PARSEC-SCALE STRUCTURE OF COMPACT RADIO SOURCES

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Abstract. High-dynamic range imaging and monitoring with Very Long Baseline Interferometry have considerably increased our knowledge of the parsec-scale properties of compact radio sources. I review some of the properties of individual sources in areas where particular progress has been made in the last few years.

1. Imaging of Luminous Objects

The study of prominent flat-spectrum sources with Very Long Baseline Interferometry (VLBI) provides arguably the best opportunity for testing physical models of parsec-scale radio jets. Routine high-quality observations are possible with the Very Long Baseline Array (VLBA), the global VLBI campaigns with various other networks, and the "World Array" campaigns. At millimeter wavelengths, ad hoc arrays have been used to make images with highest resolution, albeit modest overall fidelity. Space VLBI missions in preparation bear the potential of imaging at yet higher resolution.

For a review of the various VLBI surveys and for morphological classifications see Wilkinson (1995), and Vermeulen (these Proceedings) for a statistical analysis of superluminal motions. Here, I will focus on several recent results from various ongoing studies of individual objects. I will then review some of the results from detailed VLBI monitoring studies of specific sources.

The high-luminosity VLBI sources typically have well collimated core-jet structure at centimeter and millimeter wavelengths. The cores are identified based on compactness, flat radio spectra, and strong flux density variability. Stronger misalignment between the parsec-scale and the kiloparsec-

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scale jets have been found for BL Lac objects compared to quasars (Conway & Murphy, 1993). No clear counter-jets have been found in core-dominated, i.e., presumably strongly boosted sources, but counter-jets are seen in some lobe-dominated objects, e.g., Cygnus A and 3C 84. Structural variability and in particular apparent superluminal motion are frequently observed, and together with the one-sidedness and total flux variability this has been taken as direct evidence for the presence of bulk relativistic motion in such objects. Many of the observed jets are curved, and in some cases semi-oscillating trajectories or ridge lines have been observed.

High-quality images that show a great detail of detail in the jet structure are available for a growing number of sources. Good examples include 3C 120 (see Craig Walker for a tour de force in imaging), 3C 273 (Unwin *et al.*, 1994), 3C 345 (Zensus *et al.*, 1996), and 0836+71 (Hummel *et al.*, 1992). Such luminous sources typically show continuous jets with rich substructures, markedly different from the simple structures often seen in maps from the era of the last IAU Symposium on "Extragalactic Radio Sources". The main features in these images correspond to the "distinct components" seen in older maps, but we can now study weaker features and often directly the underlying continuous jet emission. The evidence for the apparent superluminal motions has remained strong, but it is now clear that infrequent sampling in time is bound to cause misidentifications and confusion.

2. Curved Trajectories and Variable Speeds

Statistical studies (e.g., Vermeulen, these proceedings) assume that the motion measured for a particular superluminal source component is occurring along ballistic trajectories at constant speed. We now know that in a given source not only can different components have different speeds, but accelerations and decelerations are well established. Rarely are the apparent motions along straight ballistic trajectories: kinks and bends are frequently seen and in a small number of cases, complicated curved trajectories have been found. Note that such curvature sometimes is measured not for a given component, but indirectly by tracing several components, e.g., along a jet that might be characterized by a well-defined ridge line or time-averaged mean jet axis. The curvature seen so often is perhaps the strongest evidence against the paradigm of truly moving plasmons as the physical nature of superluminally moving components.

Figure 1 shows the apparent curved trajectories for superluminal features of 3C 345 (Zensus *et al.*, 1996), within 1 mas from the stationary core D. At distances from the core larger than about 2 mas the components appear to roughly follow the same curved trajectory in the north-west direction towards the arcsecond structure near the core the trajectories differ

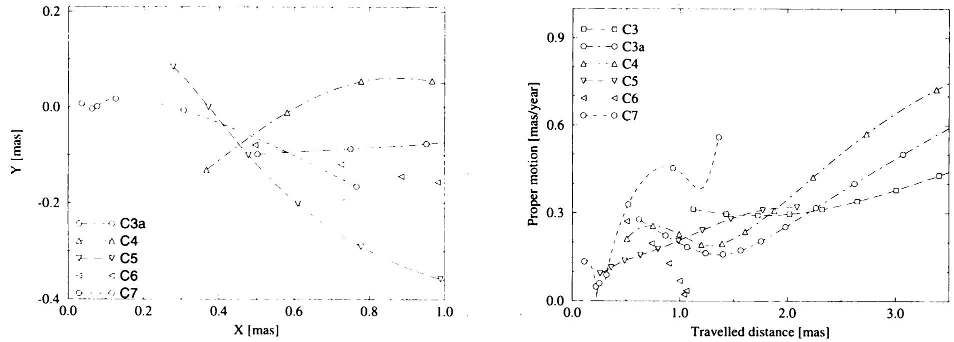

Figure 1. *Left:* Trajectories of superluminal features in 3C 345 within 1 mas from the core (Zensus *et al.*, 1995b; Zensus *et al.*, 1996), measured with respect to the core D. *Right:* Proper motions in 3C 345 (Zensus *et al.*, 1995b; Zensus *et al.*, 1996).

substantially. In this and other sources the curvature appears most pronounced near the core. Frequency-dependencies of component shapes and positions and of the observed trajectories—indicative of opacity effects—have been measured, e.g., in 3C 345 and in the quasar 4C 39.25 (Alberdi *et al.*, 1996). Similar curved trajectories or jet ridge lines are reported in a growing number of cases, especially from high-resolution observations at millimeter wavelengths (Krichbaum *et al.*, 1994).

The velocity changes that occur in 3C 345 are complex (see Fig. 1): to first order, the component speeds increase with separation from the core, but there is evidence for a systematic minimum speed at 1–1.5 mas from the core, indicating a possible transition between physically different (the inner and outer) regions of the jet (Lobanov, 1996). The kinematics and luminosity changes suggest that the acceleration measured are intrinsic (Zensus *et al.*, 1996; Lobanov & Zensus, 1995).

Of the many other examples for variable speeds, I mention here only the quasar 4C 39.25—previously thought first to be a stationary double source, and later a candidate for superluminal contraction. It shows a component moving between two stationary features. Recent observations at 22 and 43 GHz demonstrate that the apparent speed slows down as the moving feature approaches the eastern stationary feature (Alberdi *et al.*, 1993). (There is also some evidence that there are apparent differences in the curvature in the 22 and 43 GHz images (Alberdi *et al.*, 1996).) This has been explained in terms of repeated bending of the jet, where the stationary regions correspond to the Doppler enhanced underlying jet flow where it is oriented almost along the line of sight.

Most observers assume that in the sources observed with VLBI there is no difference between pattern and fluid speed; see Vermeulen (these Proceedings) for a discussion of the potential pitfalls.

In several sources, appearances of new components have been reported to be related to events in the total flux, in γ, X-ray, optical, IR-, millimeter, or centimeter bands. BL Lac is perhaps the best example for a tight correlation between variability in the centimeter regime and the appearance of superluminal features (Mutel *et al.*, 1994), but in a number of sources new components appeared following a major flux increase at centimeter wavelengths.

Superluminal motion requires that the jet must be relativistic and viewed at a narrow angle to the line of sight, so that projection effects are likely to be significant. Assuming a value of the motion's Lorentz factor, it is possible to reconstruct the three-dimensional trajectory of a moving feature (cf. Zensus, Cohen, and Unwin 1995). For example, the derived intrinsic jet curvature for 3C 345 is small, but it is greatly amplified by projection effects, and the angle of the jet to the line of sight increases smoothly with radius from the core from about 1 deg to about 4 deg. Scenarios to explain the curved trajectories include precession and orbital motion, and a number of interesting models have been proposed based on helical motion to explain the curved, quasi-periodic trajectories seen in 3C 345, 1803+78, 4C39.25, and similar sources.

We still do not know the true physical nature of the components we observe in parsec-scale radio jets. The properties at least of the core-dominated sources are thought by many to result from bulk-relativistic motion in two oppositely directed jets of plasma originating in the nucleus of the source (Blandford & Königl, 1979). Thus the optically thick cores in the VLBI images represent the base of the jet (located near the apex of the jet cone), and the superluminal features are regions of enhanced emission moving along the jet. The general properties of this "standard model" are well established (Pearson & Zensus, 1987), but in-depth comparisons between observations and models have generally been unsatisfactory.

Until recently, most monitoring studies were confined to images of the total intensity of a given source in one particular observing band. This suffices to determine basic morphology and component kinematics but it lacks important physical information that can only be obtained from measuring the jet spectra (from multi-frequency work) and the magnetic field distributions (from polarization imaging). Several sources are now being studied at multiple frequencies to determine spectral properties for comparison with models. For 3C 345, crude spectral information from the long-term monitoring can be used to measure the basic parameters of the component synchrotron spectra: turnover flux density and frequency, and integrated flux in the range 4–25 GHz (Lobanov & Zensus, 1995). At least for component C4, the observed luminosity variations of the jet components seem to require a variable pattern Lorentz factor, and the same may be true for the other components. Spectral properties are important for testing the basic idea that the jet components are caused by relativistic shocks, but the evidence in favor of the shock model is inconclusive so far. The total flux variations in some sources have been adequately explained with shocks (Hughes *et al.*, 1989), and in 3C 345 the total flux changes are well correlated with variations within about 5 pc from the core, suggesting shocks may dominate in the jet at least near the core (Lobanov & Zensus, 1995). alternative models that have been proposed involves interaction with the ambient plasma (Rose *et al.*, 1987). Marcaide et al. (1994) apply a detailed model of shock components moving on twisted trajectories to the quasar 4C39.25. BL Lac is perhaps the best understood case for the interpretation of VLBI components by shocks. In this source, the position angles of the axes of the curved trajectories of subsequent components shifting, suggesting evidence for precession caused by a binary black hole system (Mutel *et al.*, 1994).

Linear polarization sensitive VLBI observations of compact sources yield direct information on the structure and order of the underlying magnetic fields, the presence and nature of thermal material, the energy of relativistic electrons, and the geometry of emission on sub-milliarcsecond scales. There is evidence for a difference in the polarization properties of quasars and BL Lac objects, and the latter show significantly lower speeds, which argues for a physical and not merely an orientation difference between the two classes of source (Gabuzda *et al.*, 1994). Wardle et al. have studied the polarization structure at 5 GHz of 3C 345 and interpreted their results in terms of a comprehensive shock model. First polarization images of 3C 345 at 22 GHz are basically in agreement with the interpretation by Wardle et al. (Leppänen *et al.*, 1995).

3. Conclusion

VLBI monitoring studies at centimeter and millimeter wavelengths, enhanced by spectral and polarization imaging, can discriminate detailed physical models. Combined with broad-band total flux density and polarization observations they can be used to determine the overall physical conditions in parsec-scale radio jets. Some of the intriguing aspects where new insights may soon become feasible include the formation of the jets, possible jet acceleration mechanisms, the nature of any non-relativistic matter involved (e.g., the ambient medium and thermal outflows), and the influence of the central region on the jet dynamics.

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