Observations of jet dissipation

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Overview

- **X-ray – radio connections in radio galaxies and quasars:**
  - High-energy emission from non-thermal electrons.
  - The interaction of radio galaxies with external hot plasma.

- **Deceleration of relativistic jets in FRI radio galaxies:**
  - Models of synchrotron emission $\rightarrow$ 3D velocity field, emissivity, field structure.
  - Velocity + external $p$, $\rho$, $T$ $\rightarrow$ energy flux, $p$, $\rho$, Mach number, entrainment rate.

- Where are energetic particles accelerated?
X-ray – radio connections

- X-ray emission from the non-thermal electron population:
  - synchrotron - same population?
  - inverse Compton – source of photons, B
- X-ray observations of the surrounding hot plasma cavities
  - external pressure and density
  - entrainment and mixing
A weak (FRI) radio galaxy

3C 31 (VLA 1.4GHz; 5.5 arcsec FWHM)

Jets in FRI sources decelerate, becoming trans- or subsonic and produce much of their radiation close to the nucleus – see later.
X-ray synchrotron emission from FRI jets [Hardcastle]

3C 31 (Hardcastle et al. 2002)
Jets in FRII sources remain supersonic (and relativistic) until they terminate in hot-spots.
Cygnus A (FRII)

Hot-spot X-rays from SSC with B close to equipartition in this and other cases ……
but synchrotron and iC emission suggested for some hot-spots.

Cygnus A: Chandra image showing cluster gas, cavity around radio source and emission from the radio hot-spots (Wilson, Young & Shopbell (2000))
A powerful FRII quasar
Powerful jets [Georganopoulos, Harris, Jester]

3C179 (Sambruna et al. 2002)
3C219 (Comastri et al. 2003)

Synchrotron?
Beamed inverse Compton - CMB photons?
- Photons from slower regions of the jet?
Radio and X-ray emission anticorrelate: radio lobes displace X-ray emitting plasma.

Gas surrounding the cavities in low-power sources often at or below ambient temperature, but....

Evidence for heating in some sources (Cen A, Cyg A) – expected for supersonic expansion in powerful FRII’s.
Lobes [Croston, Isobe, Belsole]

X-ray emission from lobes expected from inverse Compton scattering of CMB photons.

Current results suggest that B is usually close to equipartition.

3C219 (Comastri et al. 2003)

Inverse Compton scattering of IR photons from an obscured AGN?

If so, a probe of the low-energy part of the electron spectrum.
Modelling of FRI jets

- Model FRI jets as intrinsically symmetrical, axisymmetric, relativistic flows [free models]. Derive 3D velocity, emissivity and field geometry. [Deep, high-resolution radio images. Linear polarization essential.]

- Apply conservation of mass, momentum and energy to infer the variations of pressure, density, entrainment rate and Mach number. [External density and pressure from X-ray observations.]

- Model the acceleration and energy-loss processes, starting with adiabatic models. [Images at mm, IR, optical, X-ray wavelengths.]
Progress so far

- B2 sample statistics (Laing et al. 1999)
- Free models of 3C31 (Laing & Bridle 2002a)
- Conservation-law analysis of 3C 31 (Laing & Bridle 2002b)
- Adiabatic models of 3C 31 (Laing & Bridle 2004)
- Free models of B2 0326+39 and 1553+24 (Canvin & Laing, MNRAS submitted)
- Free model of NGC 315

Alan Bridle, James Canvin – models

Diana Worrall, Martin Hardcastle, Mark Birkinshaw (Bristol) – X-ray

Bill Cotton, Paola Parma, Gabriele Giovannini, … - radio
Free models – basic principles

- Model jets as intrinsically symmetrical, axisymmetric, relativistic, stationary flows. Fields are disordered, but anisotropic.

- Parameterize geometry, velocity, emissivity and field structure.

- Optimize model parameters by fitting to IQU images.

- Derive model IQU by integration along the line of sight, taking account of anisotropy of synchrotron emission in the rest frame, aberration and beaming.

- Linear polarization is essential to break the degeneracy between angle and velocity.
Total Intensity

\[ \begin{array}{cccc}
\theta & 8^\circ & 37^\circ & 52^\circ & 64^\circ \\
\text{B2 1553+24} & \text{NGC 315} & \text{3C 31} & \text{B2 0326+39}
\end{array} \]
Total Intensity (high resolution)

\[ \theta = 8^\circ, 37^\circ, 52^\circ, 64^\circ \]
Degree of polarization

θ  8°  37°  52°  64°
Apparent magnetic field (1)

\[ \theta = 8^\circ \quad 37^\circ \]
Apparent magnetic field (2)

\[ \theta = 52^\circ \quad 64^\circ \]
Velocity $\beta = \frac{v}{c}$

- B2 1553+24
- NGC 315
- 3C 31
- B2 0326+39
Geometry and velocity

- FRI jets are initially narrow, flare abruptly and then recollimate to form conical (often almost cylindrical) outer regions.
- Their velocities are $\beta \approx 0.8$ at the start of the model.
- All of the jets decelerate abruptly in the flaring region, but at different distances from the nucleus.
- At larger distances, they have roughly constant velocities in the range $\beta \approx 0.1 - 0.2$.
- They have transverse velocity gradients, with edge/on-axis velocity consistent with 0.7 everywhere. There are no obvious low-velocity wings.
Emissivity and field

- Emissivity profile tends to flatten at large distances from the nucleus (compare with adiabatic models – later).
- FRI jets are intrinsically centre-brightened.
- Dominant field component at large distances is **toroidal**.
- The longitudinal component can be significant close to the nucleus, but decreases further out.
- Radial component behaviour is peculiar.
- Qualitatively consistent with flux freezing, but laminar-flow models, even including shear, do not fit.
FRI deceleration physics

- Jets have (at least) two regions, differentiated by collimation and kinematic properties – flaring and outer.
- The onset of jet deceleration is within the flaring region, and is sudden.

Reconfinement shock (Sanders 1983)?
Non-linear K-H instabilities (Rosen et al. 1999) or transition to fully-developed turbulence?

- There is evidence from the field structure of 3C 31 for interaction with the external medium where the jet flares.
Conservation law analysis

- We now know the velocity and area of the jet.
- The external density and pressure come from Chandra observations.
- Solve for conservation of momentum, matter and energy.
- Well-constrained solutions exist.
- Key assumptions:
  - Energy flux = momentum flux x c
  - Pressure balance in outer region
Mass, energy and momentum flux conservation

\[ \Phi = [(\Gamma^2 - 1) \rho c^2 + 4\Gamma^2 p] \beta c A \] (1)

\[ \Pi = [\Gamma^2 \beta^2 (\rho c^2 + 4p) + p - p_{\text{ext}}] A \right) \]

\[ + \int_{\tau_1}^\tau A \frac{dp_{\text{ext}}}{dr} \left[ 1 - \frac{\Gamma^2 (\rho c^2 + 4p)}{c^2(1 + \beta^2) \rho_{\text{ext}}} \right] dr \] (2)
Conservation-law analysis: fiducial numbers at the jet flaring point

- Mass flux $3 \times 10^{19}$ kgs$^{-1}$ (0.0005 solar masses/yr)
- Energy flux $1.1 \times 10^{37}$ W
- Pressure $1.5 \times 10^{-10}$ Pa
- Density $2 \times 10^{-27}$ kgm$^{-3}$
- Mach number 1.5
- Entrainment rate $1.2 \times 10^{10}$ kgkpc$^{-1}$s$^{-1}$
External pressure and density

(a) Pressure / Pa

(b) External density $\rho_{\text{ext}} / \text{kg m}^{-3}$

Distance from nucleus / kpc
The jet is initially over-pressured, then reaches equilibrium.
Mach number
Internal density

![Graph showing density versus distance from the nucleus in kiloparsecs. The y-axis is labeled as Density (kg m⁻³) and the x-axis is labeled as Distance from nucleus (kpc). The graph shows a sharp decrease in density near the nucleus, followed by a slight increase as the distance increases.](image-url)
Stellar mass loss is inadequate to slow the jet at large distances, but could provide all of the mass required for distances $<$ 1 kpc.
What are the jets made of?

- $\rho = 2.3 \times 10^{-27} \text{ kg m}^{-3}$ (equivalent to 1.4 protons m$^{-3}$) at the flaring point.

- For a power-law energy distribution of radiating electrons, $n = 60 \gamma_{\text{min}}^{-1.1} \text{ m}^{-3} \sim 10^{-28} \gamma_{\text{min}}^{-1.1} \text{ kg m}^{-3}$.

- Possibilities include:
  - Pure $e^+e^-$ plasma with an excess of particles over a power law at low energies.
  - $e^+e^-$ plasma with a small amount of thermal plasma.
  - Cold protons in equal numbers with radiating electrons and $\gamma_{\text{min}} = 20 - 50$ (not observable).
Adiabatic models

Set initial conditions at start of outer region.

Calculate evolution of particle density and field assuming adiabatic/flux-freezing in a laminar flow.

Adiabatic models give a reasonable fit, but do not get either the intensity or polarization quite right.

Not surprising if the flow is turbulent?
Adiabatic models

3C 31 I

Adiabatic, with same velocity and initial conditions.

Free model

Adiabatic model with distributed particle injection.
Where are particles injected?

- Points – X-ray
- Full line – particle injection function
- Dashed line - radio
- Pressures from conservation-law analysis

VLA + Chandra
Relativistic Jets in 3C31

at different angles to the line of sight

R.A.Laing (Oxford) & A.H.Bridle (NRAO)
Conclusions

- FRI jets are decelerating relativistic flows, which we can now model quantitatively.
- The 3D distributions of velocity, emissivity and field ordering can be inferred by fitting to radio images in total intensity and linear polarization.
- Application of conservation of energy and momentum allows us to deduce the variation of density, pressure and entrainment rate along the jet.
- Boundary layer entrainment and mass input from stars are probably both important in slowing the jet.
- Adiabatic models and flux freezing do not work, although they are closer to observations at large distances.
- Particles must be injected where the jets are fast.