Magnetic fields in jets: ordered or disordered?

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Abstract. The question of the degree of order in the magnetic fields of relativistic jets is important to any understanding of their production. Both vector-ordered (e.g. helical) and disordered, but anisotropic fields can produce the high observed degrees of polarization. We outline our models of jets in FR I radio galaxies as decelerating relativistic flows. We then present theoretical calculations of the synchrotron emission from different field configurations and compare them with observed emission from FR I jets. We show that large-scale helical fields (with significant poloidal and toroidal components) are inconsistent with observations. The combination of an ordered toroidal and disordered poloidal component is consistent with our data, as is an entirely disordered field. Jets must also contain small, but significant amounts of radial field.

Key words: galaxies: jets – radio continuum:galaxies – magnetic fields – polarization – MHD

1. Introduction

This paper addresses two questions:

1. Is the magnetic field in extragalactic radio jets vector-ordered or does it have many reversals?
2. What is its three-dimensional structure?

Observations of polarized synchrotron emission at frequencies where Faraday rotation is negligible can be used to infer a two-dimensional projection of the field structure on the plane of the sky (we refer to the *apparent magnetic field direction*, which is the perpendicular to the observed **E**-vector position angle). This emission is an emissivity-weighted integral through the jet, affected by relativistic aberration if the flow speed is comparable with c but independent of reversals in the field. Measurement of Faraday rotation can potentially be used to determine the vector field component along the line of sight within a jet, but the thermal plasma responsible must be be within the jet volume, rather than in front of it, as usually appears to be the case (e.g. Laing et al. 2005).

We have developed models of jets in low-power FR I (Fanaroff & Riley 1974) radio sources as decelerating relativistic flows. By fitting to deep radio images, we can determine the geometry and the distributions of velocity and emissivity. Our technique also constrains the three-dimensional structure of the magnetic field. We cannot determine this structure uniquely, but we can estimate the ratios of the longitudinal, toroidal and radial components and eliminate some of the simpler proposed field geometries.

Our fundamental assumption is that jets are intrinsically symmetrical and relativistic. Aberration then acts differently on radiation from the approaching and receding jets, so their observed synchrotron images are two-dimensional projections of the field structure viewed from different directions. From these, subject to some additional assumptions, we can infer the three-dimensional structure of the field. One key assumption is axisymmetry: if this holds, we can also use the symmetry of the transverse brightness and polarization profiles to distinguish (at least in some cases) between vector-ordered and disordered fields.

2. Jet models

We model FR I jets as intrinsically symmetrical, axisymmetric, relativistic, stationary flows, in which the magnetic fields are assumed to be disordered, but anisotropic (see Section 3 for a detailed discussion of this assumption). We adopt simple, parameterized functional forms for the geometry and the spatial variations of velocity (allowing both deceleration and transverse gradients), emissivity and field-component ratios. We then optimize the model parameters by fitting to deep

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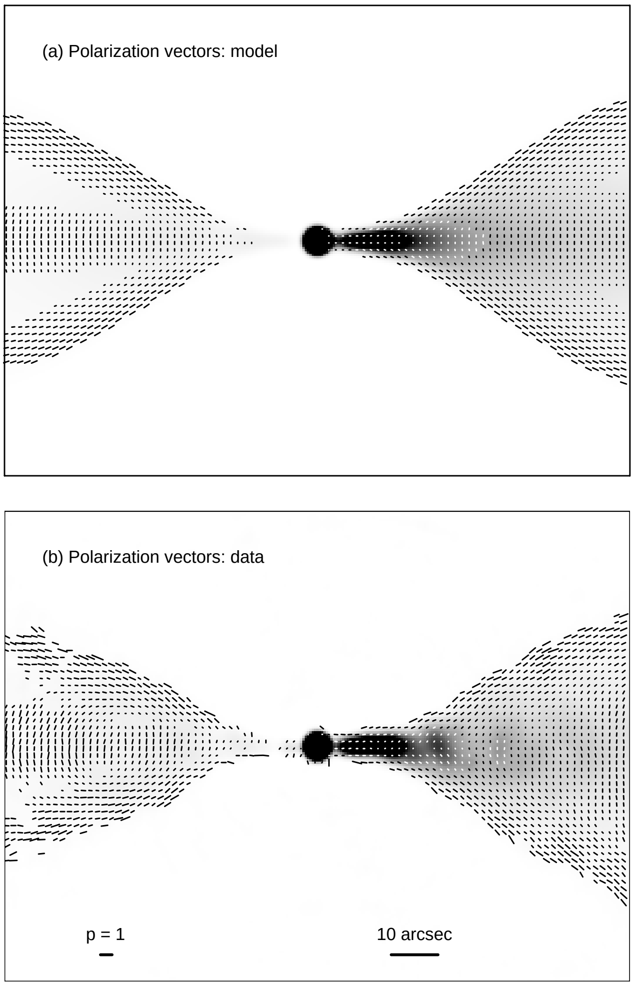

Fig. 1. A comparison of VLA data and model for NGC 315 (Canvin et al. 2005). Vectors with lengths proportional to the degree of polarization, p, and directions along the apparent magnetic field are superimposed on grey-scales of total intensity. The resolution is 2.35 arcsec. The polarization and angular scales are indicated by the labelled bars in the lower panel. (a) model; (b) data.

VLA images in I, Q and U. The model brightness distributions are derived by integration along the line of sight, including the effects of anisotropy in the rest-frame emission, aberration and beaming. Note that modelling of the linear polarization is essential to break the degeneracy between angle to the line of sight and velocity. Details of the models are given by Laing & Bridle (2002), Canvin & Laing (2004) and Canvin et al. (2005). A comparison between our best-fitting model and VLA data for the first arcminute of the jets in NGC 315 is shown in Fig. 1 (Canvin et al. 2005).

3. Field configurations

The models we have discussed so far fit the observations very well, but make a specific assumption about the structure of the field: namely that it is disordered on small scales, but anisotropic. An alternative class of field structures, proposed on theoretical grounds, has a vector-ordered, quasi-helical structure. In this section, we consider how to differentiate observationally between these structures.

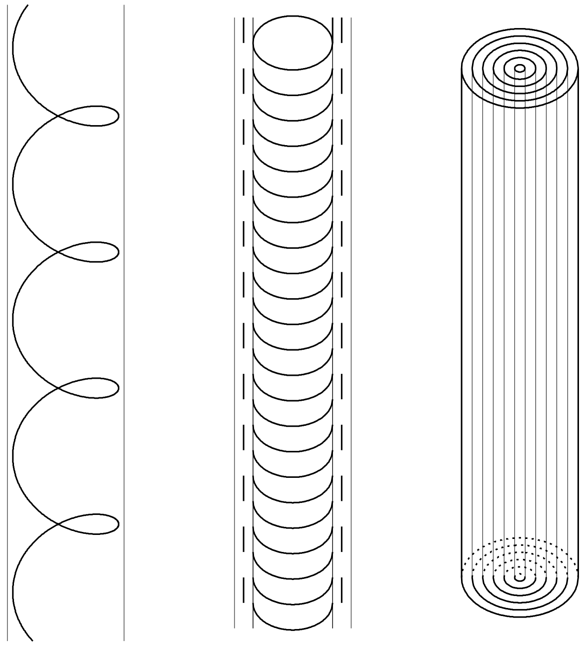

Fig. 2. Sketches of the three field configurations discussed in the text. Left: vector-ordered helix. Middle: perpendicular-field spine and longitudinal-field shear layer. Right: two-dimensional field sheets wrapped around the jet axis.

The generic polarization structure which we seek to model has an apparent magnetic field which is transverse on the axis of the jet but longitudinal at its edges (Fig. 1). Three field structures which can all produce this effect are sketched in Fig. 2. The first is an ordered, helical field. For simplicity, we take this to have a constant pitch angle, but qualitatively similar results are obtained from generically similar, but more complex configurations. The second has a spine of two-dimensional field sheets with equal components in directions orthogonal to the jet axis but no longitudinal component surrounded by a longitudinal-field shear layer (Laing 1980, 1993). The third has two-dimensional field sheets wrapped around the axis, giving equal toroidal and longitudinal, but no radial component (model B of Laing 1980).

Fig. 3 illustrates the brightness and polarization structure produced by a helical field in a jet. In general, helical fields produce asymmetric transverse brightness and polarization profiles (Laing 1981). The profiles are symmetrical only if the field is purely toroidal or the jet is at 90° to the line of sight in the rest frame of the emitting material. The condition for the approaching jet to appear side-on in the rest frame is $\beta = \cos\theta$[1]. The counter-jet can never appear edge-on in its rest frame unless $\beta = 0$ and $\theta = 90°$. Fig 4 shows average transverse profiles of total intensity and degree of polarization for the jets in NGC 315 (Canvin et al. 2005). Our modelling

[1] $\beta = \cos\theta$ is also the condition for maximum Doppler boost, so there is a selection effect in favour of observing symmetrical transverse profiles in blazar jets, even if their fields are helical.

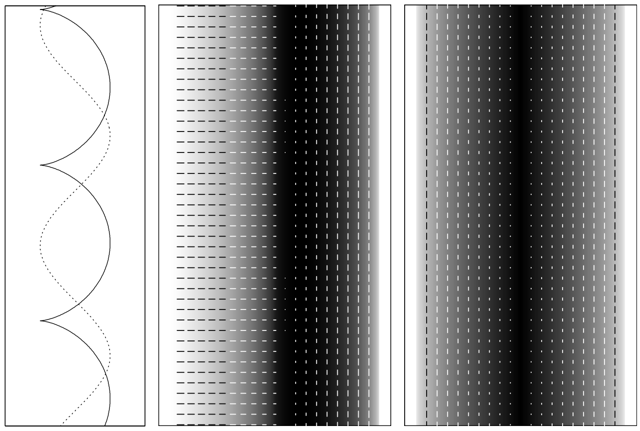

Fig. 3. Total intensity and linear polarization from a (non-relativistic) jet containing a helical magnetic field of pitch angle 45° at angles to the line of sight of $\theta = 45°$ and 90°. Left: sketch showing the projection of field lines on the plane of the sky. Full line, $\theta = 45°$; dotted line, $\theta = 90°$. Middle and right: grey-scales of total intensity with superposed vectors whose lengths are proportional to the degree of polarization and directions along the apparent magnetic field. Middle, $\theta = 45°$; right, $\theta = 90°$.

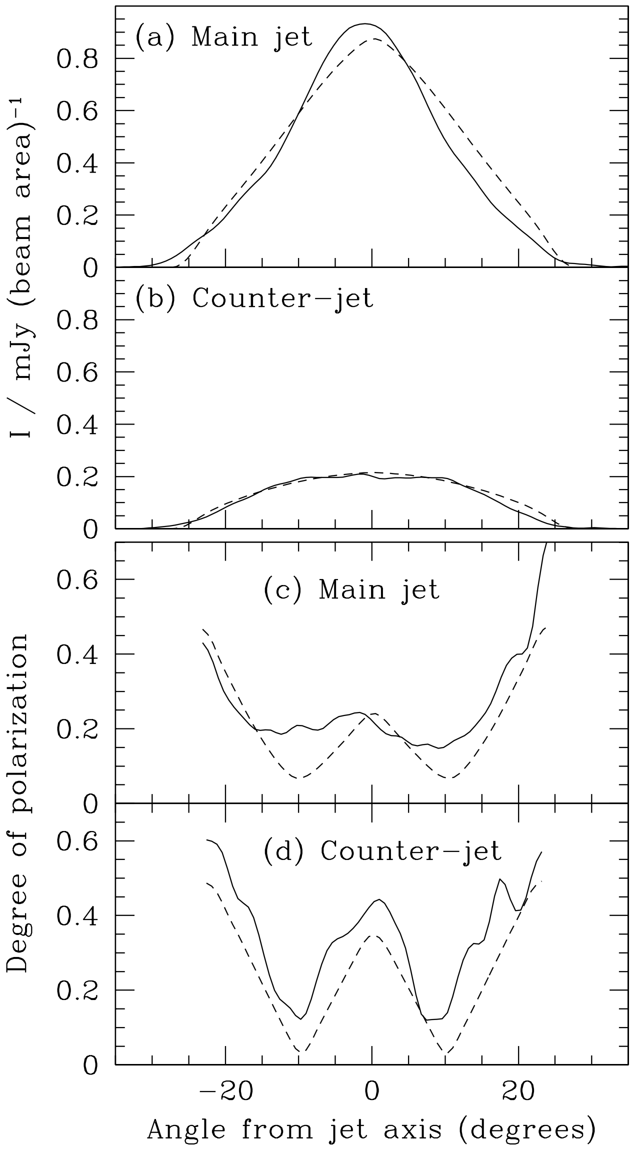

Fig. 4. Transverse profiles of total intensity and degree of polarization, p, for the jets of NGC 315 (Canvin et al. 2005). Full lines: VLA data; dashed lines: model. (a) I, main jet; (b) I, counter-jet; (c) p, main jet; (d) p, counter-jet.

shows that the angle to the line of sight is $\approx 38°$ and that the field must have a a mixture of longitudinal and toroidal components. The profiles are extremely symmetrical, especially in the counter-jet, so we can rule out an ordered helical field at least in this source. The toroidal field component could be ordered, for example if the longitudinal component has many reversals. More generally, a symmetrical transverse profile requires a symmetrical distribution of field directions in the rest frame of the jet flow.

The other two field geometries sketched in Fig. 2 can be distinguished by the relative positions of the transition between longitudinal and transverse apparent field on the jet axis in the main and counter-jets, provided that the flow is relativistic and decelerating. In the case of a perpendicular-field spine surrounded by a longitudinal-field shear layer, the apparent field transition always occurs further from the nucleus in the counter-jet and may not be seen in the main jet. For field sheets wrapped around the jet axis, giving longitudinal and toroidal components only, the converse is true. This is illustrated in Fig. 5. It has been known for some time that the brighter jet in an FR I source tends to show a transition from longitudinal apparent field close to the nucleus to transverse apparent field further out (Bridle 1984). Our deeper observations indicate that the counter-jets either show transverse apparent fields on-axis over their entire lengths, or have a transition much closer to the nucleus (Laing & Bridle 2002; Canvin & Laing 2004; Canvin et al. 2005; see also Hardcastle et al. 1997). We conclude that a first approximation to the field configuration in FR I jets is a mixture of toroidal and longitudinal components.

Detailed modelling (in which the ratios between the field components are allowed to vary as functions of position) confirms this general conclusion, but adds detail. Our conclusions for the four sources we have studied in detail are as follows:

- Fields on kpc scales in FR I radio jets are not vector-ordered helices. Nor should they be: for a conical jet with velocity βc and bulk Lorentz factor Γ, the fluxes for the longitudinal and transverse field components are $\propto r^{-2}$ and $\propto (\Gamma\beta r)^{-1}$, respectively, where r is the distance from the nucleus. The longitudinal flux must be very small at large distances from the nucleus, otherwise the energy density in the magnetic field close to the accretion disk or black hole would be too high (Begelman, Blandford & Rees 1984).
- The field is primarily toroidal and longitudinal, with a smaller radial component in some objects.
- The toroidal component could be ordered, provided that the longitudinal component has many reversals.

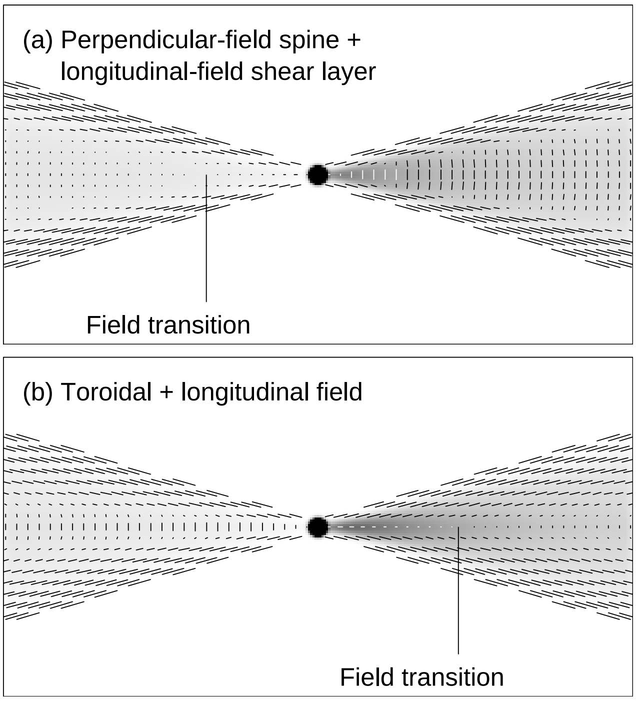

Fig. 5. Location of the transition between transverse and longitudinal apparent magnetic field on the jet axis. The images are of model decelerating, relativistic jets (the approaching jet is on the right). Vectors representing the degree of polarization and the apparent magnetic field direction are superposed on a grey-scale of total intensity. The location of the field transition is marked. (a) Perpendicular-field spine and longitudinal-field shear layer. (b) Field sheets wrapped around the jet axis, so that the toroidal and longitudinal components are equal.

– The longitudinal/toroidal field ratio decreases with distance from the nucleus, qualitatively as expected in an expanding, decelerating flow.
– The evolution of the field-component ratios is not, however, consistent with flux freezing in a laminar velocity field of the type we infer, even if we include the effects of velocity shear (Laing & Bridle 2004).

The field-component structure deduced from our model of NGC 315 is shown in Fig. 6.

4. Further work

In principle, our modelling technique should work for jets in powerful (FR II) sources on kpc scales and for pc-scale jets. There are three main reasons why this is difficult:

– counter-jets are faint and in some cases the jet/counter-jet ratios are very large (presumably the flow is faster);
– the jets are narrow and
– more powerful jets show significant sub-structure, over which we need to average in order to make a robust comparison of the main and counter-jets.

The only FR II jets which have been well enough resolved to give any idea of their 3D field structures are those in 3C 353 (Swain, Bridle & Baum 1998). There, a roughly equal mix of longitudinal and toroidal field also gives the best fit to the polarization data, although the jet velocity is not well constrained. A slightly different approach is feasible in microquasars, where components from a single ejection event can often be identified on both sides of the nucleus. Our technique could then be used to compare the brightness and polarization of the jet and counter-jet components directly, with the added advantage of known proper motions.

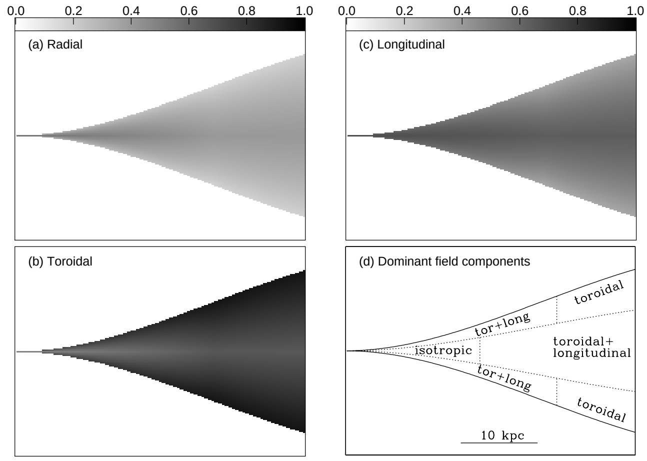

Fig. 6. Panels (a) – (c): grey-scales of the fractional magnetic-field components in NGC 315 from Canvin et al. (2005). (a) radial, (b) toroidal, (c) longitudinal. (d) Sketch of the dominant field components at different locations in the jet, as deduced from the model fits.

For these new applications, we will need sensitivities of 0.1 – 1 μJy rms and $> 10^5$:1 dynamic range at frequencies chosen to be able to resolve and remove Faraday rotation. The resolutions required range from 0.1 arcsec for the nearest FR II sources to < 0.1 milliarcsec for parsec-scale jets. We look forward to EVLA, eMERLIN and broad-band VLBI.

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References

Begelman, M.C., Blandford, R.D., Rees, M.J.: 1984, Rev. Mod. Phys., 56, 255
Bridle, A.H.: 1984, AJ 89, 979
Canvin, J.R., Laing, R.A.: 2004, MNRAS 350, 1342
Canvin, J.R., Laing, R.A., Bridle, A.H., Cotton, W.D.: 2005, MNRAS in press
Fanaroff, B.L., Riley, J.M.: 1974: MNRAS 161, 31P
Hardcastle, M.J., Alexander, P., Pooley, G.G., Riley, J.M., 1997, MNRAS, 288, L1
Laing, R.A., 1980: MNRAS 193, 439
Laing, R.A., 1981: ApJ 248, 87
Laing, R.A., 1993: in Burgarella, D., Livio, M., O'Dea, C.P., eds, Space Telescope Sci. Inst. Symp. 6: Astrophysical Jets. Cambridge University Press, Cambridge, p. 95
Laing, R.A., Bridle, A.H.: 2002, MNRAS 336, 328
Laing, R.A., Bridle, A.H.: 2004, MNRAS 348, 1459
Laing, R.A., Canvin, J.R., Cotton, W.D., Bridle, A.H., Parma, P.: 2005. these proceedings, p.
Swain, M.R., Bridle, A.H., Baum, S.: 1998, ApJ 507, L29