Radio jets as decelerating relativistic flows

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The largest-scale manifestation of Special Relativistic aberration [3] in contemporary astrophysics is the appearance of initial asymmetries in kpc-scale radio-galaxy jets. It is well known that synchrotron radiation from intrinsically symmetrical, oppositely directed bulk-relativistic outflows will appear one-sided as a result of Doppler beaming. The jet/counter-jet ratio, $I_{\rm j}/I_{\rm cj} = [(1+\beta\cos\theta)/(1-\beta\cos\theta)]^{2+\alpha}$ for isotropic emission in the rest frame, where βc is the jet velocity, θ is its angle to the line of sight and α is the spectral index. Less well known is the way in which Special Relativity modifies the observed linear polarization of such jets. As aberration acts differently on radiation from the approaching and receding jets, their observed polarization images represent two-dimensional projections of the magnetic-field structure viewed from different directions $\theta'_{\rm j}$ and $\theta'_{\rm cj}$ in the rest frame of the flow: $\sin\theta'_{\rm j} = \sin\theta[\Gamma(1-\beta\cos\theta)]^{-1}$ and $\sin\theta'_{\rm cj} = \sin\theta[\Gamma(1+\beta\cos\theta)]^{-1}$, where $\Gamma = (1-\beta^2)^{-1/2}$. This is the key [1] to breaking the degeneracy between β and θ and to estimating the physical parameters of the jets.

We model jets in low-luminosity, FR I extragalactic radio sources [4] as intrinsically symmetrical, axisymmetric, relativistic, stationary flows in which the magnetic fields are assumed to be disordered but anisotropic. 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 VLA images in Stokes 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. The model and observed images for four sources, described in refs. [1, 2, 5], are compared in Fig. 1. The asymmetry in total intensity close to the nucleus is characteristic of FR I radio jets. It is correlated with an asymmetry in linear polarization: the apparent magnetic field is *longitudinal* on-axis in the bright bases, but *transverse* at the corresponding locations in the counter-jets. We attribute the asymmetries in brightness and polarization to the effects of aberration and the decrease of both asymmetries with distance from the nucleus to deceleration of the jet by mass loading. We assume that the anisotropic field is disordered on small scales; our results would be unchanged if the

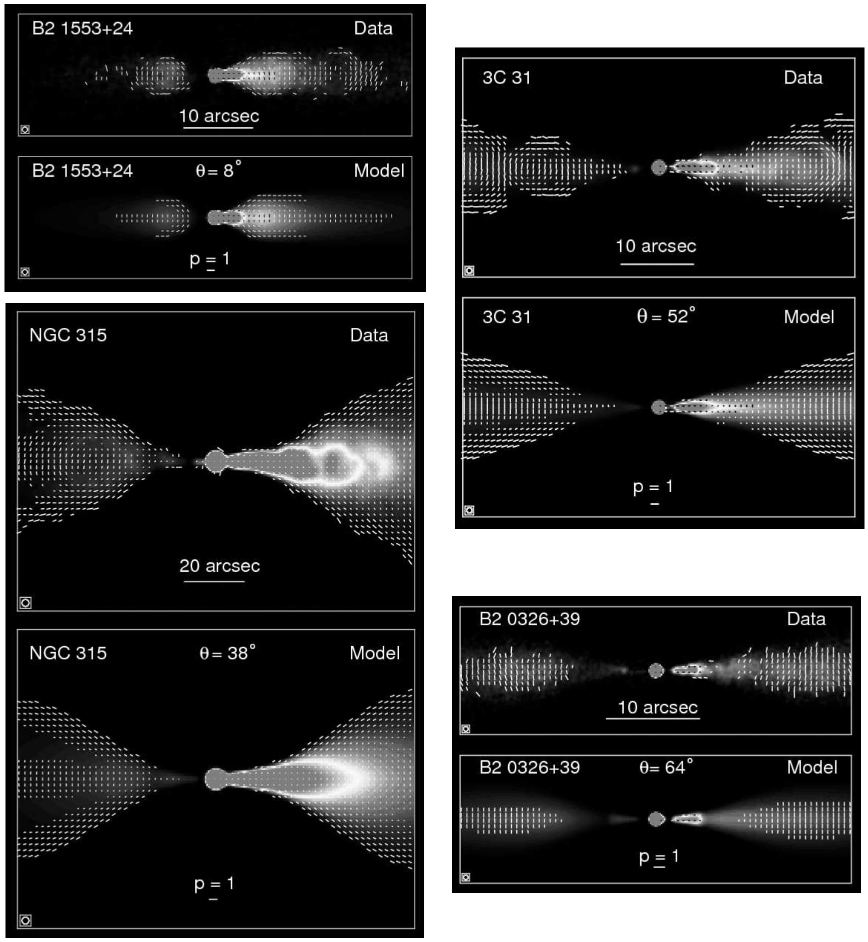

Fig. 1. The four sources we have observed and modelled. Vectors proportional to the degree of polarization, p, aligned with the apparent magnetic-field direction are superimposed on images of total intensity.

toroidal component is vector-ordered but we can rule out a helical field [2]. Our principal conclusions are:

1. Our relativistic jet model provides an excellent description of the observed total intensity and linear polarization and we can use it to estimate the angle to the line of sight and the three-dimensional distributions of velocity, emissivity and magnetic-field structure.
2. The jets in all of the sources decelerate from $\beta \approx 0.8$ to $\beta \approx 0.1$ – 0.4 over short distances within the region of rapid expansion. Further out they recollimate and subsequent deceleration is slower or completely absent. The ratio of edge to on-axis velocity is typically $\approx$0.7 (Fig. 2).

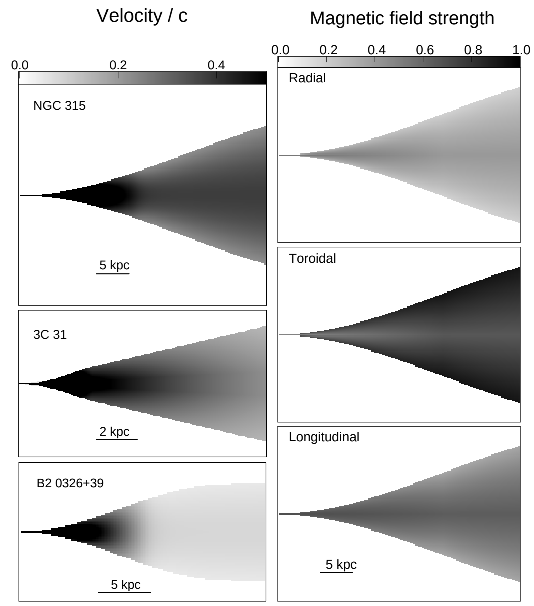

Fig. 2. Left: model velocity fields in the range $\beta = 0 - 0.5$ for three sources. Right: fractional field components for NGC 315.

3. The jets are intrinsically centre-brightened.
4. The magnetic field (e.g. Fig. 2) evolves from mainly longitudinal close to the nucleus to mainly toroidal at large distances, qualitatively but not quantitatively as expected from flux freezing in an expanding flow; the behaviour of the (weaker) radial component differs between the sources.
5. Given a kinematic model derived from the radio data and knowing the external density and pressure from X-ray data, we can apply the laws of conservation of mass, momentum and energy for a bulk relativistic flow to estimate the variation of dynamical quantities along the jets [6].

References

1. Canvin J.R., Laing R.A.: MNRAS, **350**, 1342 (2004)
2. Canvin J.R., Laing R.A., Bridle A.H., Cotton W.D.: MNRAS, **363**, 1223 (2005)
3. Einstein, A.: Annalen der Physik, **17**, 140 (1905)
4. Fanaroff B.L., Riley J.M.: MNRAS, **167**, 31P (1974)
5. Laing R.A., Bridle A.H.: MNRAS, **336**, 328 (2002)
6. Laing R.A., Bridle A.H.: MNRAS, **336**, 1161 (2002)
7. Laing R.A., Bridle A.H.: MNRAS, **348**, 1459 (2004)