Kinematics and dynamics of relativistic jets on large and small scales

R.A. Laing[⋆]

ESO, Karl-Schwarzschild-Straße 2, D-85748 Garching-bei-München, Germany

Abstract. Modelling of deep VLA images of the jets in FR I radio galaxies has allowed us to derive their three-dimensional distributions of velocity, emissivity and magnetic-field structure on kiloparsec scales. By combining our models of jet kinematics with measurements of the external pressure and density derived from *Chandra* observations, we can also determine the jet dynamics via a conservation-law approach. The result is a detailed and quantitative picture of jet deceleration. We discuss the potential application of these techniques on VLBI scales. Our fundamental assumption is that the jets are intrinsically symmetrical, axisymmetric, relativistic flows. Although this is likely to be a good approximation on average, the effects of non-stationarity in the flow (e.g. shocks/knots) may limit its applicability on pc scales. We also stress the need for both the main and counter-jet to be detected with good transverse resolution in linear polarization as well as total intensity. Two foreground effects (free-free absorption and Faraday rotation) must also be corrected. We comment on the implications of observed VLBI polarization and Faraday rotation for the field structure (and, by implication, collimation) of pc-scale jets. Where our VLA observations start to resolve the jets, about 1 kpc from the nucleus, they are travelling at about $0.8c$. We briefly discuss the deceleration of jets from a much faster initial speed.

1. Introduction

The determination of physical parameters for the non-thermal plasma in radio jets is a notoriously difficult problem. This paper describes a new approach which has met with some success in quantifying the three-dimensional distributions of velocity, emissivity and field structure of jets in low-power radio galaxies and outlines potential applications to jets on scales observable with VLBI.

2. Physical principles

2.1. Outline of the method

We make the basic assumption that the jets are intrinsically symmetrical and axisymmetric close to the nucleus, so the observed brightness and polarization differences between the main and counter-jets are due entirely to the effects of relativistic aberration. We then make parameterized models of velocity, field structure and emissivity, including variation both along and across the jets, and determine the parameters by fitting to observed Stokes I, Q and U. We calculate the emission by integration along a line of sight on a grid of points, convolve with the observing beam at one or more resolutions and evaluate χ^2 over defined areas, using estimates of the small-scale fluctuations in emission as "noise levels". The model parameters can then be optimized using the downhill simplex method. When evaluating the emissivities in I, Q and U, we use the techniques described in Laing (2002), taking proper account of the effects of relativistic aberration. Full details are given by Laing & Bridle (2002a) and Canvin & Laing (2004).

⋆ E-mail: rlaing@eso.org

2.2. The importance of linear polarization

For cylindrical constant-velocity jets emitting isotropically in their rest frames, the ratio of observed flux density per unit length for the main and counter-jets depends on both the velocity βc and the angle to the line of sight, θ via the well-known relation:

$$\frac{I_{\mathrm{j}}}{I_{\mathrm{cj}}} = \left(\frac{1 + \beta\cos\theta}{1 - \beta\cos\theta}\right)^{2+\alpha}$$

where α is the spectral index. In order to break the degeneracy between β and θ, we use the linear polarization. The relation between the angles to the line of sight in the rest frame of the flow, θ' and in the observed frame, θ, is:

$$\sin\theta'_{\mathrm{j}} = [\Gamma(1 - \beta\cos\theta)]^{-1}\sin\theta \quad \text{(main jet)}$$
$$\sin\theta'_{\mathrm{cj}} = [\Gamma(1 + \beta\cos\theta)]^{-1}\sin\theta \quad \text{(counter-jet)}$$

(Γ is the Lorentz factor). The observed polarization is in general a function of θ'. The observed distributions of the main and counter-jets can therefore be very different (see Section 3 for an example). If we know the field structure a priori, then we can solve explicitly for β and θ, but in general, we must fit the field configuration and therefore need to introduce two additional parameters to describe its anisotropy. These also determine the variation of polarization transverse to the jet axis, and can be estimated independently of the velocity and angle if the jets are well resolved in this direction.

2.3. Ordered and disordered fields

Our modelling can determine the ratio of the components of magnetic field (defined as rms values along given directions)
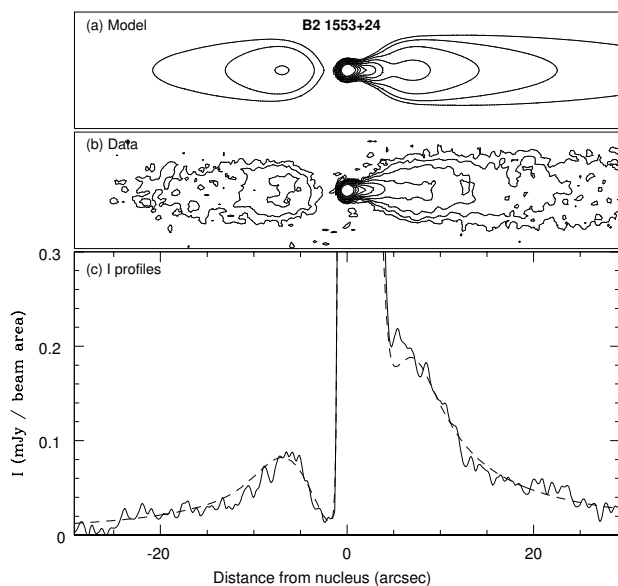
Fig. 1. Comparison of model and observed total intensity for B2 1553+24. (a) observed contours; (b) model contours; (c) longitudinal profiles for observations (full line) and model (dashed). See Canvin & Laing 2004 for details.

but can only partially constrain whether they are vector-ordered or have many small-scale reversals. We assume that the fields have zero mean with many reversals on scales smaller than the observing beam, but are made anisotropic by shear or compression (Laing 1980, 2002). If *one* of the three field components is vector-ordered, however, our results are unchanged. For example, a jet with a confining (ordered) toroidal field but disordered radial and longitudinal components could not be distinguished by its synchrotron emission from one in which all three components are disordered. [Internal Faraday rotation can be used to differentiate between these cases if the internal density of thermal plasma is high enough]. The situation for a helical field is different (Laing 1981): unless the jets are observed at $90°$ to the line of sight in the rest-frame of the emitting material, their transverse brightness and polarization distributions are not symmetrical. The very high degree of symmetry observed in FR I jets argues that no more than one of the field components is vector-ordered and flux conservation indeed suggests that the longitudinal component must have many reversals (Begelman, Blandford & Rees 1984).

3. Application to FR I jets on kiloparsec scales

We have so far completed model-fitting for four sources: 3C 31 (Laing & Bridle 2002a), 0326+39 and 1553+24 (Canvin & Laing 2004) and NGC 315 (Cotton et al., in preparation). A recent status report for the project was given by Laing, Canvin & Bridle (2004). Our principal results to date are as follows.

1. An intrinsically symmetrical, relativistic jet model provides an excellent description of the total intensity and linear polarization observed in the four sources studied so far (e.g. Figs 1 and 2).

2. We can estimate the angle to the line of sight and the three-dimensional distributions of velocity, emissivity and magnetic-field structure. The jets in all of the sources decelerate from $\beta \approx 0.8$ to $\beta \approx 0.1 - 0.2$ over short distances within the region of rapid expansion. Further out they recollimate and subsequent deceleration is slow or absent. The ratio of edge to on-axis velocity is consistent with 0.7 everywhere [Fig. 3(c)].

3. The magnetic field evolves from predominantly longitudinal close to the nucleus to mainly toroidal at large distances; the behaviour of the (weaker) radial component differs between the sources (e.g. Fig. 4).

4. By combining the kinematic model for 3C 31 with a description of the external gas density and pressure derived from *Chandra* observations (Hardcastle et al. 2002) and using conservation of particles, energy and momentum, Laing & Bridle (2002b) demonstrated that the jet deceleration could be produced by entrainment of thermal matter and derived the spatial variations of pressure, density and entrainment rate for the first time.

5. Laing & Bridle (2004) applied an adiabatic jet model (including the effects of shear and arbitrary initial conditions for the magnetic field) and showed that it provided a fair description of brightness and polarization at projected distances of $3 - 10$ kpc from the nucleus, but failed completely closer in. They showed that additional particle acceleration is required precisely where the X-ray emission from the jet is bright.

4. Application to parsec-scale jets

4.1. Requirements

In order to model jets using the technique described above, there are several obvious requirements:

1. Both the main and counter-jets must be detected and well resolved along and across their lengths. This probably rules out objects at a very small angle to the line of sight.

2. Linear polarization must be measurable in both jets and any effects of (internal or external) Faraday rotation must be removed.

3. The jets must be close enough to intrinsic symmetry that observed differences between them are dominated by the effects of aberration.

4. Sources close to the plane of the sky cannot be modelled, as there should then be no significant differences between the two jets.

These requirements immediately rule out the majority of the bright core-jet sources observed with VLBI, but this is hardly a surprise: selection of such objects is heavily biased by Doppler boosting. Not only are their counter-jets normally invisible, but the main jets have any bends amplified by projection. The most suitable targets are sources at less extreme orientations with known counter-jets, such as Cygnus A (Krichbaum et al. 1998; Bach et al. 2002) and Centaurus A (Tingay et al. 1998).
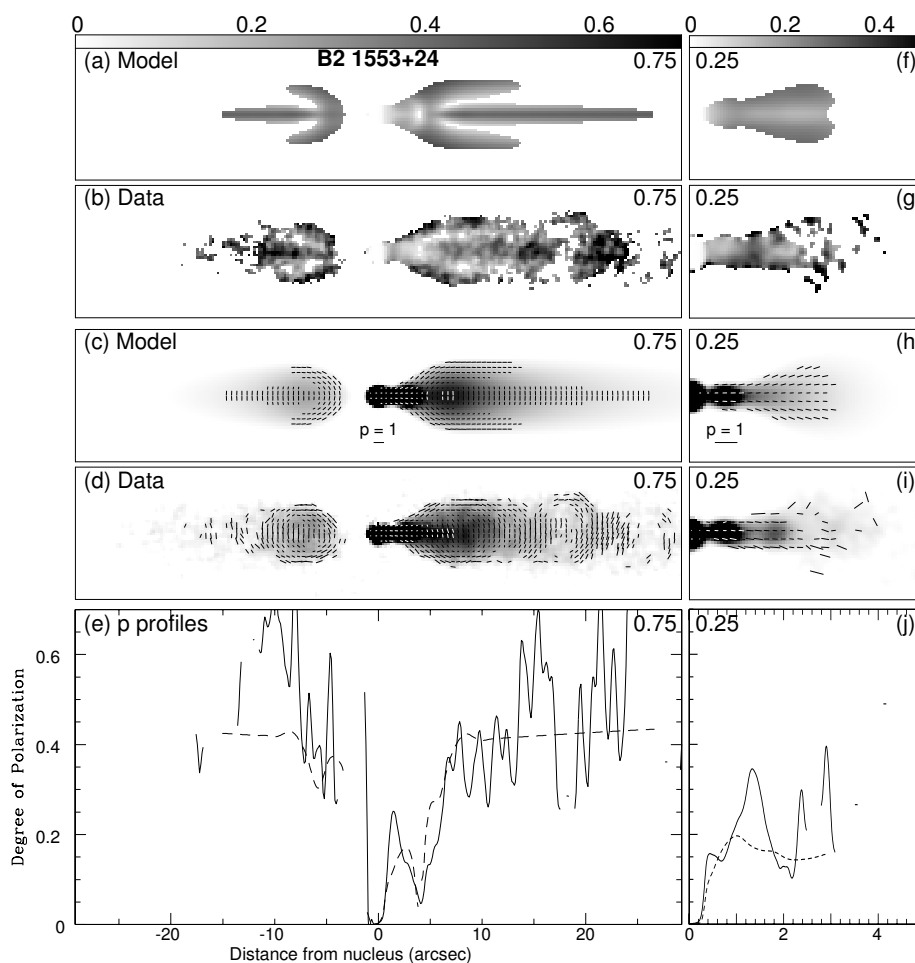
Fig. 2. Comparison of model and observed linear polarization for B2 1553+24. (a) – (e) 0.75 arcsec FWHM. (a) model and (b) observed degree of polarization. (c) model and (d) observed vectors showing the degree of polarization and the apparent magnetic field direction, superposed on grey-scales of *I*. (e) longitudinal profile of degree of polarization. Panels (f) – (j) show the same quantities at 0.25 arcsec resolution. Note the large differences in polarization between the main and counter-jets (panels a - d); these are successfully modelled as an effect of relativistic aberration.

4.2. Complications

We assume that the jets are intrinsically symmetrical, stationary flows. It is a reasonable hypothesis that parsec-scale jets are symmetrical on average and that environmental asymmetries are no more important than on larger scales. The flow in parsec-scale jets is certainly not stationary, however. This may not matter provided that the observations average over significant numbers of discrete features: all that is necessary is that the properties of the main and counter-jets are on average the same. If the brightness distributions are dominated by a few stochastic features (shocks, for example), then the approach will fail. It is also essential to remove the effects of free-free absorption (e.g. Tingay & Murphy 2001) before comparing jet and counter-jet brightnesses.

We can rule out ordered helical fields for the FR I jets we have modelled (Section 2.3) but the possibility needs to be re-evaluated for pc-scale jets (e.g. Lyutikov et al. 2004). Faraday rotation offers both a threat and an opportunity. Detection of internal rotation may provide evidence for the much-sought-after

toroidal confining field (Asada et al. 2002; Gabuzda, Murray & Cronin 2004) but foreground material, perhaps interacting with the jet, will confuse the issue (Zavala & Taylor 2003). In either case, our models depend on accurate measurement of the polarization uncorrupted by Faraday effects. As with the free-free absorption problem, this may require observations at very high frequencies.

Where we first determine the velocities of kpc-scale jets in FR I sources, they are $\approx 0.8c$. Given the strong evidence for faster flow on smaller scales in these objects (e.g. Giovannini et al. 2001), the jets must decelerate significantly on scales of 10 pc – 1 kpc. This region may be accessible to observation using the EVN and e-MERLIN.

5. Conclusions

We conclude that the techniques developed to model FR I jets on kiloparsec scales as intrinsically symmetrical, relativistic flows can in principle be applied to VLBI observations. The requirements are stringent: both jets must be imaged in de-
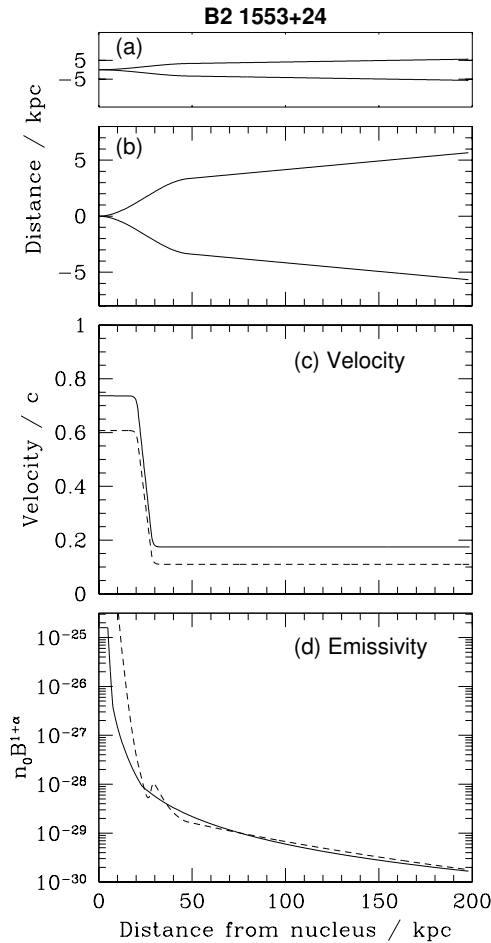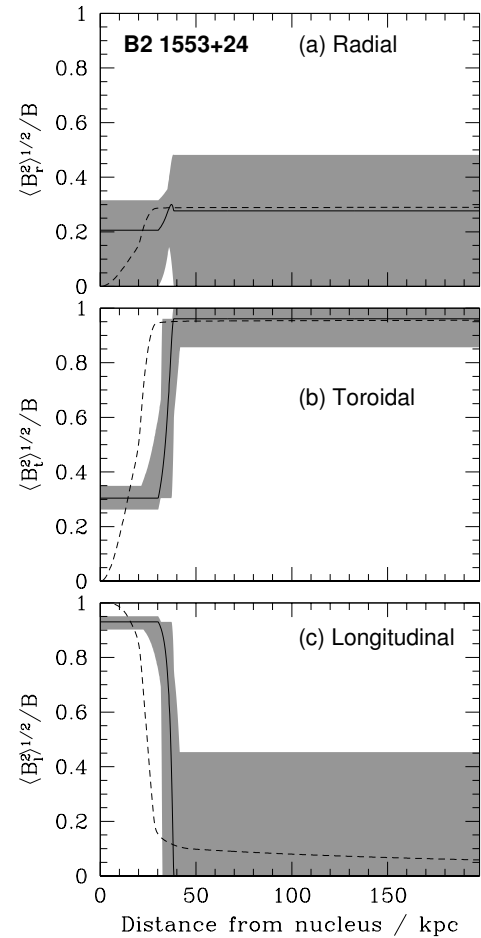
Fig. 3. Inferred variation of physical quantities along the jets of B2 1553+24. (a) and (b) jet geometry (note the different scales); (c) on-axis (full) and edge (dashed) velocity; (d) proper emissivity (full line; the dashed line shows a quasi-one-dimensional adiabatic model).

Fig. 4. Profiles of the relative strengths of the three orthogonal magnetic-field components in B2 1553+24. The full lines show the best values and the shaded areas the uncertainties. the dashed lines are predicted from flux-freezing in a laminar flow. (a) radial; (b) toroidal; (c) longitudinal.

tail in total intensity and linear polarization and propagation effects such as Faraday rotation and free-free absorption must be corrected. If such observations are feasible on sources such as Cyg A and Cen A, they will allow the three-dimensional distributions of velocity, emissivity and magnetic field to be determined for the first time.

References

Asada, K. et al. 2002, PASJ, 54, L39

Bach, U., Krichbaum, T.P., Alef, W., Witzel, A. & Zensus, J.A. 2002, 6th European VLBI Network Symposium, eds Ros, E., Porcas, R.W., Lobanov, A.P. & Zensus, J.A., MPIfR, Bonn, 155

Begelman, M.C., Blandford, R.D. & Rees, M.J. 1984, Rev. Mod. Phys., 56, 255

Canvin, J.R. & Laing, R.A. 2004, MNRAS, 350, 1342

Krichbaum, T.P. et al. 1998, A&A 329, 873

Gabuzda, D.C., Murray, É. & Cronin, P. 2004, MNRAS, 351, L89

Giovannini, G., Cotton, W.D., Feretti, L., Lara, L. & Venturi, T. 2001, ApJ, 552, 508

Hardcastle, M.J., Worrall, D.M., Birkinshaw, M., Laing, R.A. & Bridle, A.H. 2002, MNRAS, 334, 182

Laing R.A. 1980, MNRAS, 193, 439

Laing R.A. 1981, ApJ, 248, 87

Laing, R.A. 2002, MNRAS, 329, 417

Laing, R.A. & Bridle, A.H. 2002a, MNRAS, 336, 328

Laing, R.A. & Bridle, A.H. 2002b, MNRAS, 336, 1161

Laing, R.A. & Bridle, A.H. 2004, MNRAS, 348, 1459

Laing, R.A., Canvin, J.R. & Bridle, A.H., 2004, New AR, 47, 435

Lyutikov, M., Pariev, V.I. & Gabuzda, D.C., MNRAS, submitted, astro-ph/0406144

Tingay, S.J. et al. 1998, AJ, 115, 960

Tingay, S.J. & Murphy, D.W. 2001, ApJ, 246, 210

Zavala, R.T. & Taylor, G.B., 2003, ApJ, 589, 126