Coupling Jets to their Surroundings: the Role of Entropy

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Physics of Intracluster Medium
Jet of Cygnus A

Powerful, near FR II radio source (Carilli & Barthel 1994); radio luminosity ≈ 7×10^{44} \text{ erg s}^{-1}; z = 0.056; D_L = 250 \text{ Mpc}; scale = 1,088 \text{ kpc/arcsec}

Hosted by cluster central galaxy

Smith et al (2002), Chandra shows AGN, jets, radio hotspots, cocoon shock, etc

SW shock: Mach 1.37, r ≈ 40 kpc, age ≈ 1.6×10^7 yr, mean power ≈ 4×10^{45} \text{ erg s}^{-1}
X-ray jet is resolved by Chandra
- not coincident with radio jet (Steenbrugge & Blundell 2007)
Symmetry (also: eastern jet receding) => jet X-ray emission not Doppler boosted
X-ray spectrum for 11”×5.7” region at eastern end => power law (photon index 1.69±0.26, 90%).

ICCMB (100 < ν < 10,000; p = 2.38) would require electron pressure > 10× surrounding gas pressure.

IC on beamed optical from AGN would require > 10^{46} erg s^{-1} beamed along jets
Pressure equipartition in eastern lobe gives $B \approx 55 \, \mu G$

- 1 keV synchrotron photons radiated by electrons with $\gamma \approx 4 \times 10^7$

Synchrotron X-ray model requires $\sim 10^{-5} \times$ electrons as ICCMB model

- $t_{\text{synchrotron}} \approx 200 \, \text{yr}$
- requires acceleration in situ

X-ray jet traces the path of the jet now
- radio does not
X-ray vs radio jet

Unsharp masked 0.7 – 7 keV Chandra image (red)

Radio 6 cm (cyan)

Excess hotspot pressure due to jet ram pressure

SSC model (Harris et al 1994) -> \( B_{\text{hotspot}} \approx 246 \, \mu G \);
Wilson (2003) -> \( B_{\text{hotspot}} \approx 150 \, \mu G \)

\[ \frac{p_{\text{hotspot}}}{p_{\text{jet}}} \approx \left( \frac{B_{\text{hotspot}}}{B_{\text{jet}}} \right)^2 \approx 10 - 20 \]

Jet radius in eastern lobe \( \approx 3 \, \text{kpc} \)
Jet Flow Model

Proper density of jet rest mass, $\rho$, rate of mass flow through jet:

$$\dot{M} = \gamma \beta c A \rho$$

Power through jet ($h =$ enthalpy per unit volume,

$$h = p + e = \Gamma p/(\Gamma - 1),$$

for pressure $p$):

$$P = (\gamma - 1) \dot{M} c^2 + hA c \beta \gamma^2$$

Momentum flux:

$$\Pi = (P/c + \dot{M} c) \beta$$

Have estimates for: power (from shock); $P$, area, $A$, and pressure, $p$.

Jet comes to (near) halt in hotspot => hotspot pressure $\approx$ ram pressure, so $\Pi \approx p_{\text{ram}} A$, also known ($p_{\text{ram}} = p_{\text{hotspot}}$: hotspot width matches jet)

$$\frac{P}{p A c} = \left( \frac{p_{\text{ram}}}{\gamma + 1} + \frac{\Gamma}{\Gamma - 1} \right) \beta \gamma$$

Power + momentum equations give:

– solve for jet speed, mass flow rate, etc
Cyg A Jet Flow Model

For $P_{jet} = 2 \times 10^{45} \text{ erg s}^{-1}$, jet pressure $p = 2.4 \times 10^{-10} \text{ erg cm}^{-3}$, $r_{jet} = 3.1 \text{ kpc}$, ratio of specific heats, $\Gamma = 5/3$ (see below), $p_{ram}/p = 20$, get:

$\beta_{jet} = 0.079$; mass flow rate through jet = $9 \ M_{\odot} \ yr^{-1}$; $n_{e, jet} = 4.4 \times 10^{-4} \ cm^{-3}$; for pressure balance, $kT_{jet} = 175 \ keV$ (hence gas is non-relativistic).

Note a) 1-dimensional flow model, b) no correction for projection.

As above, with $p_{ram}/p = 10$ and $\Gamma = 13/9$:

$\beta_{jet} = 0.12$; mass flow rate through jet = $3 \ M_{\odot} \ yr^{-1}$; $n_{e, jet} = 9.5 \times 10^{-5} \ cm^{-3}$; for pressure balance, $kT_{jet} = 810 \ keV$ (electrons relativistic, protons not).

Increasing $P/(pAc)$ or decreasing $p_{ram}/p$ will increase flow speed.

Large ram pressure => large mass flux => significant entrainment by the jet.
Flow Model for Cen A Jet

Steady, near 1-d flow => \( v = v(R) \).

Area of cross section, \( A(R) \), and external pressure, \( p(R) \), known (\( kT \approx 0.55 \text{ keV}, n_e \sim r^{-1.26} \)) – equate to internal pressure (cf. Laing & Bridle 2002).

Mass flow through jet:

\[
\dot{M} = \gamma \beta c A \rho
\]

Entrainment rate, \( \alpha \), per unit volume:

\[
\left. \dot{M} \right|^2 = \frac{2}{1} \int \alpha A dR
\]

Assume constant power along jet: (enthalpy \( h = \Gamma p / (\Gamma - 1) \), with \( \Gamma = 13/9 \) here).

\[
P = (\gamma - 1) \dot{M} c^2 + h A c \beta \gamma^2
\]

Momentum flux \( \Pi = (P/c + \dot{M} c) \beta \) is affected by buoyancy

\[
\left. \Pi \right|^2 = \frac{2}{1} \int \frac{dp}{dR} A dR
\]
Flow Parameters

Fiducial values: Jet power, \( P = 6 \times 10^{42} \text{ erg s}^{-1} \) (Croston et al 2009).

Initial speed, \( \beta = 0.7 \) (radio knots move at \( \approx 0.5c \) near inner end; Hardcastle et al 2003).

Stellar mass loss: star density = \( f \times \) gravitating mass density (hydrostatic equilibrium), with \( f \approx 1 \) at \( R = 100 \text{ arcsec} \) (1.8 kpc; consistent with photometry) and \( \alpha = f \rho_{\text{grav}} / \tau \), with \( \tau = 10^{12} \text{ yr} \) (Faber & Gallagher 1976).

Other entrainment – let \( f \) vary.

Radio and X-ray measurements of jet width agree.

No dissipation (constant \( \dot{M} \))

\( P \) eqn: speed must decrease
\( \Pi \) eqn: speed must increase

\( \Rightarrow \) Flow is dissipative

Flow is over-determined: adjust \( f \) to make 3 equations consistent.
Fiducial Model

Solution determined by 2 equations, energy & mass flow.

Choose \( f \) to make \( \Delta \Pi = \text{buoyant force} \)

\[ \Rightarrow f = 0.60 \]

Insensitive to flow parameters
Effect of Environment

Dissipation due mass entrainment makes a jet unstable:
larger cross section => more entrainment => more dissipation => jet broadens

Model:
\[ \frac{dM}{dR} = \alpha A; \quad \frac{d\Pi}{dR} = -A \frac{dp}{dR}; \quad P = \text{constant} \]

Same power, initial speed, mass injection (\(\alpha\)) as fiducial model, but bounding pressure is
scaled by down factors of up to 2:

Moderate asymmetry in environment can make the
difference between a jet and a lobe.
Effect of Environment

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$$dM \cdot dR = \alpha A; \quad d\Pi dR = -A dp dR; \quad P = \text{constant}$$

Moderate asymmetry in environment can make the difference between a jet and a lobe.
Conclusions

- Appears to be substantial entrainment in the jets of both Cyg A (FRII) and Cen A (FRI)
- Dissipation due to entrainment places the Cen A jet close to the margin for rapid inflation
- Fate of the jet is sensitive to environmental influence
- Details of jet physics affect the site and manner of energy deposition by AGN jets