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Models of decelerating relativistic jets in 3C 31

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Abstract. We model the brightness and polarization structure of the inner jets in the low-luminosity radio galaxy 3C 31 on the assumption that they are intrinsically symmetrical, axisymmetric relativistic jets. Our approach is to make parametrized models of velocity, emissivity and field ordering, to predict the radio emission and to optimize the parameters by fitting to deep, high-resolution VLA observations of Stokes I, Q and U. Our models are in excellent agreement with the observations for an angle to the line of sight of $\approx 50°$. The jets decelerate from $v/c \approx 0.9$ to sub-relativistic speeds on several-kiloparsec scales. We use this velocity variation, together with the formulation of conservation of particle number, energy and momentum given by Bicknell (1994), to calculate the physical parameters of the flow. ROSAT observations constrain the external pressure distribution, allowing us to derive unique solutions for pressure, density, Mach number and mass flux as functions of distance from the nucleus. Both stellar mass injection and entrainment of the surrounding IGM are likely to contribute to jet deceleration.

1. Introduction

The idea that jets in low-luminosity (FR I; Fanaroff & Riley 1974) radio galaxies decelerate from initially relativistic speeds rests on five main arguments:

1. evidence for relativistic motion on parsec scales in BL Lac objects, coupled with the idea that these are FR I sources seen end-on (e.g. Urry & Padovani 1995);
2. proper motions exceeding c in M 87 (Biretta, Zhou & Owen 1995);
3. models of decelerating relativistic flows (Bicknell 1994; Komissarov 1994; Bowman, Leahy & Komissarov 1996);
4. the interpretation of correlated depolarization and jet sidedness (Morganti et al. 1997) as an effect of Doppler beaming (Laing 1988);
5. observations of brightness and width asymmetries in jets which decrease with distance from the nucleus but correlate with fractional core flux (Laing et al. 1999).

Here, we summarize the results of an attempt to fit decelerating relativistic jet models to a single source: the well-known nearby FR I radio galaxy 3C 31. We assume that $H_0 = 70 \mathrm{km\,s^{-1}\,Mpc^{-1}}$, giving a linear scale of 0.34 kpc/arcsec.

2. Observations

The large-scale radio structure of 3C 31 is described by Laing et al. (these proceedings). Here, we are concerned with the central ±30 arcsec of the source, observed at high resolution. The observations were made with long integrations in all four configurations of the VLA at 8.4 GHz. The final combined images, after self-calibration and careful correction for core variability, had rms noise levels of 6 μJy in all Stokes parameters. We chose to work at resolutions of 0.75 and 0.25 arcsec FWHM. The residual effects of foreground Faraday rotation were removed using the rotation-measure images described by Laing et al. (these proceedings).

3. Models

3.1. Principles

Our key assumption is that the bases of the two jets are intrinsically symmetrical, antiparallel, axisymmetric stationary flows, and that all observed differences between them result from relativistic aberration. This ignores small-scale structure and requires environmental and intrinsic asymmetries to be small: Laing et al. (1999) argue that this is a good approximation for most sources.

Our basic approach is to model the jets using simple parametrized expressions for the variables that determine the synchrotron emission – velocity, emissivity and field ordering – and to determine the free parameters of these expressions by fitting to the observed images. We adopt the observed jet geometry for a given angle to the line of sight and then integrate through the model, taking full account of Doppler boosting and the effects of aberration on linear polarization, finally convolving to the resolution of the observations. We use a χ^2 between model and observed IQU as a measure of goodness of fit and optimize using the downhill simplex method (Press et al. 1992).

3.2. Fits

In Figs 1 and 2, we compare our best-fitting model (described in the next Section) with the observed IQU images of 3C 31. In all cases, the images have been rotated so that the brighter (approaching) jet is on the right. The models fit the data within limits set by small-scale structure and account for the large observed asymmetries in total intensity and linear polarization.

4. Results

Our best-fitting models have a narrow decelerating spine, with no transverse velocity gradient, surrounded by a shear layer whose velocity decreases towards the edge of the jet (Fig. 3 shows a contour plot of the velocity field). The

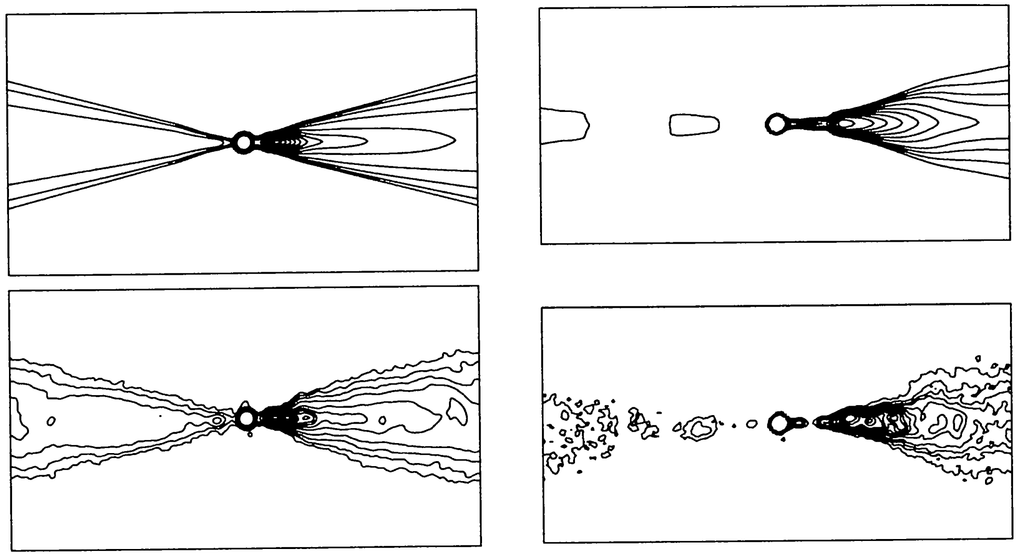

Figure 1. Comparison of model and observed *I*. Left panels: 0.75 arcsec FWHM, showing the inner ±28 arcsec (±9.5 kpc) of the jets. Right panels: the inner ±10 arcsec of the jets at 0.25 arcsec FWHM. Upper panels: model; lower panels: data.

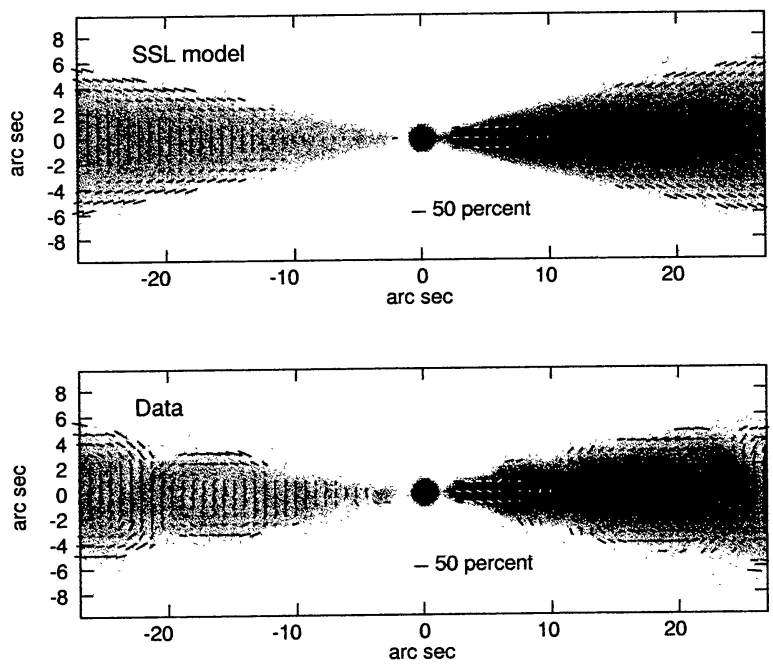

Figure 2. Comparison of model and observed linear polarization at a resolution of 0.75 arcsec FWHM. Vectors representing the degree of polarization and the apparent magnetic field direction are superimposed on a grey-scale of total intensity. The inner ±28 arcsec (±9.5 kpc) of the jets is shown. Upper panel: model; lower panel: data.

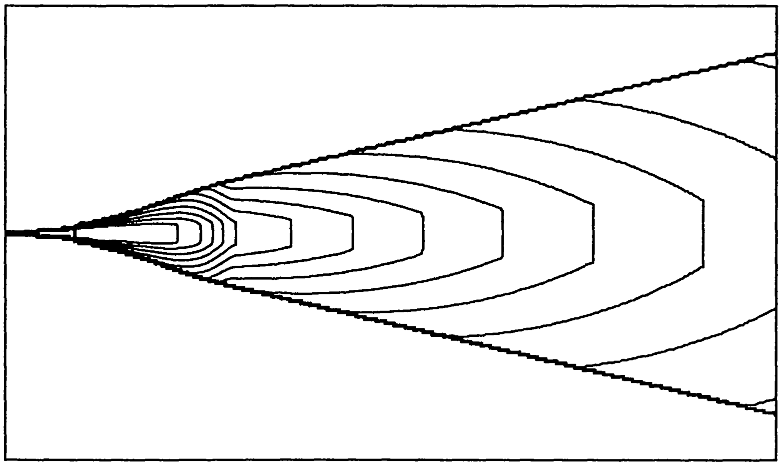

Figure 3. A contour plot of velocity (in units of c) for the best-fitting model. The contours are plotted at intervals of $0.05c$ between $0.15c$ and $0.8c$.

angle to the line of sight is inferred to be 52°. The magnetic field has primarily toroidal and longitudinal components, although it must be disordered on small scales rather than arranged in a regular helix.

The jet can be divided into three regions by the observed collimation properties of the outer isophotes. An important result is that these regions also have distinct kinematic properties, as we now summarize (here, distances from the nucleus, z, are measured in the jet frame).

Inner region (0 – 1.1 kpc) This is characterized by low intrinsic emissivity and slow lateral expansion (a cone of half-angle 6.7°). The fitted velocity is $0.8 - 0.9c$, with no clear evidence for deceleration.

Flaring region (1.1 – 2.6 kpc) This was defined initially by the more rapid spreading of its outer isophotes (Fig. 1; right panels). Our modelling shows that several other dramatic changes occur: the on-axis velocity decreases rapidly to $0.54c$ after an initial slow decline from $0.77c$; the edge velocity is always about 0.7 of its central value; the intrinsic emissivity increases suddenly at the boundary with the inner region, thereafter declining as z^{-3} and the magnetic field becomes essentially isotropic at the edge of the jet.

Outer region (2.6 – 12 kpc) In this region, the jets recollimate, but continue to expand on a cone of half-angle 13.1°. They decelerate less rapidly, reaching an on-axis velocity of $0.25c$ by 10 kpc, but with an essentially unchanged transverse profile. The radial field component disappears, and the relative strength of the toroidal component increases.

We have investigated the possibility that the flow is adiabatic (cf. Bondi et al., these proceedings) using a self-consistent treatment of velocity field, particle density and magnetic-field structure. The emission from the inner region is not remotely consistent with such a model, and that of the flaring region is also clearly non-adiabatic. The outer region is quite well fitted by an adiabatic model, however.

5. Dynamics

It is clear from our models that the transition between the inner and flaring regions marks a discontinuity in the jet where significant deceleration begins. The isotropic field at the edge of the flaring region is intriguing, and may indicate interaction with the external medium.

To slow down, jets must acquire additional material, either from stellar mass loss (Phinney 1983; Komissarov 1994; Bowman et al. 1996) or by entraining surrounding material (e.g. Bicknell 1984). As the jets decelerate, they expand, but they can be accelerated and collimated by the outward force of an external pressure gradient. We have analysed this process by applying conservation of particle number, energy and momentum, following Bicknell (1994) but including the effects of buoyancy, which are significant for 3C 31. We calculate internal density and pressure as functions of distance from the nucleus for given initial energy and momentum fluxes, and look for solutions which satisfy X-ray constraints. Our analysis is restricted to the flaring and outer regions and starts 1.1 kpc from the nucleus.

Unfortunately, uncertainties in the aspect solution for the ROSAT HRI make it difficult to estimate the pressure and density distributions close to the nucleus of 3C 31 (Komossa & Böringer 1999), and we have had to investigate a range of models. Despite this, the value of the energy flux, $1.0 - 2.0 \times 10^{37}$ W, is surprisingly well constrained. Fig. 4 shows a typical set of derived profiles of internal jet flow variables. We conclude that:

1. The jets must be overpressured compared with the external medium at the start of the flaring region, but the outer region can be close to pressure equilibrium.

2. The synchrotron minimum pressure is close to the derived internal pressure.

3. The density, as expected, is low – between 10^{-28} and 10^{-27} kg m^{-3}. Electron-proton jets cannot yet be ruled out, but would require a minimum electron Lorentz factor of $\gamma_{\rm min} \sim 50 - 100$. A jet consisting initially of pair plasma which has picked up some thermal material before the flaring point would also satisfy our constraints.

4. The jets are indeed transonic, with Mach numbers between 1 and 2.

5. The initial entrainment rate at the beginning of the flaring region is close to that predicted from stellar mass loss (Komissarov 1994), but additional mass input is required at large distances from the nucleus.

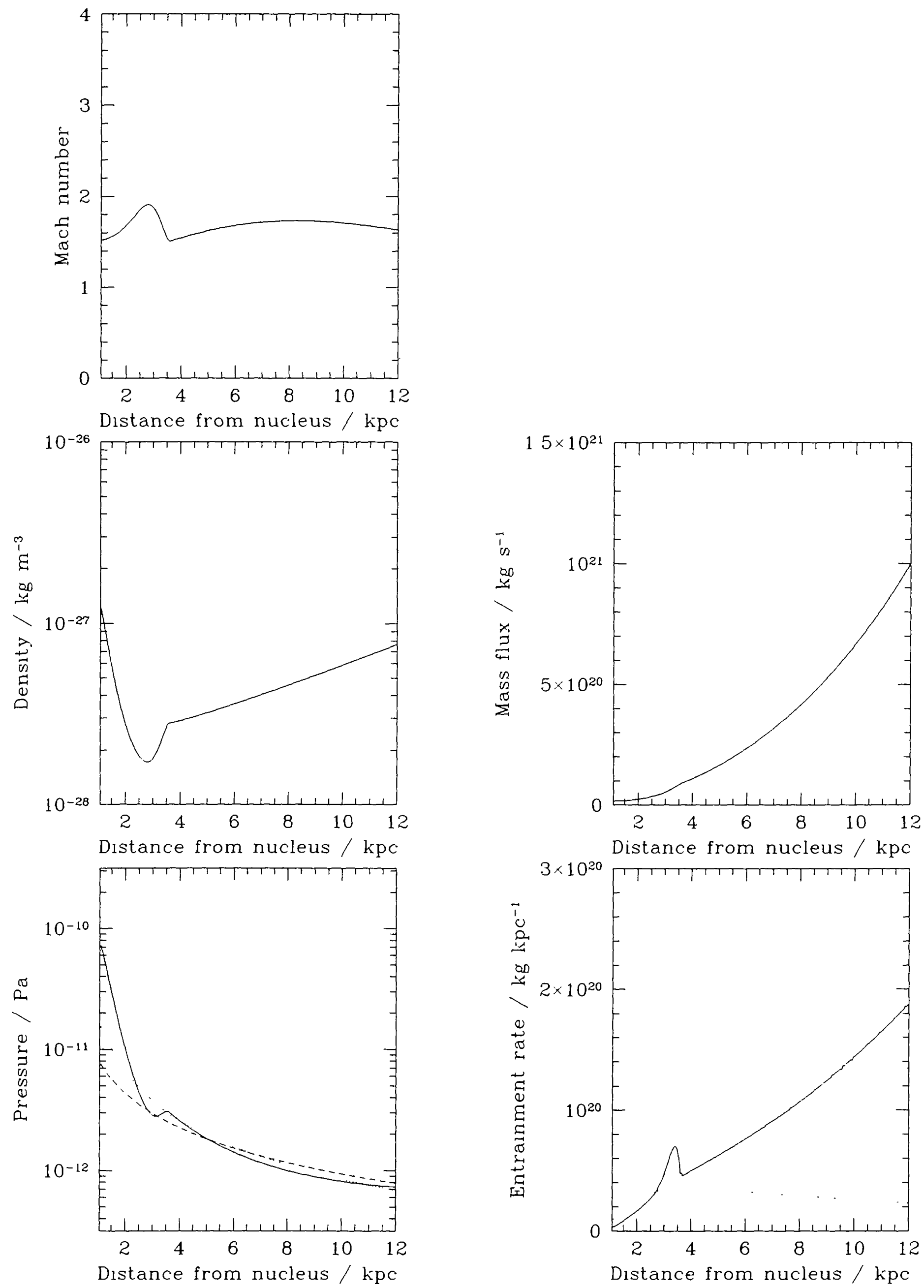

Figure 4. Profiles of pressure, density, Mach number, mass flux and entrainment rate along the jets of 3C 31 derived from the conservation-law analysis. In the pressure plot, the internal, external and synchrotron minimum pressures are represented by full, dashed and dotted lines, respectively. In the plot of entrainment rate, the full line is derived from the model and the dotted line is an independent estimate of mass input from stars.

6. Summary

We have, for the first time, derived three-dimensional models of the emissivity, magnetic field structure and velocity in a radio jet. This has allowed us to apply a conservation-law analysis to estimate the internal density and pressure. Given better X-ray data from *Chandra*, we should be able to refine our dynamical model to give a comprehensive picture of jet deceleration.

References

Bicknell, G.V. 1984, 'A model for the surface brightness of a turbulent low Mach number jet. I. Theoretical development and application to 3C 31', ApJ, 286, 68–87

Bicknell, G.V. 1994, 'On the relationship between BL Lacertae objects and Fanaroff-Riley I radio galaxies', ApJ, 422, 542–561

Biretta, J.A., Zhou, F. & Owen, F.N. 1995, 'Detection of proper motions in the M 87 jet', ApJ, 447, 582–596

Bowman, M., Leahy, J.P. & Komissarov, S.S. 1996, 'The deceleration of relativistic jets by entrainment', MNRAS, 279, 899–914

Fanaroff, B.L. & Riley, J.M. 1974, 'The morphology of extragalactic radio sources of high and low luminosity', MNRAS, 167, 31P–35P

Komissarov, S.S. 1994, 'Mass loaded relativistic jets ', MNRAS, 269, 394–402

Laing, R.A. 1988, 'The sidedness of jets and depolarization in powerful extragalactic radio sources', Nature, 331, 149–151

Laing, R.A., Parma, P., de Ruiter, H.R. & Fanti, R. 1999, MNRAS, 'Asymmetries in the jets of weak radio galaxies', 306, 513–530

Morganti, R., Parma, P., Capetti, A., Fanti, R. & de Ruiter, H.R. 1997, 'Asymmetric depolarization in double low-luminosity radio galaxies', A&A, 326, 919–923

Press, W.H., Teukolsky, S.A., Vetterling, W.T. & Flannery, B.P. 1992, Numerical Recipes (Cambridge: Cambridge University Press)

Phinney, E.S. 1983, Ph.D. Thesis, University of Cambridge

Urry, C.M. & Padovani, P. 1995, 'Unified schemes for radio-loud active galactic nuclei', PASP, 107, 803–845