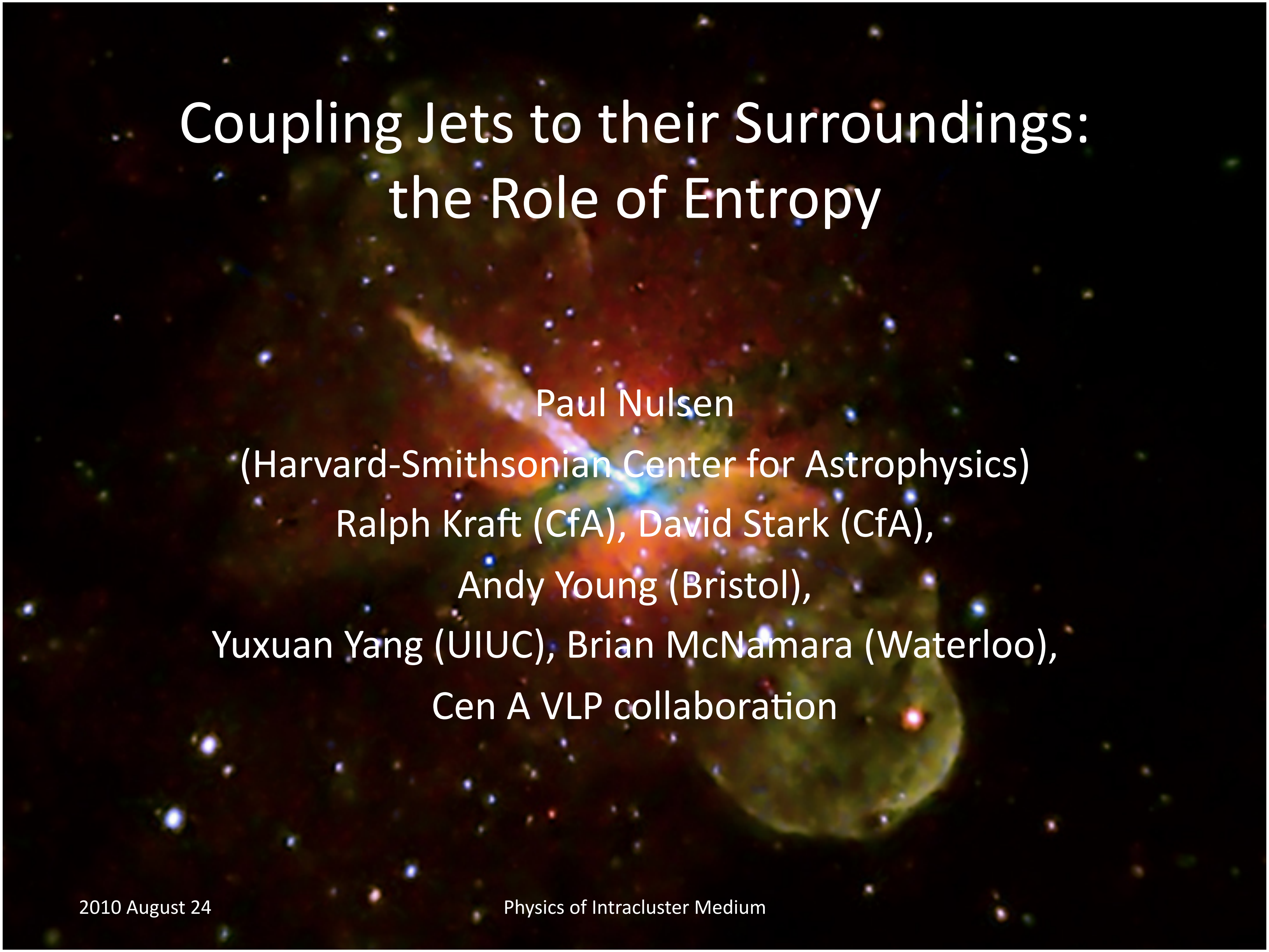

Coupling Jets to their Surroundings: the Role of Entropy

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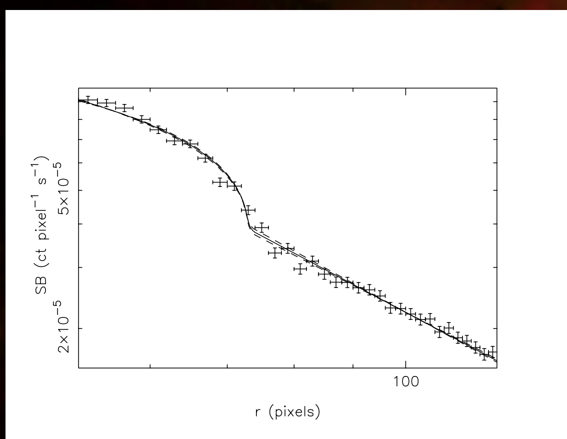
Cen A VLP collaboration

Jet of Cygnus A

Powerful, near FR II radio source (Carilli & Barthel 1994); radio luminosity ≈ 7×10^{44} erg s^{-1}; $z = 0.056$; $D_L = 250$ Mpc; scale = 1.088 kpc/arcsec

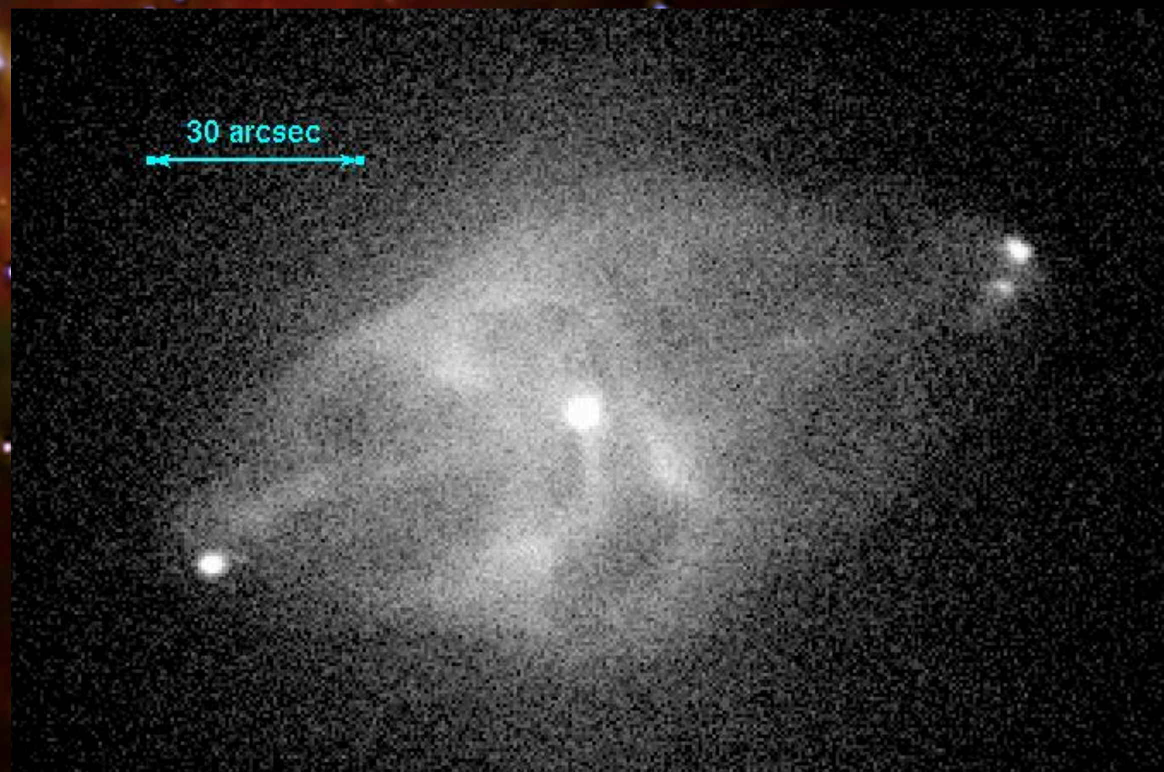
Hosted by cluster central galaxy

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

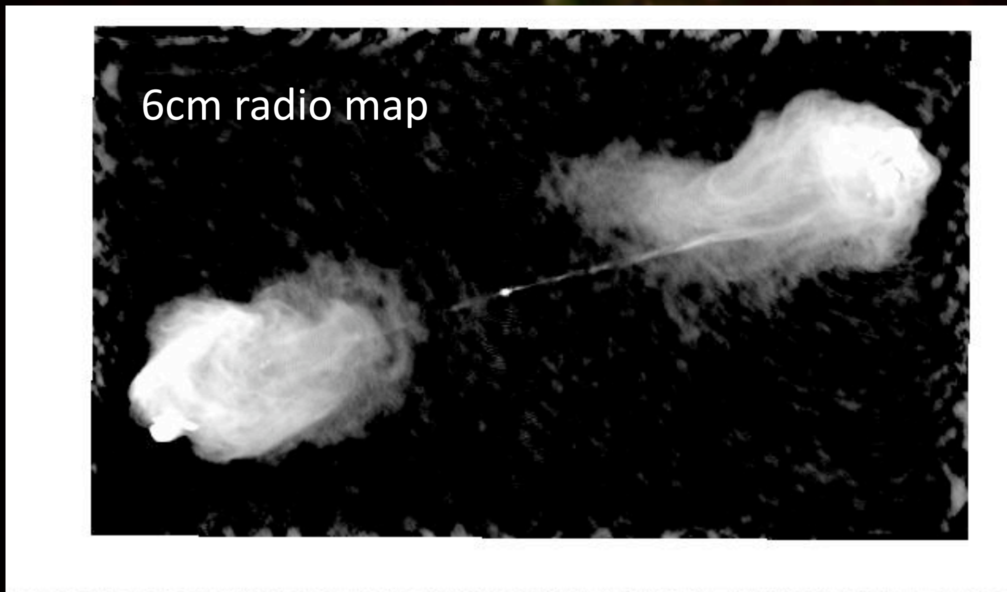


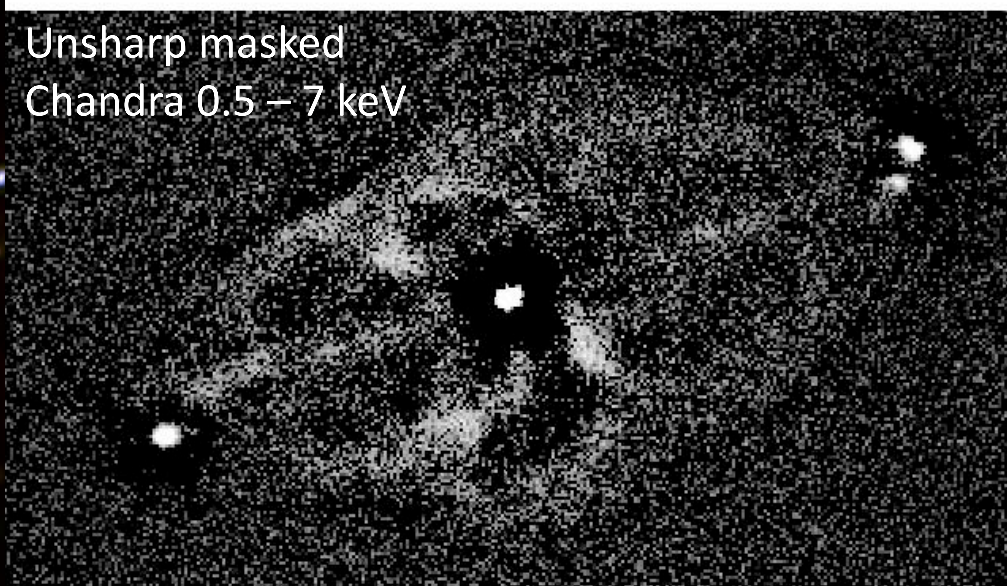
SW shock: Mach 1.37,
$r \approx 40$ kpc, age ≈ 1.6×10^{7} yr,
mean power ≈ 4×10^{45} erg s^{-1}

Chandra 0.5 – 7 keV



X-ray vs radio jet





X-ray jet is resolved by Chandra

- not coincident with radio jet (Steenbrugge & Blundell 2007)

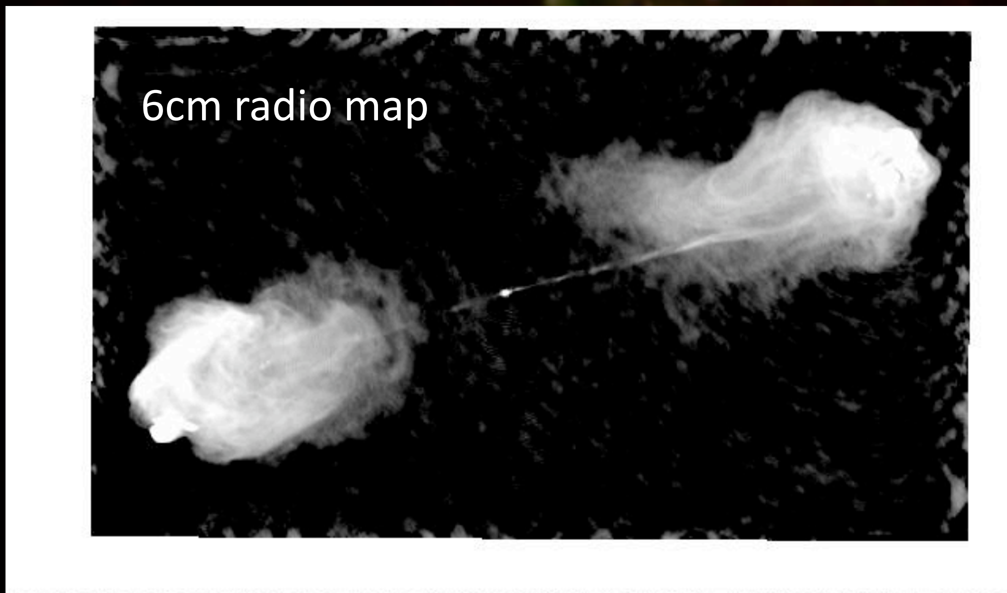
Symmetry (also: eastern jet receding) => jet X-ray emission not Doppler boosted

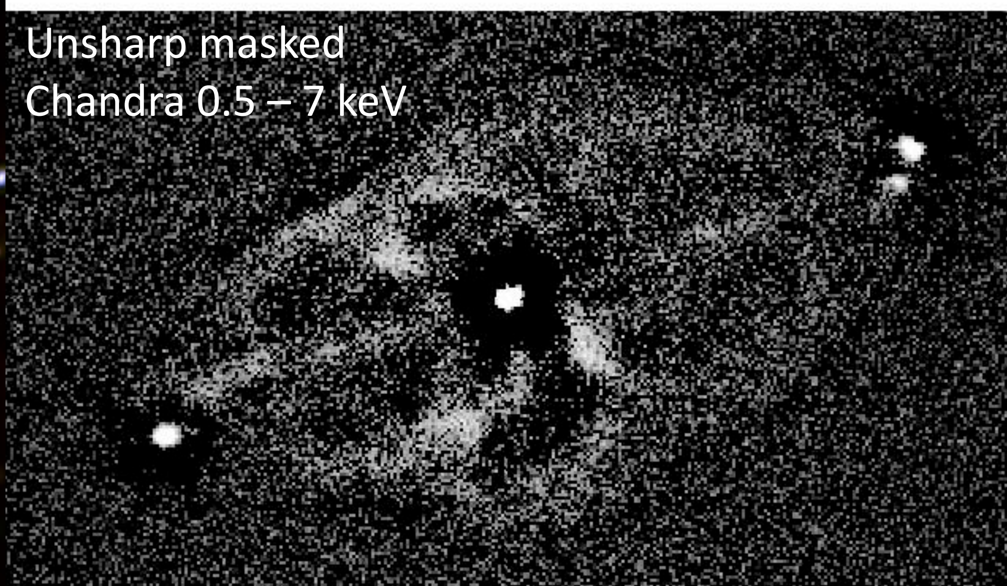
X-ray spectrum for 11”×5.7” region at eastern end => power law (photon index 1.69±0.26, 90%).

ICCMB (100 < γ < 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

X-ray vs radio jet





Pressure equipartition in eastern lobe gives B ≈ 55 μG

– 1 keV synchrotron photons radiated by electrons with γ ≈ 4×10^7

Synchrotron X-ray model requires ~10^{-5}× electrons as ICCMB model

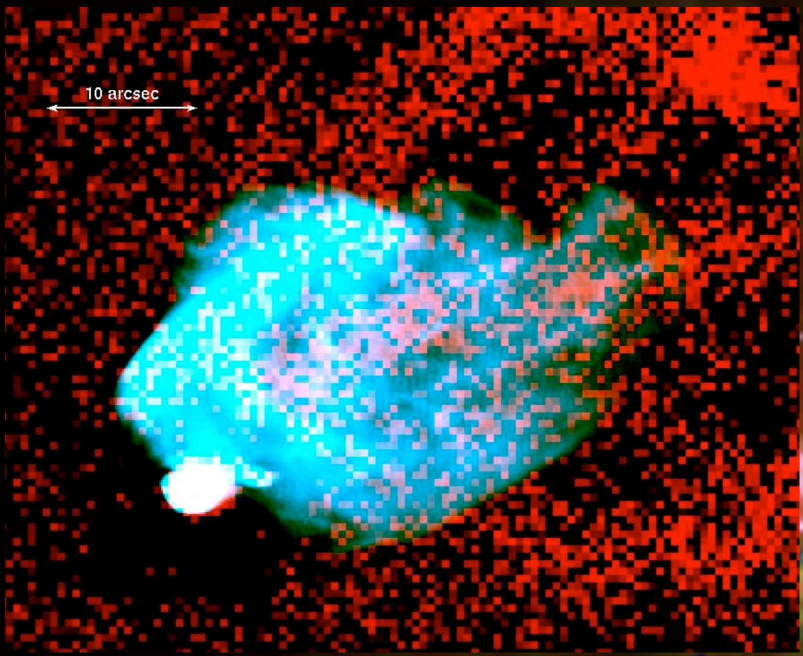
– $t_{synchrotron}$ ≈ 200 yr

– requires acceleration in situ

X-ray jet traces the path of the jet now

– radio does not

X-ray vs radio jet

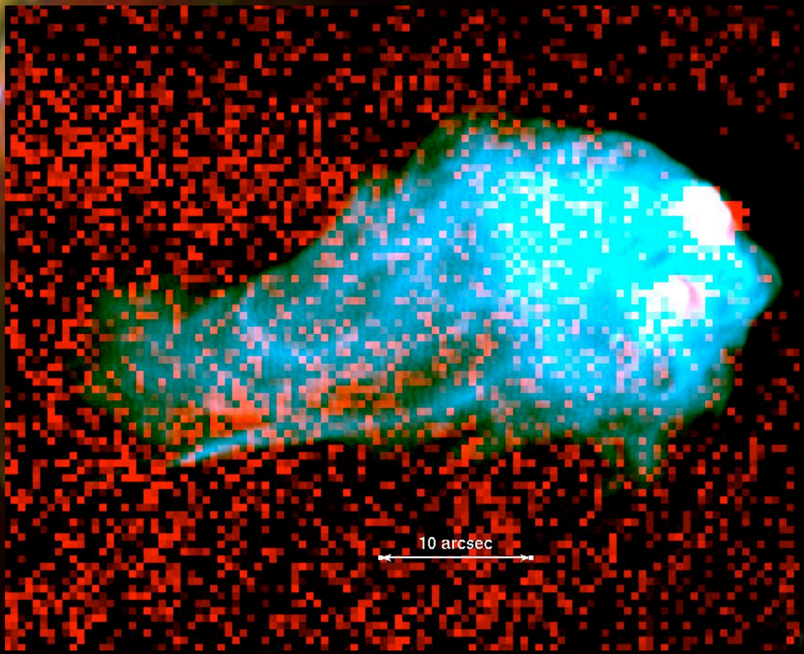


Unsharp masked 0.7 – 7 keV Chandra image (red)

Radio 6 cm (cyan)

Excess hotspot pressure due to jet ram pressure

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



$p_{hotspot}/p_{jet} \approx (B_{hotspot}/B_{jet})^2 \approx 10 - 20$

Jet radius in eastern lobe ≈ 3 kpc

Jet Flow Model (Laing & Bridle 2002)

Proper density of jet rest mass, ρ, rate of mass flow through jet: $\dot{M} = \gamma\beta c A\rho$

Power through jet (h = enthalpy per unit volume,
h = p + e = Γp/(Γ-1), for pressure p): $P = (\gamma - 1)\,\dot{M}\,c^2 + hAc\beta\gamma^2$

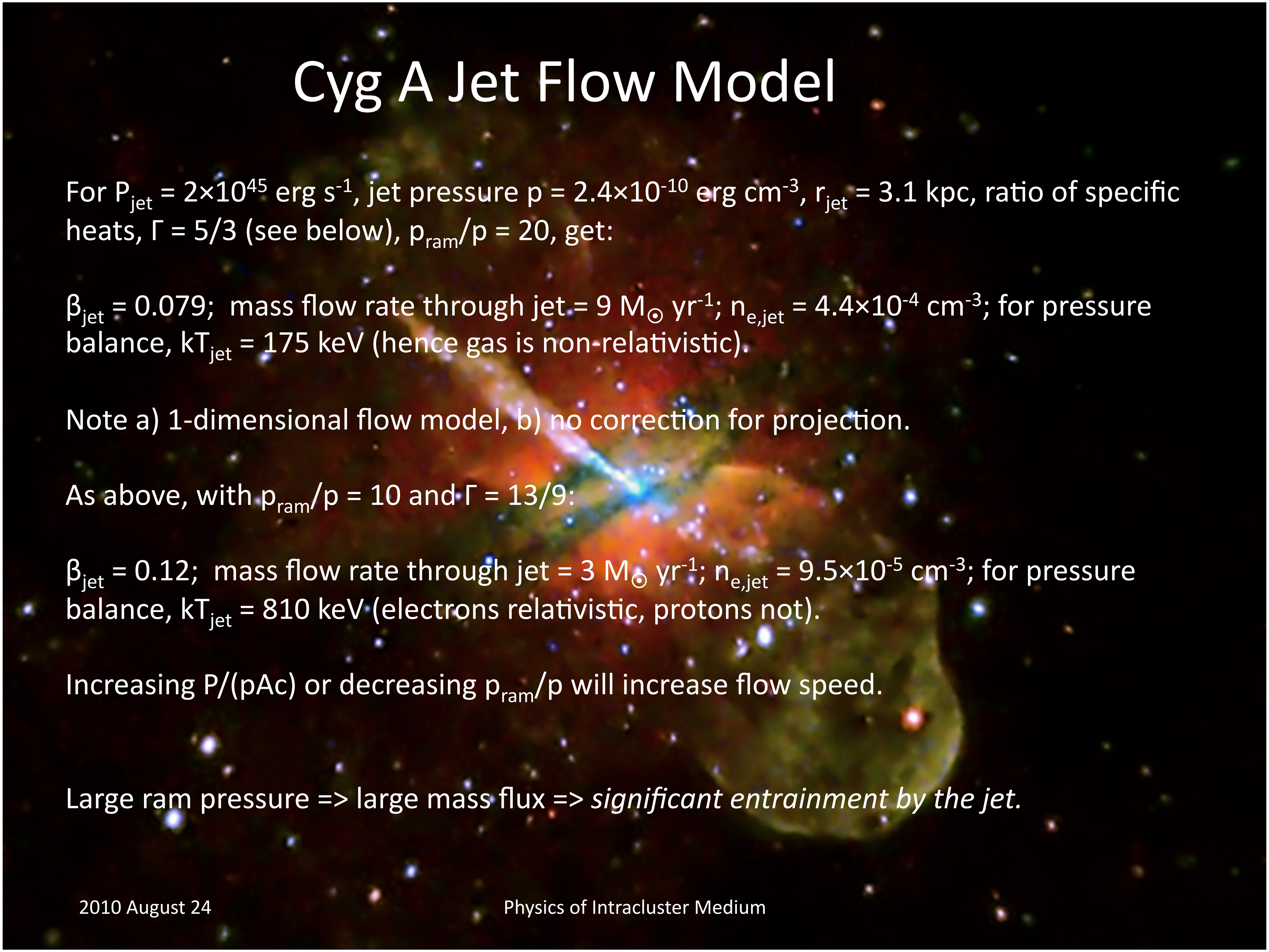
Momentum flux: $\Pi = (P/c + \dot{M}\,c)\beta$

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

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

Power + momentum equations give: $$\frac{P}{pAc} = \left(\frac{p_{\rm ram}/p}{\gamma+1} + \frac{\Gamma}{\Gamma-1}\right)\beta\gamma$$

– solve for jet speed, mass flow rate, etc



Cyg A Jet Flow Model

For $P_{jet} = 2\times10^{45}$ erg s^{-1}, jet pressure $p = 2.4\times10^{-10}$ erg cm^{-3}, $r_{jet} = 3.1$ 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}; $n_{e,jet} = 4.4\times10^{-4}$ cm^{-3}; for pressure balance, $kT_{jet} = 175$ keV (hence gas is non-relativistic).

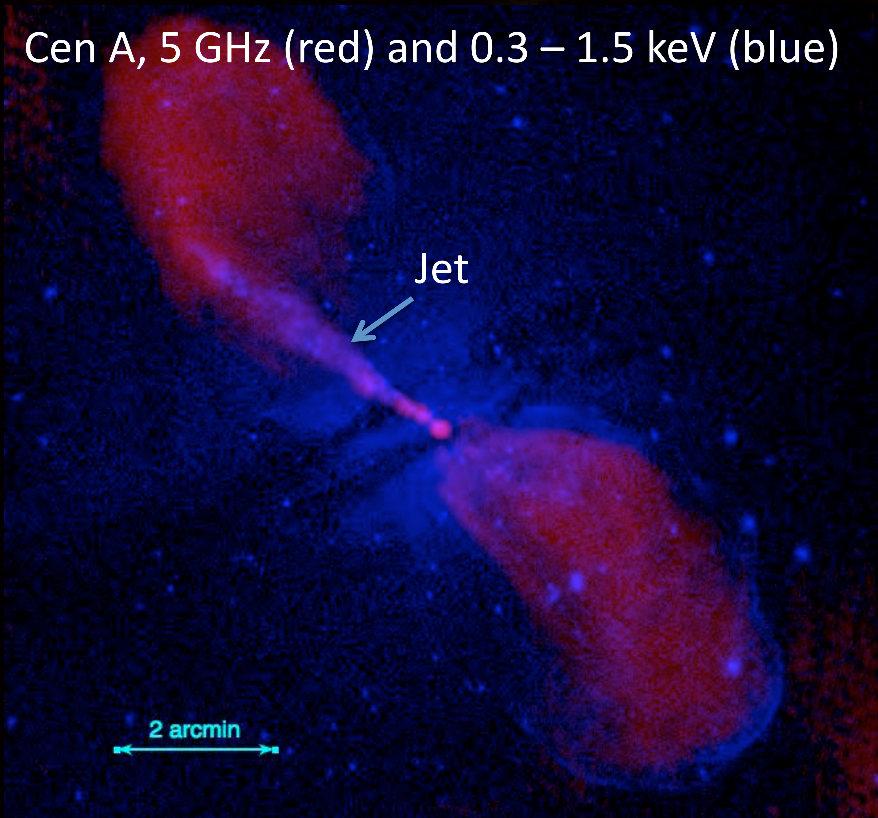
Note a) 1-dimensional flow model, b) no correction for projection.

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}; $n_{e,jet} = 9.5\times10^{-5}$ 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.*



Cen A, 5 GHz (red) and 0.3 – 1.5 keV (blue)

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 ≈ 0.55 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, α, per unit volume:

$$\dot{M}\Big|_1^2 = \int_1^2 \alpha A dR$$

Assume constant power along jet: $P = (\gamma - 1)\dot{M}c^2 + hAc\beta\gamma^2$
(enthalpy h = Γp/(Γ-1), with Γ = 13/9 here).

Momentum flux $\Pi = (P/c + \dot{M}c)\beta$ is affected by buoyancy $\Pi\Big|_1^2 = \int_1^2 \frac{dp}{dR} AdR$

Flow Parameters

Fiducial values: Jet power, $P = 6\times10^{42}$ erg s^{-1} (Croston et al 2009).

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

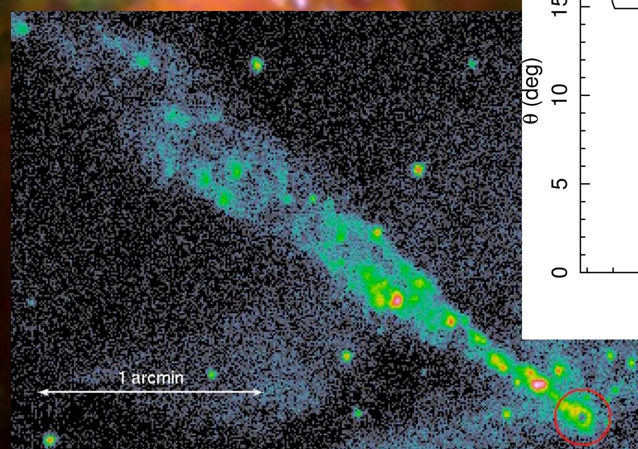
Stellar mass loss: star density = f × gravitating mass density (hydrostatic equilibrium), with f ≈ 1 at R = 100 arcsec (1.8 kpc; consistent with photometry) and $\alpha = f\,\rho_{grav} / \tau$, with $\tau = 10^{12}$ yr (Faber & Gallagher 1976).

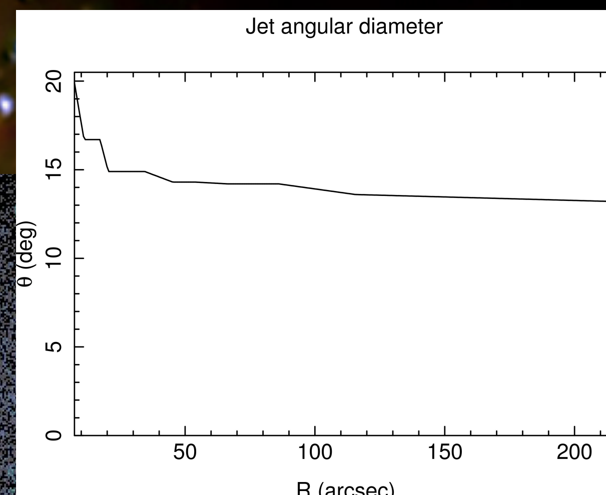
Other entrainment – let f vary.

Radio and X-ray measurements of jet width agree.

No dissipation (constant $\dot{M}$)
P eqn: speed must decrease
Π eqn: speed must increase

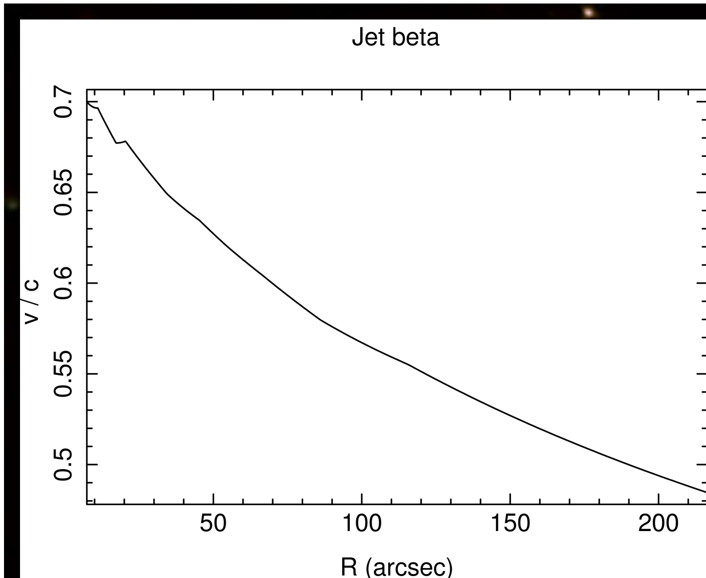
=> ***Flow is dissipative***





Flow is over-determined: adjust f to make 3 equations consistent.

Fiducial Model

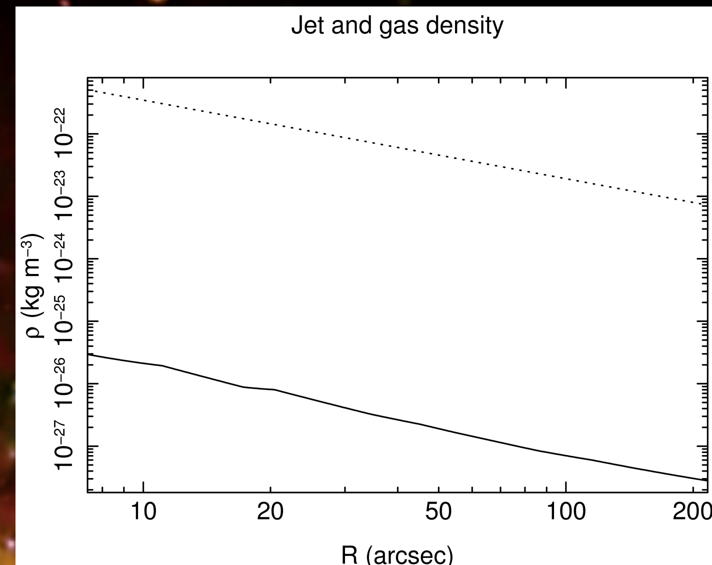


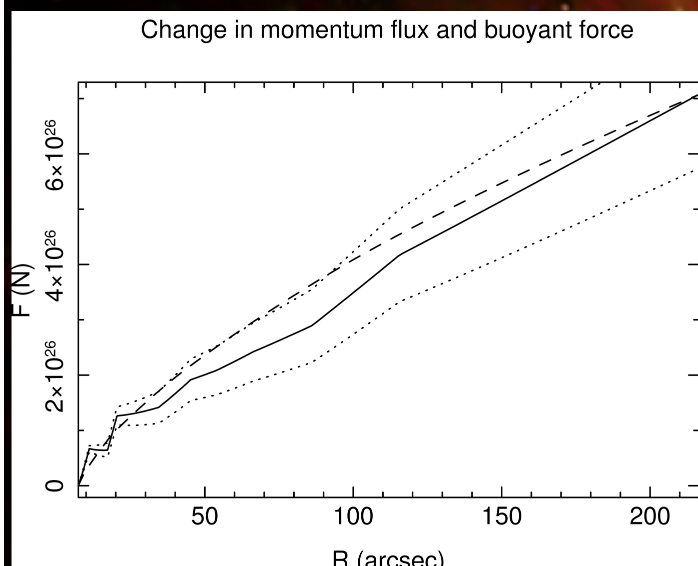
Solution determined by 2 equations, energy & mass flow.

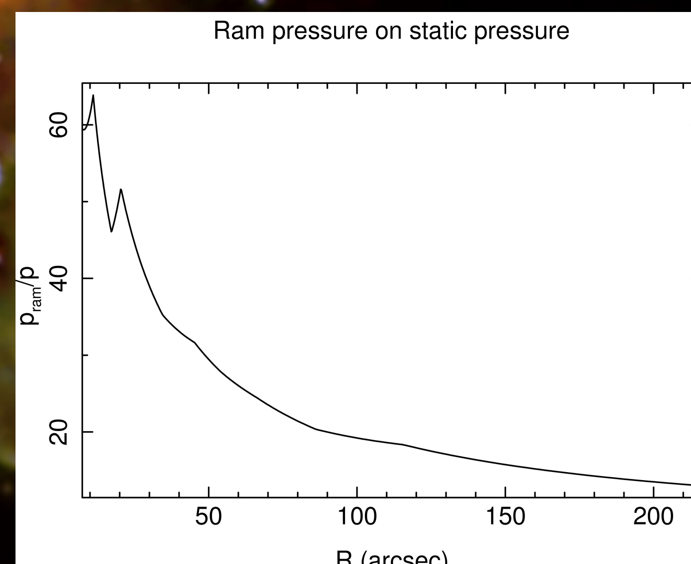
Choose f to make $\Delta\Pi$ = buoyant force

$\Longrightarrow f = 0.60$

Insensitive to flow parameters





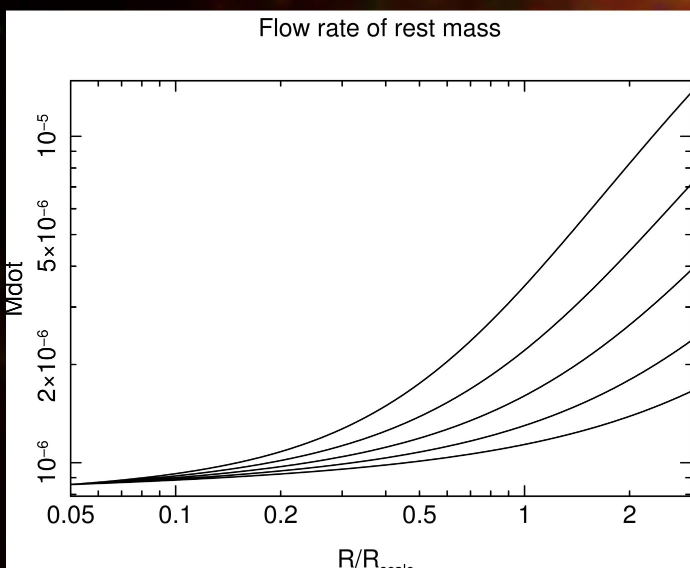


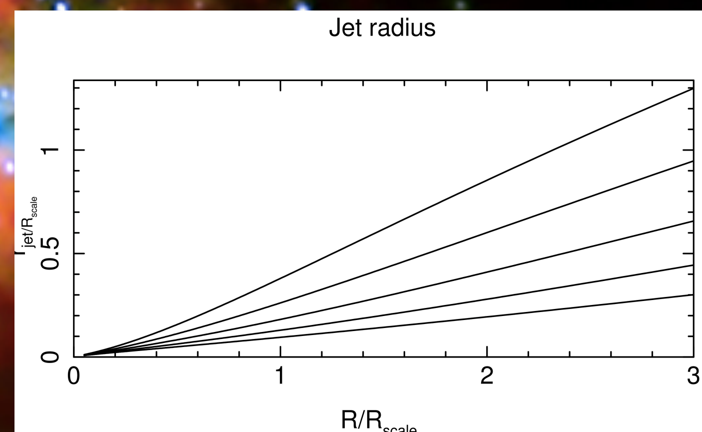
Effect of Environment

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

Model: $\frac{d\dot{M}}{dR} = \alpha A;\ \frac{d\Pi}{dR} = -A\frac{dp}{dR};\ P = \text{ constant}$

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





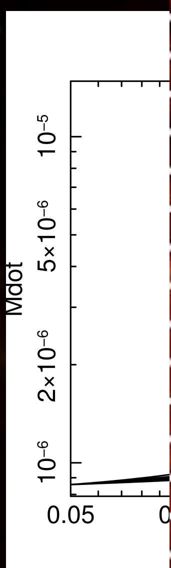
Moderate asymmetry in environment can make the difference between a jet and a lobe.

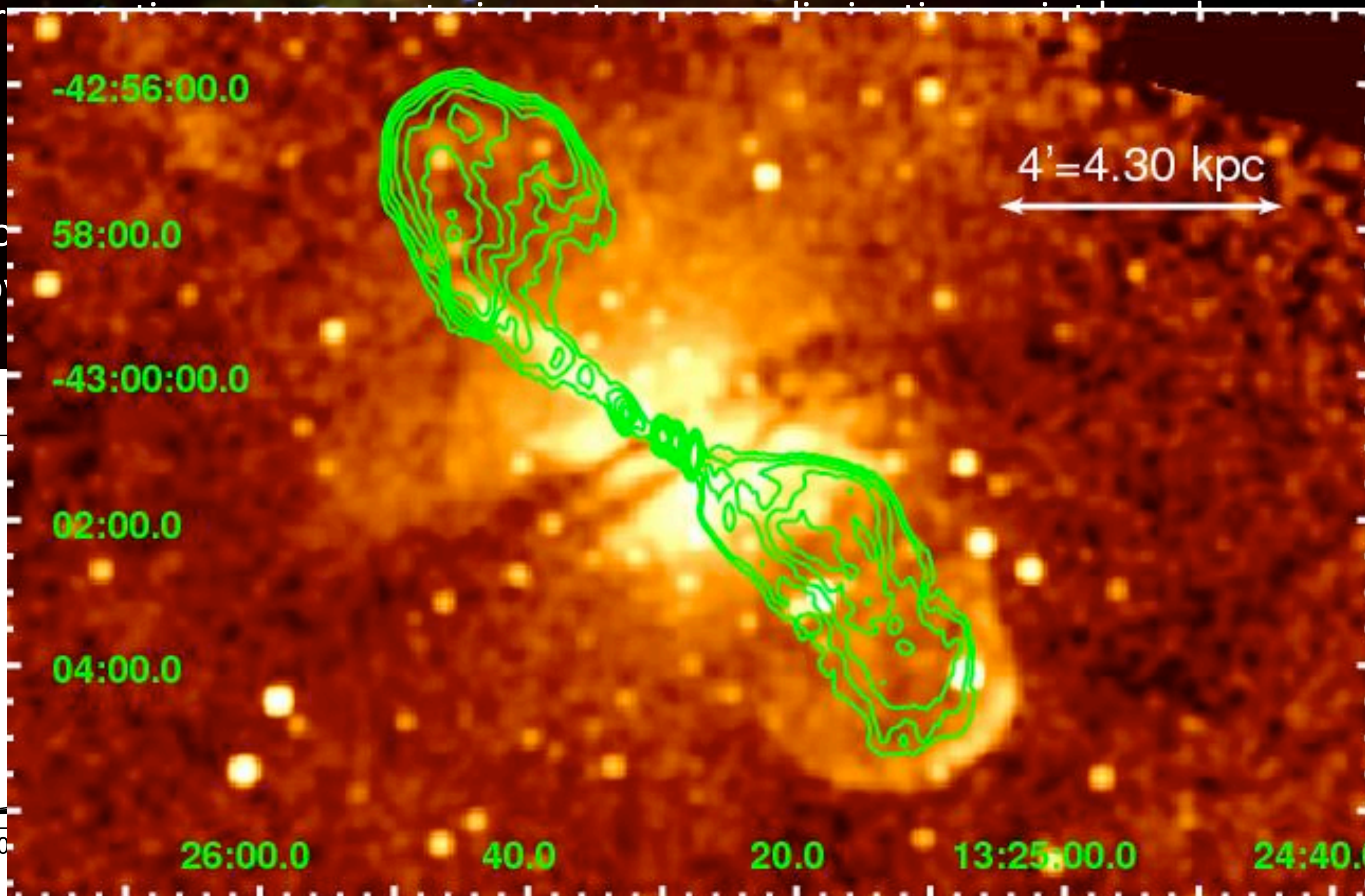
Effect of Environment

Dissipation due mass entrainment makes a jet unstable:
larger cr

Model:

Same pc ... re is
scaled by





ake 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