down to 1 mas. Essentially all sources were detected, and typically 50% of the radio flux comes from components $\lesssim$ 1 mas (this corresponds to $\lesssim$ 10 pc for most quasars). Barthel et al. (1984) made similar observations on a sample of flat spectrum cores of quasars also exhibiting extended radio structures. Of 16 objects with core flux > 0.1 Jy, almost all were detected, again confirming that for flat spectrum quasars a high fraction of the flux comes from pc-scale components.

A number of surveys of compact radio structure have been made, notably by Pearson and Readhead (1984) (45 sources > 1.2 Jy mapped) and Eckart et al. (1985b) (13 sources > 1.0 Jy). Romney et al. (1984) have mapped 21 sources which exhibit low frequency flux variability, and Hodges et al. (1984) have observed 9 sources with peaked radio spectra. A rough classification of structures as "compact", "core-jet", "compact double" or "complex" can be made (see e.g. Porcas 1985). CSS sources have been studied with the EVN by Fanti et al. (1985) and with the VLA at high resolution by van Breugel et al. (1984) and Pearson et al. (1985). In contrast to radio galaxies, which tend to be "doubles", CSS quasars are generally core-jets or complex (Fanti et al. 1985).

3. EXAMPLE QUASARS

To illustrate the range of morphologies seen, I have selected 12 quasars which exemplify the different spectral and structural classifications which can be made with resolutions > 1 arcsecond. An additional criterion for inclusion of a source was the availability of data on a number of angular scales. Maps are presented in Fig. 1 which, for each source, show the radio structures ranging from the most extended structure down to the most compact known. The maps are arranged so that the compact core features are aligned across the page. With the exceptions of BL Lac and 3C273, all the sources have similar redshifts, so that the conversion from angular to linear scales are similar. References to unpublished material are given without date. Where no interferometer is specified the maps have been obtained using transatlantic VLBI.

<u>3C263 (z = 0.652) and 3C179 (z = 0.846)</u> are both steep spectrum sources, exhibiting extended, classical double-lobed (D1) structure, and relatively weak flat spectrum cores. The mas maps show compact cores and secondary "knot" features, whose position angle (pa) is extremely well aligned with the extended structure (see also Shone et al. 1985).

<u>3C216 (z = 0.670) and 3C147 (z = 0.545)</u> are CSS sources, with complex structure in the range 0.1 to 1 arcsecond (a few kpc). Both sources show compact mas cores (that in 3C216 being more prominent) with lower brightness extensions; in 3C147 this shows a wiggling morphology. The intermediate resolution maps show that these jet-like extensions continue out in roughly the same pa until 1 or 2 kpc from the core, where they change direction abruptly. At present, the connection to the arcsecond scale morphology, which has features at rather different angles, is unclear.

<u>3C454.3 (z = 0.859), 3C345 (z = 0.595) and 3C273 (z = 0.158)</u> belong to the D2 category, consisting of a dominant, compact, flat spectrum

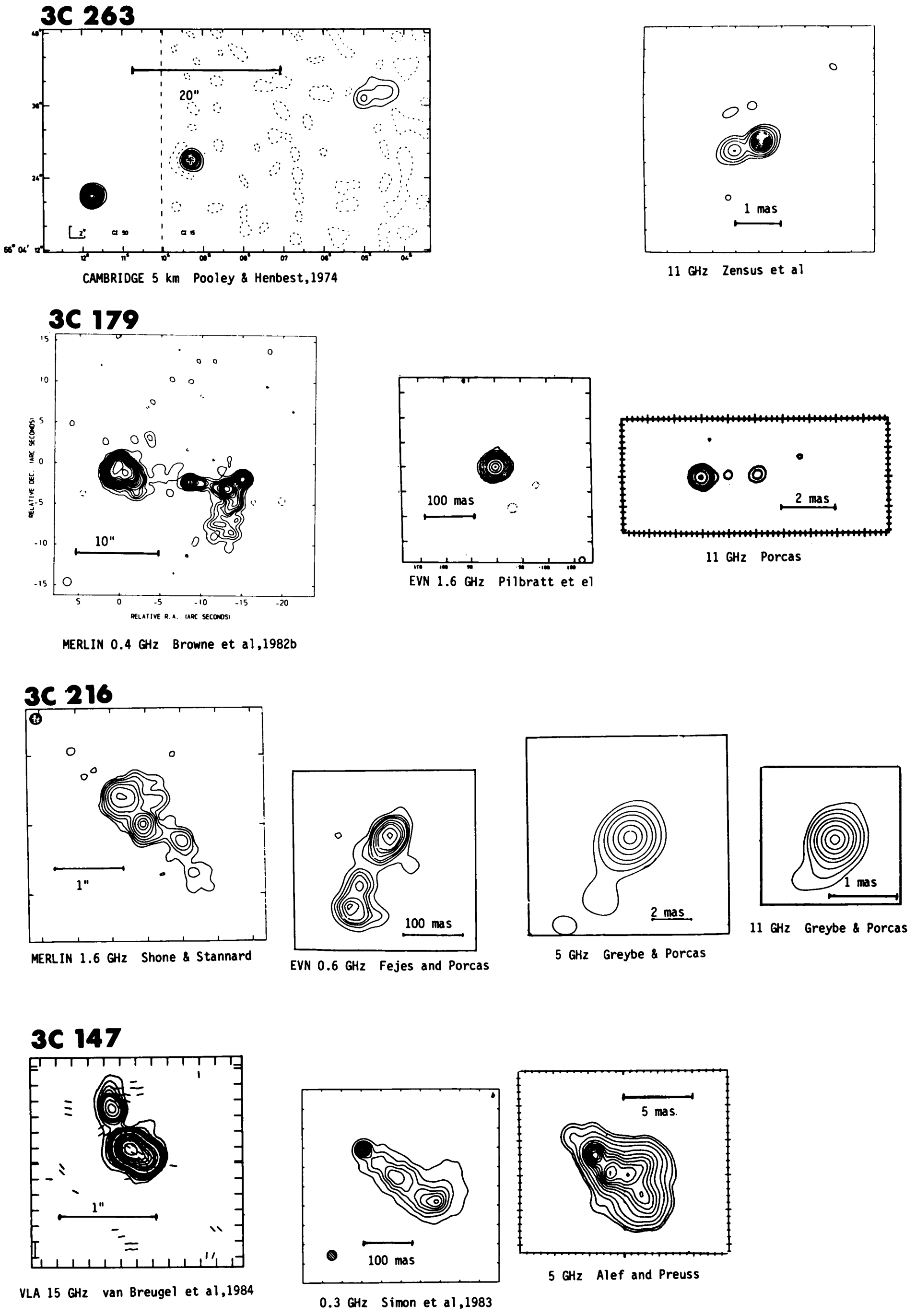

Figure 1: Arcsecond to mas structure of representative quasars.

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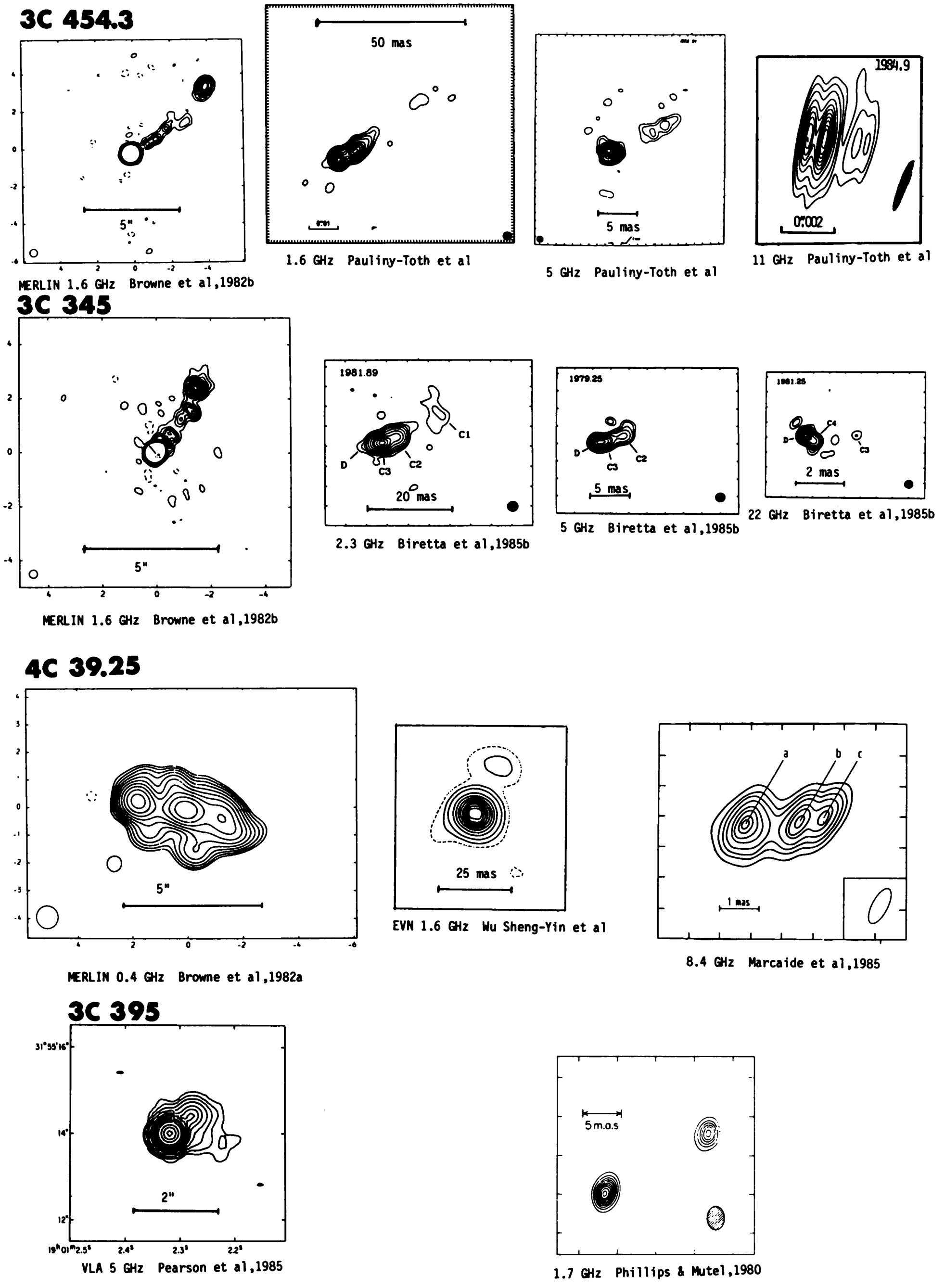

Figure 1 (contd.)

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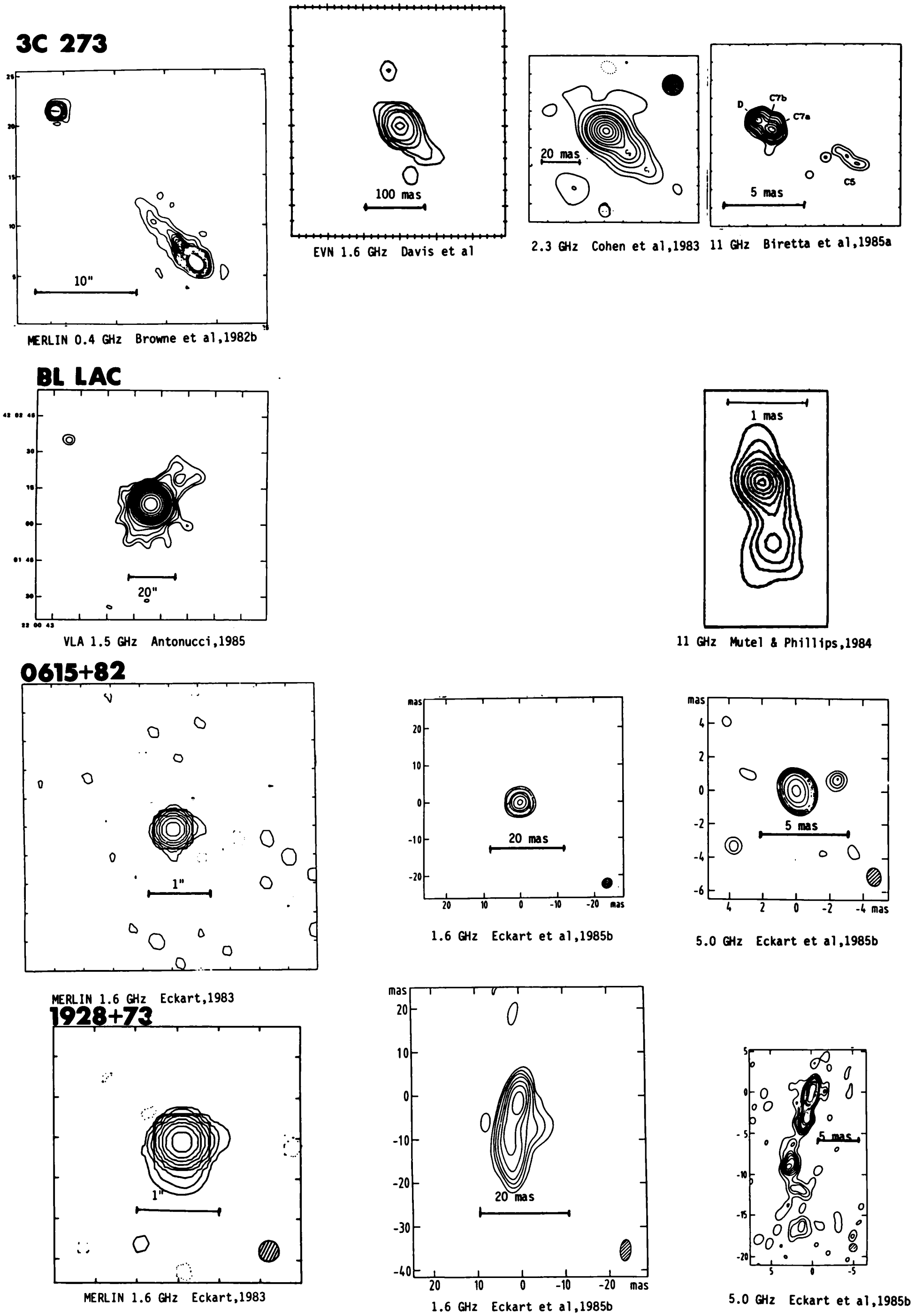

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component and an extended 1-sided jet on the arcsecond scale. For these quasars a similar morphology is seen on both intermediate angular scales and in the very highest resolution maps. A clear continuity is traced out by the jet structure, from the innermost core regions out to the arcsecond scale, although in the cases of 3C454.3 and 3C345 there is a large change of pa very near the centre. In these inner regions the jet is composed of a number of knots.

4C39.25 (z = 0.698) and 3C395 (z = 0.635) are also core-dominated in their arcsecond scale structures. 4C39.25 has 2-sided extensions and may be thought of as "D1.5". The mas structure is dominated by 3 components, the westernmost being a compact core. 3C395 has only 1-sided structure in the VLA map. On the mas scale it consists of 2 widely spaced components, similar to sources in the "compact double" class (Phillips and Mutel 1982). However, the 2 components have different spectra, the western being flatter, apparently the core (Johnston et al. 1983). In both these sources the relationship between mas and arcsecond structures is unclear. It is of interest that the steep spectrum mas component in 3C395 is on the opposite side of the nucleus to the arcsecond extension.

BL Lac (z = 0.070), 0615+82 (z = 0.71) and 1928+73 (z = 0.30) are all sources dominated by single, compact flat spectrum components on the arcsecond scale, with hardly any trace of extended radio emission. BL Lac and 1928+73 both show core-jet structures at 1 mas resolution. In 1928+73 the jet is broken up into many knots and extends all the way out to 20 mas. 0615+82 is still core-dominated even at 1 mas resolution and shows little trace of any jet.

The compact structures exhibited by these quasars are fairly typical of compact radio structures in general. In all cases the mas structure is asymmetric even when the arcsecond scale extended structure is symmetric. It consists of a compact, flat spectrum component, identified as the core, and a 1-sided extension which may be broken up into knots. Marcaide (1984) has shown that there is a spectral gradient along the jet extensions in the quasar pair 1038+528A, B. It is perhaps significant that none of these quasars shows the symmetric "compact double" morphology seen in some radio sources identified with less luminous optical objects, the closest case being the (asymmetric) double structure of 3C395. The similarity of the mas structures of these quasars seems to indicate that the structural differences seen on the scales of 100 pc to 100 kpc are due primarily to the galactic environment and not to the central energy sources.

4. STRUCTURAL VARIABILITY

Multiple epoch VLBI observations have now been made for quite a number of quasars, and the number showing "superluminal" structural changes certainly exceeds the $\sim$ dozen listed by Porcas (1985). Not all these sources show the same phenomenon. A number of sources show "classical" superluminal motion, consisting of apparent faster-than-light motion of a compact knot with respect to the core. 3C345 (Biretta et al. 1985b), 3C273 (Unwin et al. 1985), 3C179 (Porcas 1984), BL Lac (Mutel & Phillips

1984) and NRAO140 (Marscher & Broderick 1985) are examples of this. For 3C345 there is also an upper limit of 0.7c for any motion of the core (Bartel et al. 1985). Two sources which show a rather slower motion of $\sim$ 2c are 3C263 (Zensus et al., in preparation) and 3C279 (Unwin, these proceedings), the latter in contrast to earlier reports of much higher velocities. Other recently discovered examples are the motion of knots in 1928+73 (Eckart et al. 1985a) and 1642+69 (Pearson et al. 1986).

At least two quasars show both moving and stationary knots. Shaffer and Marscher (1985) report that the central component of 4C39.25 (b in Fig. 1) is apparently moving superluminally with respect to the core (c), whilst the easternmost component (a) is stationary. This explains the apparent source contraction reported by Shaffer (1984). Waak et al. (1985) report a similar behaviour for a newly discovered component located between the 2 main mas components of 3C395.

3C454.3 (Pauliny-Toth et al., in preparation) deserves special mention. Following a flux density outburst in 1981, the compact core showed a superluminal brightening (Pauliny-Toth et al. 1984). From 1982 on, an extension to the core appeared, of size of $\sim$ 1.6 mas in pa $\sim -95^o$, some 35^o away from the pa of the jet feature seen at $\sim$ 6 mas. If this was ejected from the core, it corresponds to motion of $\gtrsim$ 30c (H_o = 55 km s^{-1} Mpc^{-1}, q_o = 0.05). However, the extension is composed of a number of knots, and although their relative brightness changes, there is no obvious systematic motion of the knots in subsequent epochs.

Recent mapping of multi-epoch data of the CSS quasar 3C147 (Alef and Preuss, in preparation) has resulted in the identification of knots in the complex mas structure. The knot nearest to the core is apparently moving away at a rate corresponding to $\sim$ 2c. Pearson et al. (these proceedings) have reported possible superluminal expansion in the other example of a CSS source, 3C216.

It is now clear that superluminal structural changes are very common in quasars, and the phenomenon is by no means confined to the "core dominated" sources. Studies of structural variations in the weak cores of extended quasars (Zensus & Porcas, these proceedings; Barthel et al. 1985) and in CSS sources will hopefully allow us to determine whether the "Unified Schemes" involving relativistic jets can be modified to explain the phenomenon, or whether a radically new model of superluminal motion is needed.

I wish to thank all my colleagues for use of data prior to publication.

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DISCUSSION

Mutel : Are there any multi-epoch VLBI observations of D2 Quasars which are not consistent with superluminal motion ?

Porcas : I think this is a case where the dictum "absence of evidence is not evidence of absence" applies. I would not be surprised if all D2 quasars are shown to exhibit superluminal motion. However, as a result of the work which Toni Zensus and I are carrying out, I would not now be surprised if all D1 quasars show superluminal motion !

Hutchings : What is the evidence for optical beaming in the superluminal sources as a group ? Are they line-weak like BL Lacs, do they have characteristic or variable line profiles, polarization or continuum variability ?

Porcas : Many different optical classes are represented among the superluminal sources. 3C 345, 3C 454.3, 3C 216 are OVVs, BL Lac is a BL Lac. These all show high optical variability and polarization. 3C 273,3C 179, 3C 263 are normal quasars, showing only moderate variability, if any. 3C 120 is a Seyfert galaxy. Whether any of these optical classes show evidence for optical beaming is, of course, a matter of speculation.

Wilkinson : Do you believe there have been any unequivocal detections of components on both sides of the flat-spectrum "nuclei" which you have defined ? i.e. have we seen milliarcsecond counter-jets yet ?

Porcas : I believe Peter Barthel has reported 1 or 2 examples of 2-sided VLBI jets. In general, I believe they are very rare.

Kundt : How many double sources are known, and what are their scales ?

Mutel : Dozen. 10-150 mas.

Swarup : Do you find any increased brightness near the bends seen at around 1 kpc ?

Porcas : Sometimes ! In the CSS source 3C 216 which I showed, there is a strong concentration of radio emission some 120 mas away from the core, at the point where the structure changes direction sharply. On the other hand, in the CSS source 3C 147 which I also showed, there does not seem to be such a knot at the equivalent distance.

Wandel : Do objects like 3C 216, in which the compact structure is not aligned with the larger scale, show spectra different from those of aligned objects ?

Porcas : No. For example the two sources, 3C 216 and 3C 179 both have similar spectra, at low frequencies dominated by steep spectrum emission from optically thin regions, and a slight flattening at high frequencies

(> 5 GHz) as the compact cores start making a significant contribution to the total flux. 3C 179 shows good alignment, 3C 216 not. The difference is in the arcsecond scale structure, the steep spectrum compact sources ($\lesssim 1''$) generally having large misalignments.

Segal : Since you suggest that one must stick with the beaming model since it is the only one known, I should mention that the redshift-distance relation in the chronometic cosmology, $z = \tan^2 \frac{1}{2}$ (distance in radians), reduces all distances to a level that eliminates superluminal motions. Is there any observational reason to reject the very simple explanation that the Friedman distances are wrong ?

Porcas : I did not wish to imply that the relativistic jet aligned at a small angle to the line of sight is the only suggested explanation for superluminal motion. Gravitational lenses and screens, real "tachyonic" motion, non-cosmological redshifts and a much larger Hubble constant all have their advocates and can all explain the bare facts of superluminal motion. The criterion for acceptability is the range of agreement with observations over broad areas in astronomy and physics.