Magnetic fields in kiloparsec-scale Relativistic Jets

Robert Laing (ESO)
Outline

Background

Strong and weak-flavour jets
Jet modelling methods

1 A strong-flavour jet: NGC 6251
2 Weak-flavour jets

We really want to know how jets are formed – but the (synchrotron) light is brighter two blocks (kpc) downstream
What do we want to know?

- Magnetic-field topology
  - Component ratios: toroidal:longitudinal:radial
  - Vector-ordered or disordered?

- What are the jet velocity fields
  - Deceleration
  - Transverse structure

- How does jet composition change with distance?
  - Leptons and baryons; mass flux and entrainment rates

- What are the energy and momentum fluxes?

- Confinement
  - Gas pressure, B-field, not at all, ...

- Effects on external environment
  - Energy input, shocks, magnetic field
FRI/Weak-flavour jets: deceleration
Low-luminosity; transverse
apparent magnetic fields
FRII/Strong-flavour Jets – always fast?
Powerful; longitudinal apparent fields

3C353: Swain, Bridle & Baum

3C334: Bridle et al.
Apparent field direction and radio luminosity

Bridle (1984)
Jet Models

- What distributions of flow velocity, field geometry and rest-frame emissivity are consistent with observations?

- Observe:
  - Deep, high-resolution radio images; IQU, corrected for Faraday rotation

- Assume:
  - Symmetrical, axisymmetric, stationary, relativistic flow
  - Power-law energy distribution, optically-thin synchrotron

- Parametrised model of:
  - Geometry
  - Velocity field in 3D
  - Emissivity
  - Magnetic-field component ratios

- Calculate I, Q, U; optimise
How does this work?

- Assumption of intrinsic side-to-side symmetry **close to AGN**
- Modelling side-to-side asymmetries
  - Total intensity alone is not enough: ratio
    \[ \frac{I_j}{I_{cj}} = \frac{(1+\beta \cos \theta)/(1-\beta \cos \theta)}{(1+\beta \cos \theta)/(1-\beta \cos \theta)}^{2+\alpha} \]
    depends only on $\beta \cos \theta$ for isotropic rest-frame emission ...
  - ... but polarized emission cannot be isotropic in rest frame
  - Use both $I$ and linear polarization, for which asymmetries depend on a different combinations of $\beta$ and $\theta$
  - Aberration $\rightarrow$ we look at approaching and receding jets at different angles to the line of sight in the rest frame
  - Enough information to separate $\beta$ and $\theta$ if we know the field structure a priori ....
  - ... which we don't, so need to fit
- Hence need good S/N and transverse resolution in IQU
Understanding the field structure

2D transverse field sheets on-axis + longitudinal field shear layer

Wrong

2D toroidal and longitudinal; component rms equal

Right

Longitudinal – transverse field transition
(1) Strong-flavour jets

- At least mildly relativistic velocities on kpc scales:
  - Depolarization asymmetry (RL, Garrington et al. 1988)
  - Continuity of sidedness from pc scales, where there is ample evidence for highly relativistic motion ....
  - ... very hard to decelerate powerful jets without destruction

- But:
  - Integrated jet/counter-jet rations $\rightarrow \beta \approx 0.6$ (Wardle & Aaron; Mullin & Hardcastle)
  - Beamed inverse Compton X-rays require $\Gamma \approx 10$ (Tavecchio et al.; Celotti et al.) ....
  - ... as do proper motions on pc scales

- Spine/layer models?
  - $\Gamma \approx 10$ spine surrounded by $\Gamma \approx 2$ (shear?) layer?

- Longitudinal apparent field
  - What is the 3D structure?
Observing strong-flavour jets is painful

- Narrow
- Faint (especially the counter-jets)
- Emission superimposed on lobes, which have filaments and other junk emission of great interest
- Really need resolution <0.05 arcsec; sensitivity <10 nJy/beam and dynamic range >10^7
- While waiting for this, try
  - Cygnus A (very bright) - in progress
  - NGC 6251 (a transition case)
    - Jansky VLA
    - 5-7 GHz
    - 1.5 arcsec resolution
    - Fighting interference, dynamic range and leakage corrections, but can show preliminary results .....
NGC6251

Transition case between weak and strong flavour jets

Giant radio galaxy NGC6251 (z=0.0247; 1.8 Mpc projected)

Collimated jets

Jet/counter-jet ratio is high at all distances

Fermi LAT detection:
- variable
- emission from outer main jet instead of/as well as core?

(Abdo et al. 2010; Grandi et al. 2013)
Observed and model I
Observed and model fractional polarization

\[ \text{Observed } p = \frac{P}{I} \]

\[ \text{Model } p = \frac{P}{I} \]

\[ \text{= longitudinal – tranverse apparent field transition} \]
Observed and model B vectors

Caution: Faraday rotation corrections uncertain
Velocity and Magnetic Field Structure
Best fit (so far)

- Geometry
  - $\theta = 34^\circ$

- Velocity
  - Deceleration from $\beta = 0.992$ ($\Gamma = 8$) to $\beta = 0.86$ ($\Gamma = 2$) on-axis
  - Edge velocity ~constant ($\beta = 0.55$ to $\beta = 0.51$)
  - At large distances, velocity is well constrained at edge; could be larger on-axis
  - Assumed transverse profile (truncated Gaussian) does not give enough limb-brightening in counter-jet – modify assumed functional form

- Magnetic field
  - Longitudinal and toroidal components comparable close to AGN; toroidal becomes dominant at larger distances
(2) How does NGC6251 compare with weak-flavour jets?

Differences:

Weak flavour jets:
- expand rapidly
- decelerate from $\Gamma \approx 2$ to $\Gamma \approx 1$

Similarities:

- Longitudinal $\rightarrow$ toroidal field
- Transverse velocity gradients

Laing & Bridle (2014)

10 radio galaxies
$0.015 < z < 0.05$
Low-power, FRI
An example: I model

How important are intrinsic asymmetries?

From statistics of jet sidedness reversals, the mean intrinsic emissivity ratio is \( \approx 1.5 \) at 10 kpc.
Polarization fits

Vectors
- along apparent magnetic field direction
- lengths $\propto$ degree of polarization

(d) NGC 315

$\theta = 49.8^\circ$

$p = 1$

20 arcsec
Another representation: $Q/I$

$Q/I > 1$
apparent field transverse

$Q/I < 1$
apparent field longitudinal

$U \approx 0$
Jet velocities

(a) 1553+24
(b) 0755+37
(c) 0206+35
(d) NGC 315
(e) 3C 31
(f) NGC 193
(g) M84
(h) 0326+39
(i) 3C 296
(j) 3C 270
Fractional magnetic field components

**Longitudinal**

(a) 1553+24  
(b) 0755+37  
(c) 0206+35  
(d) NGC 315  
(e) 3C 31

(f) NGC 193  
(g) M84  
(h) 0326+39  
(i) 3C 296  
(j) 3C 270

**Toroidal**

(a) 1553+24  
(b) 0755+37  
(c) 0206+35  
(d) NGC 315  
(e) 3C 31

(f) NGC 193  
(g) M84  
(h) 0326+39  
(i) 3C 296  
(j) 3C 270
Constraining the field configuration

- From synchrotron emission alone (in the absence of associated Faraday rotation), we cannot tell whether a field is vector-ordered, or disordered with many reversals.
- Partially ordered fields can produce very high fractional polarizations (if viewed at the right orientation).
- Specific field configurations can be excluded if they fail to reproduce the observed polarization.
- Ambiguities (especially between vector-ordered and disordered, anisotropic fields with similar component ratios) often remain.
- It helps to see both sides of a relativistic twin-jet source (provided that it is really symmetrical, of course).
Transverse profiles can help

$\theta = 90^\circ$

$45^\circ$ pitch angle helix

$\theta = 45^\circ$

Relativistic Jets, Krakow, April 2015
Measured transverse profiles for NGC315: field is not a grand-design helix

Ambiguity

Field is toroidal + longitudinal

We do not know whether the toroidal field is vector-ordered

(Suspect ordered toroidal + longitudinal with reversals)
A consistency test: Faraday Rotation
Rotation measure gradients on kpc scales

Guidetti et al. (2010, 2011)
RL et al. (2008)
Data from F. Owen

Hydra A

3C449

M87
A second consistency test: core fraction

Core is the optically-thick base of the jet

Assume intrinsic ratio of core/extended emission is constant

Doppler beaming causes observed ratio $f$ to be anticorrelated with $\theta$
Spectrum and speed

Spectrum becomes flatter with increasing distance from AGN
Opposite to effect of synchrotron losses
Velocity-dependent particle acceleration?

Laing & Bridle (2013)
Summary and Next Steps

- Weak flavour jets can be described in quantitative detail
  - Deceleration and transverse velocity gradients
  - Field evolution longitudinal to toroidal
  - Flattening spectrum and decreasing particle acceleration
- First attempt at strong-flavour jet model implies
  - Initially very fast ($\Gamma = 8$) spine and slower shear layer
  - On-axis deceleration possible but not certain
- Strong-flavour jets are hard to study, even with the new generation of arrays, but watch this space