

The physics of jets in FR I radio galaxies

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Abstract

We model jets in low-luminosity (FRI) radio galaxies as intrinsically symmetrical, axisymmetric, decelerating relativistic flows with transverse velocity gradients. This allows us to derive velocity fields and the three-dimensional distributions of magnetic-field ordering and rest-frame emissivity. A conservation-law analysis, combining the kinematic model with X-ray observations of the surrounding IGM, gives the profiles of internal density, pressure, Mach number and entrainment rate along the jets. We summarize our recently-published results on 3C 31 and outline new work on other sources and adiabatic jet models.

Key words: galaxies: jets, radio continuum:galaxies, X-rays: galaxies, magnetic fields, polarization

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1 Introduction

This paper is a progress report on a project whose aim is to derive quantitative estimates for the physical parameters of jets. We have developed techniques to derive the three-dimensional distributions of velocity,

rest-frame emissivity and magnetic-field structure and hence to deduce the jet dynamics via a conservation-law approach. Our fundamental assumption is that jets may be approximated as intrinsically symmetrical, time-stationary, axisymmetric relativistic flows. We model their observed radio synchrotron emission in total intensity and linear polarization, using the observed differences between approaching and receding jets to constrain velocity, emissivity and field. We then combine this

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model of jet kinematics with a description of the surrounding IGM and use conservation of energy, momentum and particles to estimate the internal pressure and density. For this technique to work, we need sources with two-sided but asymmetrical and straight radio jets. We then make deep observations with many resolution elements to derive total intensity and linear polarization, corrected for any Faraday rotation. We also require X-ray observations of the hot gas surrounding the radio source from which the external pressure and temperature may be derived. At present, these requirements are met only by VLA and *Chandra* observations of nearby FR I radio galaxies.

2 3C 31

The first source to which we have applied these techniques in full is 3C 31: the kinematic model, X-ray observations and conservation-law analysis are described by Laing & Bridle (2002a), Hardcastle et al. (2002) and Laing & Bridle (2002b), respectively. The kinematic model requires the jets to be at $\theta \approx 52^\circ$ to the line of sight. The jets may be divided into three distinct sections by geometry, velocity and emissivity variation: a well-collimated inner region, a flaring region in which the jets widen rapidly and then recollimate and a conical outer region. Both deceleration (from $\beta = v/c \approx 0.8$ where the jet flares to $\beta \approx 0.25$ at the end of the modelled region) and transverse velocity gradients are inferred. The

toroidal magnetic field component is larger than the longitudinal component almost everywhere and the radial component is small except at the edge of the jet in the flaring region, where the field is roughly isotropic, perhaps as a result of turbulent entrainment. The beginning of the flaring region marks a discontinuity in emissivity and, probably, velocity.

The conservation-law analysis shows that the jets must be extremely light ($\rho \approx 10^{-27} \text{ kg m}^{-3}$). The entrainment rate has a local maximum where the expansion is fastest; thereafter, it increases smoothly and monotonically. The required entrainment could be provided by stellar mass loss close to the nucleus, but interaction with the external medium is required at larger distances. The jet is overpressured with respect to the surrounding medium where it flares, but the outer region is likely to be in pressure equilibrium. The composition of the jet is not determined uniquely by this analysis, but an electron-positron jet with entrained thermal matter would be consistent with all of the available evidence.

3 New results

We have applied simplified kinematic models to describe less detailed observations of a complete sample of FR I radio galaxies from the B2 sample (Laing et al. , 1999). Two of these, 0326+39 and 1553+24, have been reobserved with the VLA at 8.4 GHz and modelled in detail (Canvin & Laing, in preparation).

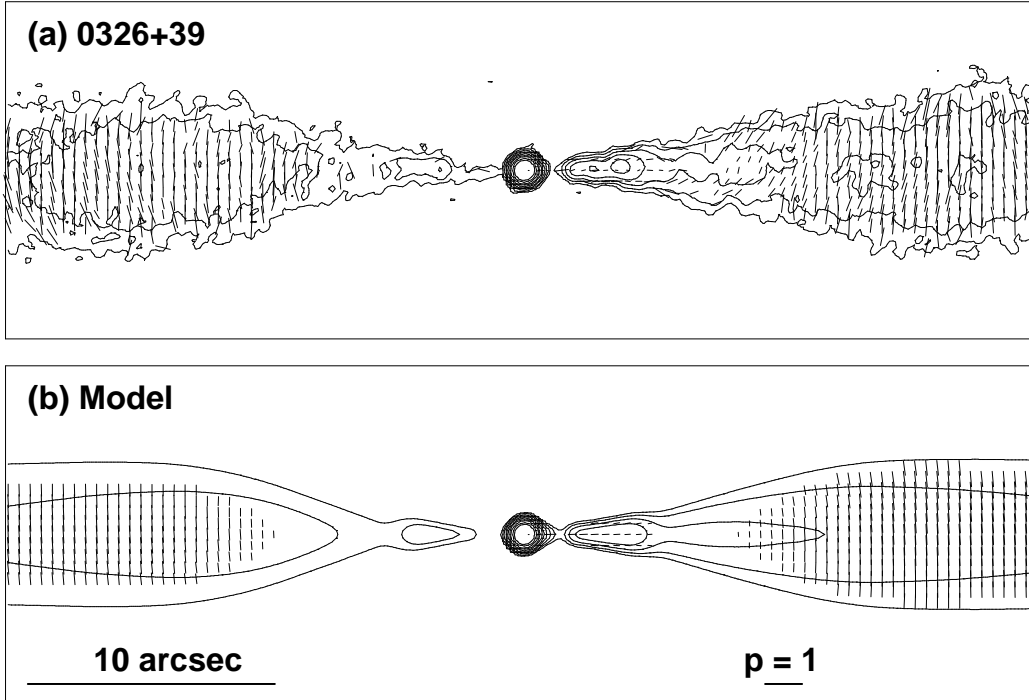


Fig. 1. Contours of total intensity superimposed on vectors with lengths proportional to the degree of polarization, p , and directions representing the apparent magnetic field. (a) VLA observations; (b) model. The resolution is 0.5 arcsec FWHM and the contour levels are 1, 2, 4, 8, 16, $\dots \times 25 \mu\text{Jy} / \text{beam area}$. The angular and polarization vector scales are shown by the labelled bars.

Good fits were again obtained: we show a comparison between model and data for 0326+39 in Fig. 1. The basic picture of jet deceleration with transverse velocity gradients holds for both sources, but there are interesting differences in the field structures: 1553+24 (like 3C 31) has a dominant toroidal component but the outer part of 0326+29 (Fig. 1) has roughly equal radial and toroidal components, but no longitudinal field (cf. Laing, 1980).

Thus far, we have assumed that emissivity and field structure are independent of the velocity field. This is appropriate if we aim to deduce the internal parameters without imposing preconceptions about the un-

derlying physics, but to make further progress, we need to make additional assumptions. The simplest approximation is that the jets are “adiabatic” in the sense defined by Burch (1979): the relativistic particles lose energy only by the adiabatic process and the magnetic field is convected passively with the flow. Baum et al. (1997) derived analytical relations for the surface-brightness of a relativistic jet with no transverse velocity gradient and either a transverse or longitudinal magnetic field. We have generalized their approach to include shear and arbitrary initial field geometry, using a formalism based on that of Matthews & Scheuer (1990).

In Fig. 2, we show the results of fit-

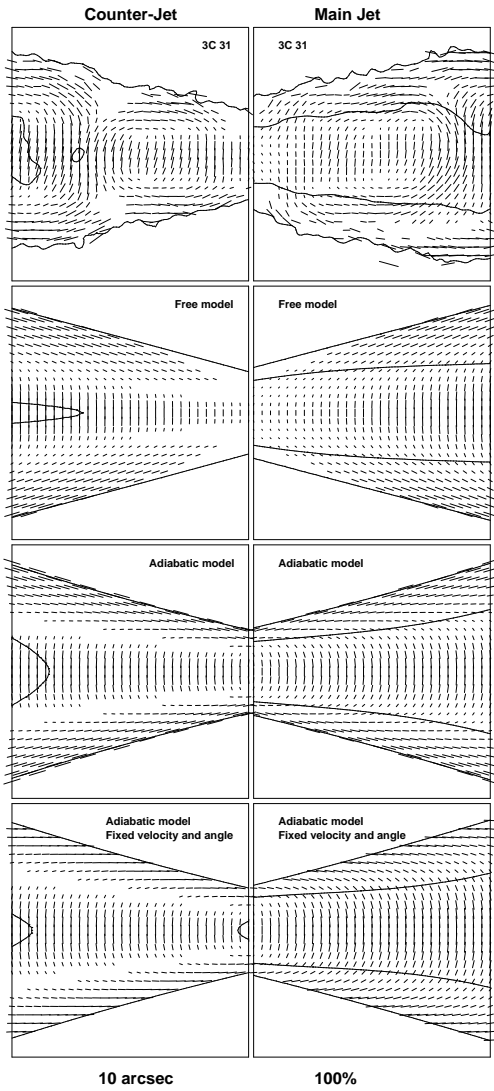


Fig. 2. Vectors with magnitudes proportional to the degree of polarization and directions of the apparent magnetic field superimposed on contours of total intensity at a resolution of 0.75 arcsec for the outer regions of the jets in 3C 31. The plots cover the range 10 – 27 arcsec on either side of the nucleus. Right: main jet; left: counter-jet. From the top: observations; free Gaussian model from Laing & Bridle (2002a); adiabatic model with initial conditions set at the outer boundary and optimized velocity and angle to the line of sight; adiabatic model with geometry and velocity from free model.

ting adiabatic models to the outer regions of the jets in 3C 31, with initial conditions set as profiles of emissivity and field-ordering across the jet at the start of the region. The models fit reasonably well, but cannot accurately describe the observed polarization at the jet edges. A likely possibility is that the velocity field is more complicated than the simple laminar flow we assume, and that some turbulent component is present, leading to changes in field ordering and strength which are not described by our model. In contrast, adiabatic models fail completely in the inner and flaring regions. This should not come as a surprise: the X-ray emission detected in these regions by Hardcastle et al. (2002) is most likely to be synchrotron radiation, requiring significant particle acceleration.

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