Spines, Boundary Layers, and Doppler Hiding

-- or --

Finding the Fast Lane in Extragalactic Jets

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FRI jet deceleration (3C31)

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FRII jet boundary layer (3C353)

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FRII jet spine (3C219)

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Bottom Line:

All radio-galaxy and quasar jets are born with bulk relativistic velocities.

In FRI sources, these jets decelerate to subrelativistic velocities on kiloparsec scales that we can observe with the VLA.

In FRII sources, these jets do not fully decelerate until the hot spots (or even beyond).

Velocity fields in decelerating jets strongly control what we see of them in radio images.

We are biased towards imaging the slowest parts of the jet flows in all lobe-dominated sources.
The fast lane is Doppler-hidden.

Relativistic Jet Birth

Central Engine Performance Specification:

(powerful radio-galaxy/quasar models)

Total Energy Available ~ $10^6 M_\odot c^2$
Continuous Power ~ 0.02 $M_\odot c^2$ per year
Collimated jets formed on sub-parsec scales

Only plausible model:

B++

Black Hole (~$10^8 M_\odot$)
plus
Accretion Disk
plus
Twisted Magnetic Fields

End-on Relativistic Jets

Early VLBI studied brightest, most compact sources:

Superluminal motions
Rapid variability
Low self-Compton X-ray fluxes
One-sided radio structures
Large apparent distortions

All consistent with bulk-relativistic jets
($\Gamma \sim 5$, $v \sim 0.98c$)
seen at small angles to line of sight

Time-of-flight effects--->superluminal motion.
Time dilation--->fast variability, low X-ray fluxes.
Doppler boosting of approaching jet--->one-sidedness,
dominance of compact over extended structure.

N.B. Not restricted to powerful radio galaxies and
quasars. Similar phenomena in lower-power "blazars".

Main Points:

Strong evidence that all radio galaxy and quasar jets are born with bulk relativistic velocities.

In weak (plumed, FRI) sources these jets decelerate via interactions with E galaxy atmospheres on kpc scales.

Deceleration imposes a jet velocity field: a fast spine and slower boundary layer.

Kinematics can be probed with VLA imaging and polarimetry in some nearby galaxies.

In lobed (FRII) sources, jet velocity field biases us toward seeing just a boundary layer until jet decelerates

In FRII sources, the jet spines may not decelerate fully until the hot spots.

The fast lane of energy transport --- the jet spine --- may thus stay Doppler-hidden to the very end.

High-Power Extended Sources

Fanaroff-Riley Class II

Well-bounded, edge-brightened, twin-lobed sources.

Lobes often have bright "hot spots"
(strong-shock jet terminations?)

One-sided jets, prominent in quasars (broad opt lines)
less prominent in radio galaxies (narrow opt lines)

Jets highly collimated
Jets dominated by axial field components

Low-Power Extended Sources

Fanaroff-Riley Class I

Poorly-bounded, edge-darkened, twin-plumed sources.

Lobes never have bright "hot spots"
(subsonic plume terminations?)

Two-sided large-scale jets, but
one-sided bases with initial "gaps" at nucleus

Jets spread rapidly at bases, then recollimate
Jets dominated by perpendicular field components on-axis, some parallel field at edges
One-sided jet bases are dominated by axial field

The FR I/II Division

Not a sharp function of radio power alone.
Not a sharp function of optical luminosity alone.

Well-defined boundary in **bivariate** radio-optical luminosity plane (Owen & Ledlow 1984).

Radio power at which FRII behavior "begins" is higher in more luminous galaxies.

As if:

Powerful engines make FRII sources in any environment
Weak engines make FRI sources in any environment
Intermediate ---> FRI in "stronger" environments
FRII in "weaker" environments

Orientation-based Unification

Bulk-relativistic jets--->radio orientation-dependence

Obscuring torus ~ scale of broad-line region--->
optical orientation dependence

FRII sources (Barthel)

Near plane of sky: weak jets, broad lines obscured
Intermediate: stronger jets, broad lines may be seen
Near line of sight: core-dominated quasar

Pc-scale and kpc-scale jets share same sidedness
Depolarization asymmetry--->brighter jet approaching
(Laing/Garrington)

FRI sources (Urry, Padovani)

Near plane of sky: twin-plumed radio galaxy
Near line of sight: blazar

Pc-scale jets and kpc-scale jet bases
share same sidedness (recent VLBI)
Depolarization asymmetries--->
brighter jet base is approaching (Bologna sample)

Jet Deceleration in FRI Sources

If:

Large-scale plumes ~ symmetric, slow
Parsec-scale jets relativistic

Where and why do FRI jets become subrelativistic?

Key is the one-sided bases ~ kpc scales?

Strong deceleration ~ scale of host galaxy "core"?

Suppose "gaps" are where flow initially Doppler-hidden,
jet brightening by removal of unfavorable beaming.

Explains longer gaps on counterjet side (Komissarov)

What could be deceleration mechanism in galaxy core?

How does a Galaxy Decelerate a Jet?

1. Entrainment of gas from ISM

Jets will try to expand until they reach pressure balance with surroundings (static or ram)

Surface of pressure-confined jet K-H unstable

Boundary layers become turbulent,
eddy pairing gulps material from atmosphere into jet.

Jet k.e. shared with entrained material (slowdown)

Internal heating tends to decollimate jet.
Galactic pressure gradient tends to recollimate jet.

At moderate Mach numbers, this competition can decelerate a jet without destroying it. (Phinney)

Initial formation of slow boundary layer
Flaring followed by recollimation?

FRI ---> enough mass entrained to slow whole jet
FRII ---> not so!

How does a Galaxy Decelerate a Jet?

2. Loading by gas from stellar winds

Jets do not sweep stars out of their path

Gas is injected into jets by stellar winds
$\langle \dot{M} \rangle \sim 10^{-12}\ M_\odot$/yr/star
Possible mass-loading rates ~ $10^{-4}\ M_\odot$/yr?
Significant for FRI jets?

Mass-loading of jet via turbulent trails from stars
If turbulent trails fill jet volume ---> slowdown

Loading is strongest in the galactic core
(highest stellar densities)

"Prepares" jet for later slowdown by entrainment?

3C31 as a Decelerating Relativistic Jet

VLA all-configuration syntheses at 1.4, 5 and 8 GHz.

Detailed structure of the jet base and RM screen:

1. Brighter jet base is on side with less depolarization.
(i.e., geometry is correct!)

2. Outer edges of jet and counterjet are much more
intensity-symmetric than emission near jet axis.

3. Both jets flare as they initially brighten:
deceleration signature.

4. Sidedness image ---> model jet velocity field,
fast and decelerating in center, slower at edges.

5. Polarization structure is consistent with:
no radial field in outer layers,
no axial field in central spine,
spine and outer layers decelerating,
when you allow for relativistic beaming and aberration!

Implications for jets in FRII sources

Atmospheres will still try to decelerate the jets by entrainment (mass-loading less important)

Emission from jets away from the line of sight (most lobe-dominated sources?) dominated by slowest-moving parts of flow -- outer shearing layers? This will explain the observed B-parallel dominance.

Most of energy transport in fast, hidden jet spines?

Jet Lorentz factors estimated from jet/counterjet sidedness data biased low!

Prediction:

"Hollow" radio jets in narrow-line FRII radio galaxies, more "filled center" jets in quasars?

Doppler Hiding!

i.e. dimming by relativistic beaming

$D(\theta) < 1$ even for the approaching jet

$\beta = v/c$	Γ	"hiding" if
0.995	10	$\theta > 25^\circ$
0.980	5	$> 35^\circ$
0.865	2	$> 55^\circ$
0.6	1.25	$> 70^\circ$

Structure of jet in 3C353

VLA all-configuration syntheses at 1.4, 5, 8 GHz
Mark Swain Ph.D. thesis

Radio galaxy just on FRII side of boundary
Best-resolved FRII jet on sky (8-10 beams across it)

Narrow jet and counterjet.

Flat-topped intensity profiles.

Deep polarization minima along both edges, little polarized emission from center of jet.

Jet sits on lobe in which B mainly perpendicular to jet.

Polarization minima + flat-topped intensity profiles well modeled by:

Outer half of jet has no radial field component
Inner half of jet has no axial field component
Emissivity of jet spine <1/4 that of outer layer

i.e. simple extrapolation of model that also fits 3C31!

Structure of jet in 3C219

VLA synthesis at 8 GHz

Restarting jet/counterjet pair in FRII radio galaxy.

Length asymmetry interpreted as relativistic time-of-flight effect (further jet seen at earlier retarded time)

Most of jet is broad "stripe", no center brightening.
Fine structure: ultracompact knots at both jet tips.

These knots align to <0.2 deg across nucleus.

Part of flow extremely well-collimated!

Knots = shocks at ends of restarting jet spines?

Hot Spots in lobes of 3CR quasars

Long-standing problem: (Laing 1989; Bridle et al 1994)

"Jetted" hot spots systematically more compact than "counterjetted" hot spots.

If the jet asymmetries are Doppler-mirages, why do the hot spots "know" about them?

Relativistic asymmetries of <u>hot spots</u>?

Requires bulk relativistic flow through hot spot shocks, yet Lorentz factor estimates for pre-hot-spot jet flows only $\Gamma \sim 2$. (Bridle et al. 1994; Wardle & Aaron 1996)

Answer: hot spots are deflection points (oblique shocks in) spine outflows with $\Gamma > 2$.
Parent flow "hidden" inside the observed jet?

Part of approaching flow may align with line of sight.
Receding flow must decelerate, broaden to be seen.