Large-scale AGN Jets
Physical conditions and particle acceleration

SQUARE KILOMETRE ARRAY
Exploring the Universe with the world’s largest radio telescope

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Extragalactic jets

Bipolar, relativistic outflows, powered by supermassive black holes in Active Galactic Nuclei.

In this talk, I will mostly discuss large-scale (kpc-Mpc) jets.

- Jet power $\sim 10^{41} - 10^{47}$ ergs$^{-1}$
- Relativistic bulk flow: pc-scale Lorentz factor $\Gamma \sim <2 - 40$
- Supermassive black holes $M \sim 10^6 - 2 \times 10^{10} M_{\text{Sun}}$
- Formation scale $<50 \ r_g$ in M87
- Ages (with persistent directions) up to $\sim 10^8$ yr
- Observed synchrotron and inverse Compton radiation
- Relativistic electrons and magnetic field; thermal particles + …
- Accelerate electrons to very high Lorentz factors
Jets as particle accelerators

Centaurus A radio + X-ray

Mkn 501 average (Abdo et al. 2011)

M87 TeV gamma rays
FRI jets: Low-luminosity Deceleration

Radio Galaxy 3C31 (RL et al. 2008)
FRII: Powerful, fast, well-collimated jets
(Swain, Bridle & Baum)

Why the difference?

I will talk mostly about FRI jets (and one transition case). Markos will discuss FRII’s.
Hosts: old, red and undead

Massive elliptical galaxies
Slow rotators; core profiles
Form early; grow by dry mergers

Very massive black holes

Old stars (mostly)

Hot plasma on galaxy and group scales

Molecular gas and dust – fuel?

Absorption line/LINER spectra
Broad lines weak or absent
No evidence for obscuring torus

Energy output dominated by jets

\[ \frac{L_{\text{acc}}}{L_{\text{Edd}}} \ll 1 \] and low accretion rate
\( v \approx c: \text{Proper motions and aberration} \)

- Flux density in observer's frame at frequency \( v \)
  - \( S(\theta, v) = D^{2+\alpha} \int \varepsilon'(\theta, v) \, dV/d^2 \)

- Doppler factor
  - \( D_j = [\Gamma(1 - \beta \cos \theta)]^{-1} \) (approaching)
  - \( D_{cj} = [\Gamma(1 + \beta \cos \theta)]^{-1} \) (receding)

- \( \sin \theta' = D \sin \theta \)

- Approaching jet appears brighter and the two jets are observed at different angles to the line of sight in the flow rest frame \( \theta' \)

- Polarization depends on \( \theta' \) – different in the two jets

Meyer et al. (2015)

\( \beta_{\text{app}} = 1.8 - 7.0 \)
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

Ten FRI radio galaxies (Laing & Bridle 2014) + one transition case
Consistency check: Faraday rotation

![Consistency check: Faraday rotation](image)
Consistency check: core flux

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 $\theta$

Fit is simple single-speed model
NGC6251: a FRI/II transition jet

![NGC6251 Image at 5.5GHz](image-url)
Looking deeper

Flying saucer
NGC6252
Model Fits ($\theta = 30^\circ$)

Sidedness ratio → transverse velocity gradient
Polarization model fits

Colour: I
Vector length p
Vector angle $\chi_0 + 90^\circ$

Q/I
Inferred velocity field

Independent longitudinal velocity profiles for spine and layer
No transverse variation in either component

Simplest model:

Spine: constant $\beta \approx 0.89 \ (\Gamma \approx 2.2)$
Layer: $\beta \approx 0.4 \ (\Gamma \approx 1.1)$

.... but cannot exclude faster spine close to the AGN where jets are poorly resolved in width

This is very different from jets in FRI sources ...
FRI jet velocities: deceleration

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FRI jet physics: velocity

Laing & Bridle (2014)
Deceleration starts in the high-emissivity region and stops where the jets recollimate.
In close up

NGC 315

High $\epsilon$

Deceleration
Particle acceleration

NGC315 spectral index
(RL et al. 2006)

Radio/X-ray
(Worrall et al. 2007)
Distributed particle acceleration

Cen A X-ray emission

(Goodger et al. 2010)
M87 jet knot spectral energy distributions

Consistent with a single energy distribution for radiating electrons.

Broken power law spectrum to a first approximation.

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

Laing & Bridle (2013)
FRI jets: relativistic particles

(c) Radiating particles

High emissivity

Complex non-axi-symmetric structure

$\mathcal{M} > \mathcal{M}_{\text{crit}}$

$\alpha = 0.66$

$\alpha = 0.59$

Flattening emissivity profile

Adiabatic evolution

$\gamma_{\text{max}} \sim 10^7$

$\gamma_{\text{max}} \sim 10^5$

None

Particle acceleration
Field components for NGC6251

Longitudinal $\rightarrow$ Toroidal, just as in FRI sources ....
Field components in FRI jets

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
(b) **Field Evolution**

- isotropic
- longitudinal (+ toroidal)
- isotropic
- toroidal (+ longitudinal)
- toroidal
- Flux-freezing
FRI jet dynamics: conservation law analysis

Velocity fits from Laing & Bridle (2014)

Conservation-law analysis following Laing & Bridle (2002)

3C31

NGC315

B2 0326+39

3C 296

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Tails and lobes

Tails (Plumes)  Lobes

Speed at recollimation

High  Low

$\rho c^2/w$ at recollimation
(energy density cold:relativistic)

Low  High

Entrainment  Jets keep on going
restarts
NGC6251 (if pressure confined)

Spine:
- fast
- (mildly) supersonic
- very light
- almost no entrainment
- carries most of the energy

Kinetic power $3 \times 10^{37}$ W

Layer:
- mildly relativistic
- transonic
- carries more of the mass
- but still very light

Kinetic power $6 \times 10^{36}$ W
Conclusions

- FRI jets
  - Widen rapidly, decelerate from relativistic to sub-relativistic speeds and recollimate
  - Develop transverse velocity gradients as they decelerate, implying external entrainment
  - Have energy fluxes up to $\sim 10^{37}$ W ($10^{44}$ erg s$^{-1}$)
- The jets in NGC6251 (a transition case)
  - Remain narrow and maintain roughly constant speeds
  - Show persistent transverse velocity structure, with a central supersonic spine ($\beta \approx 0.9$) and a slower ($\beta \approx 0.4$) outer layer
  - Entrain very little
  - Have energy fluxes of $\sim 3 \times 10^{37}$ W
- I suspect that true FRII jets are faster ... but not fast enough to produce beamed iCCMB (see Markos’s talk)
  - Observations of FRII counter-jets are very hard, but we are trying ....
Particle acceleration questions

• In FRI jet bases:
  – Low frequency spectral index is significantly steeper than 0.5 (energy index > 2)
  – Correlation with flow speed: faster flow → (slightly) steeper spectrum
  – Particle acceleration up to electron $\gamma \approx 10^7$ for bulk $\Gamma \approx 2$
  – Characteristic “broken power-law” spectrum
  – Acceleration not restricted to a few discrete sites (distributed/multiple small sites)

• Shocks?
  – Complex, non-axisymmetric brightness structure at start of deceleration
  – No evidence for shocks where jets recollimate
  – Conservation-law analysis (no dynamically important field) → transonic flow
  – Weak relativistic shocks might explain velocity - spectral index relation (Summerlin & Baring)

• Shear?
  – Evidence for velocity gradients
  – One example of association with spectral index

Are any of the proposed mechanisms efficient enough?