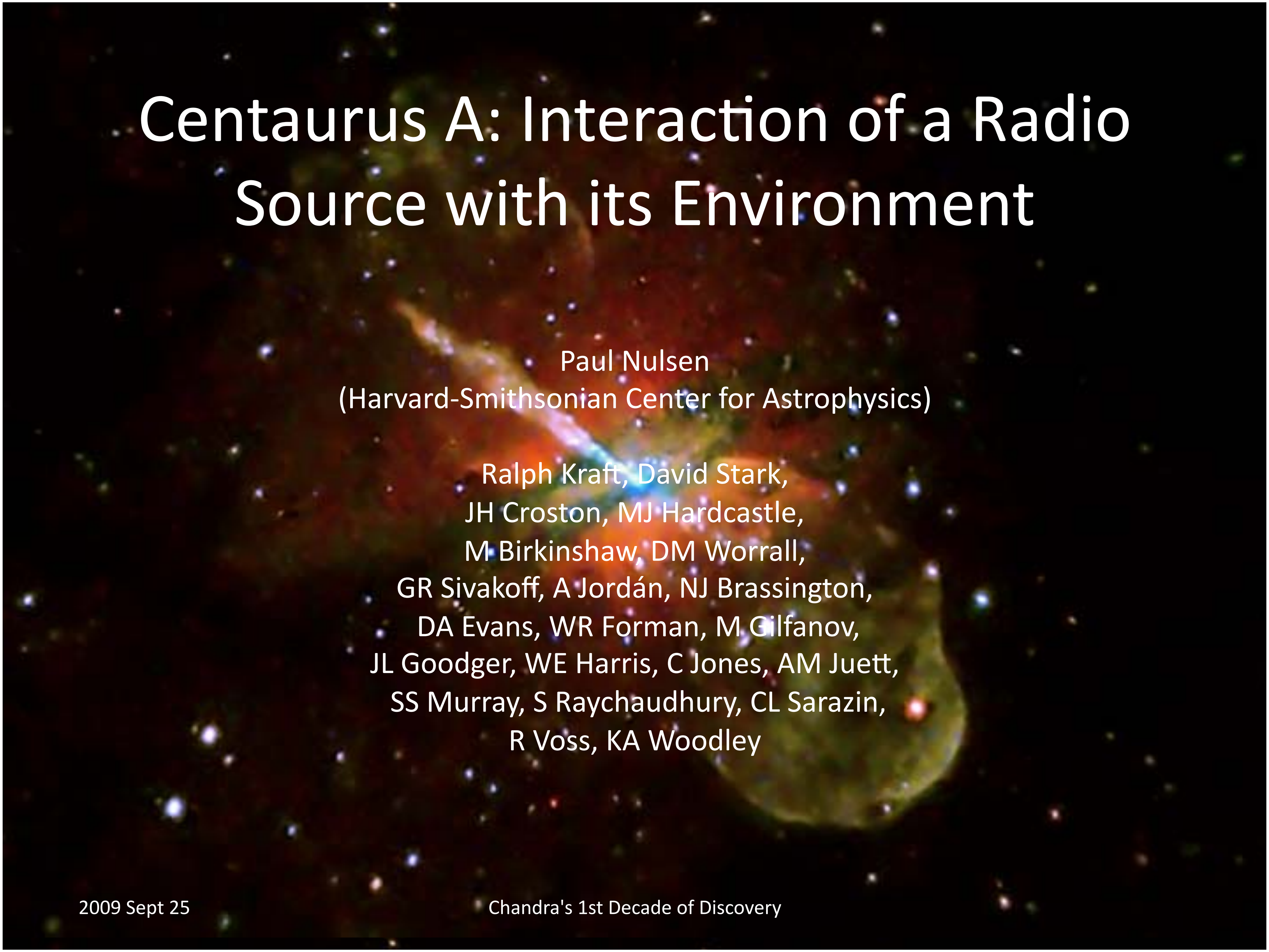

# Centaurus A: Interaction of a Radio Source with its Environment

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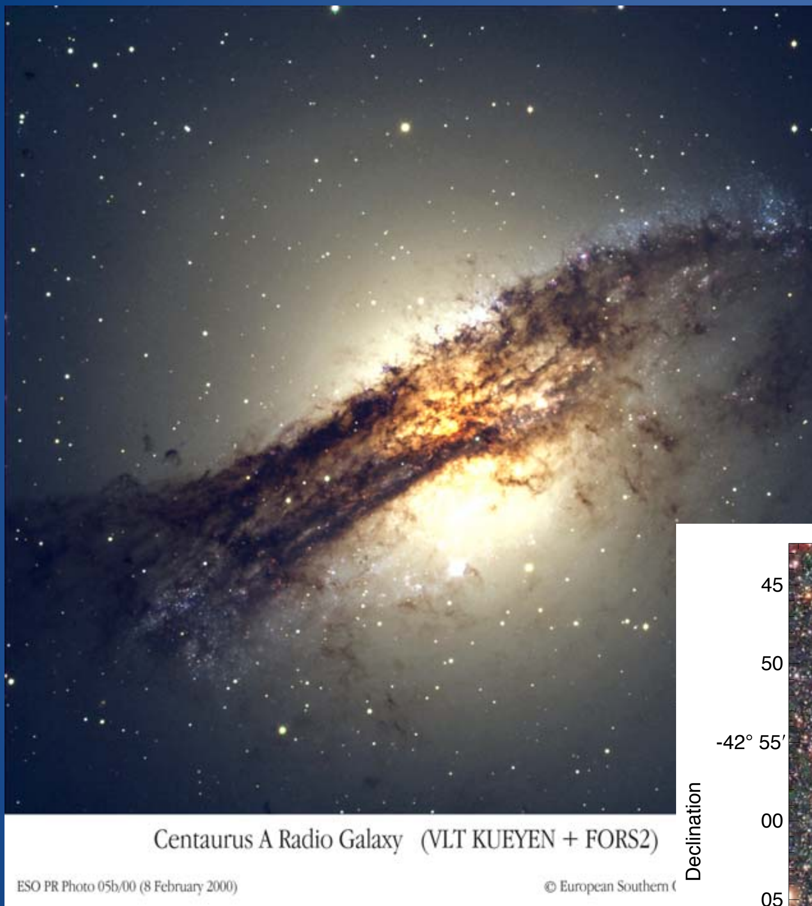
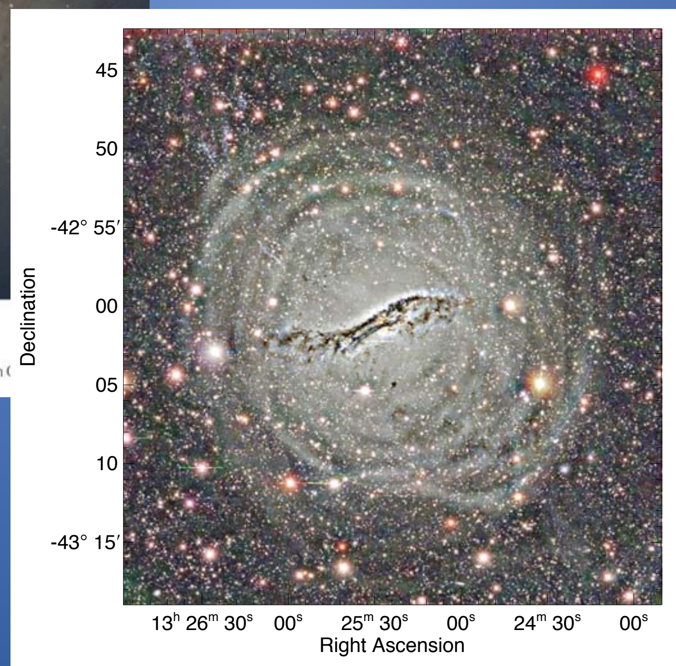
M Birkinshaw, DM Worrall,
GR Sivakoff, A Jordán, NJ Brassington,
DA Evans, WR Forman, M Gilfanov,
JL Goodger, WE Harris, C Jones, AM Juett,
SS Murray, S Raychaudhury, CL Sarazin,
R Voss, KA Woodley

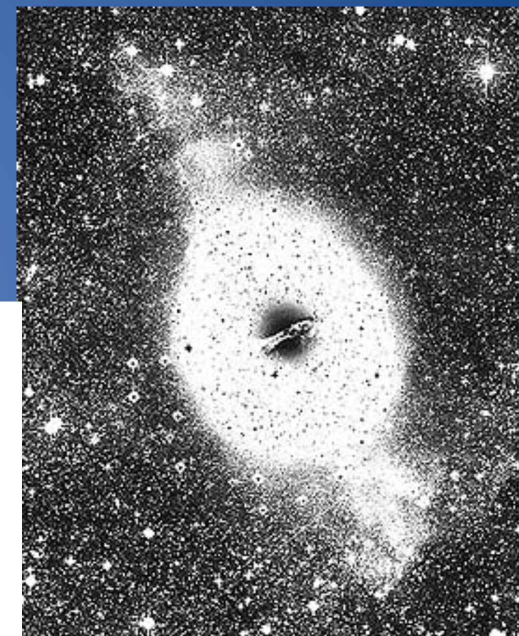
# Centaurus A




Near – distance ≈ 3.7 Mpc (average of 5 values discussed in Ferrarese et al. 2007).

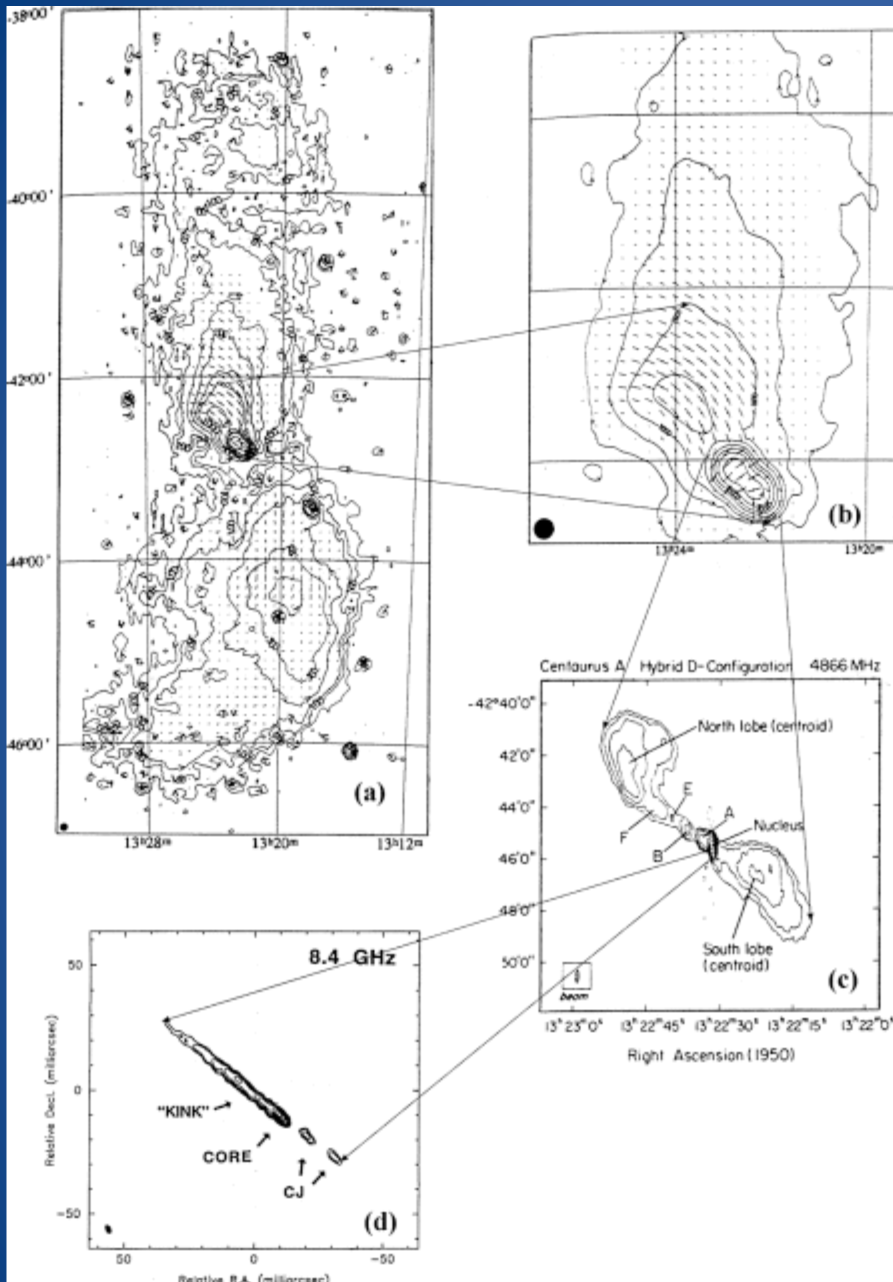
Elliptical galaxy with clear signs of a merger - dust lanes and shells



Review by Israel (1998)

Peng et al. 2002




# Centaurus A

Nearest extragalactic radio source
- active galaxy

Morganti et al. (1999)

# Chandra Image of Centaurus A

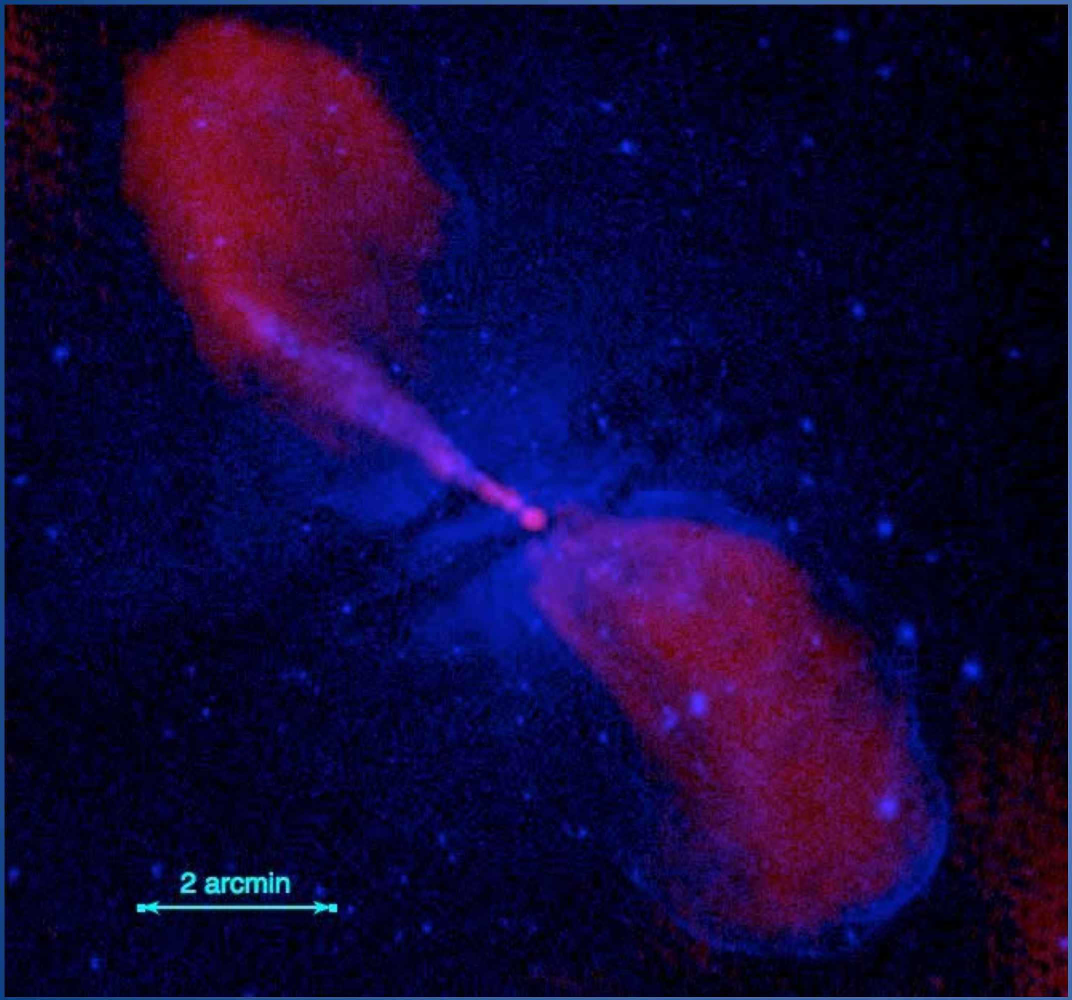
Dust lane

Hot gas

Southwest radio lobe, surrounded by shock – to ~5.5 arcmin (6 kpc)

Jet to northeast

# Southwest Radio Lobe

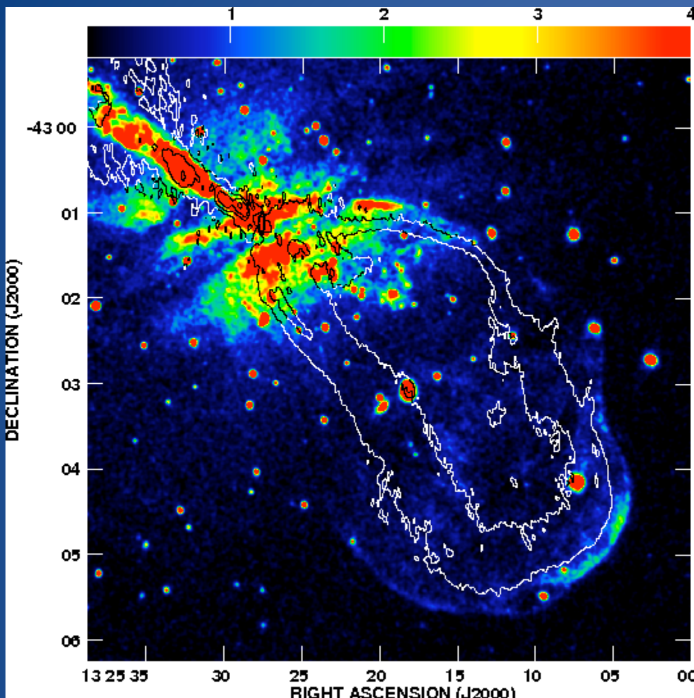



0.3 – 1.5 keV X-ray emission in blue and 5 GHz radio emission in red.

Lobe emission was originally interpreted as shocked ISM (Kraft et al 2003; 2007)

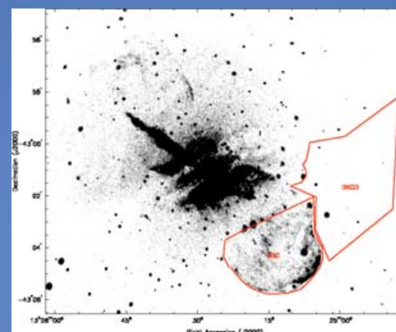
Apparent density jump exceeded 4, maximum compression for hydrodynamic shock with ratio of specific heats $\Gamma = 5/3$.

# Synchrotron Shock Model

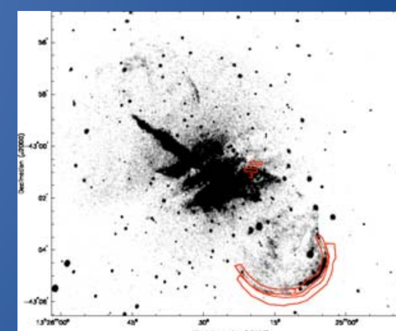



Croston et al (2009):

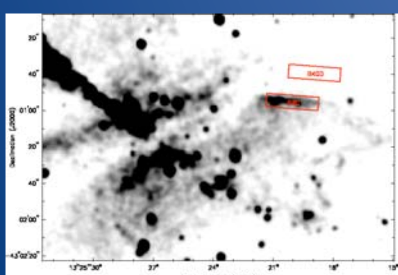
X-ray spectral fits to regions around the SW lobe strongly prefer power-law to thermal models.



Power law fit: $\chi^2$ = 931/744 dof vs worse than 1010/743 for thermal models (adding thermal component gave insignificant improvement). No line emission.



Power law fit: $\chi^2$ = 333/309 dof vs worse than 344/308 for thermal models

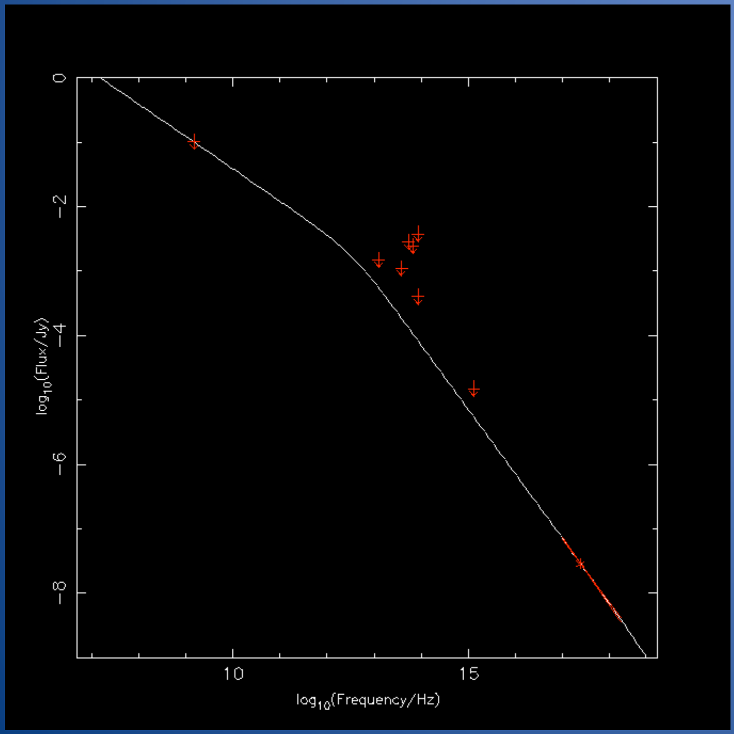


Thermal model is preferred for region closer to the nucleus: $\chi^2$ = 137/97, kT ≈ 1 keV, vs 445/98 for power law model. Emission lines prominent.

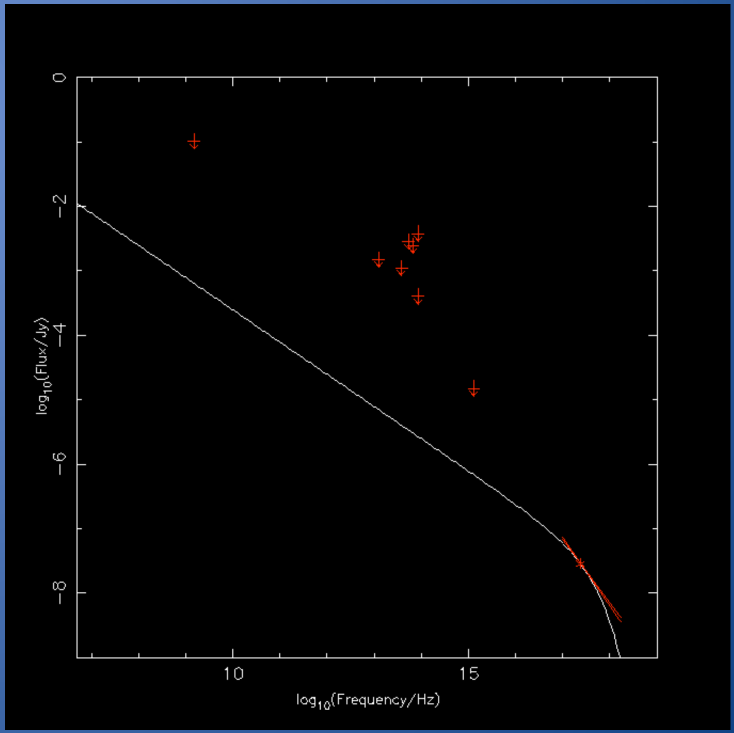
# Synchrotron Shock Model

Expect synchrotron emission across a wide range of frequencies. Reasonable models for the electron energy distribution can produce the X-ray emission without exceeding upper limits at other wavelengths. (IC models inconsistent with lack of radio emission.)

$\alpha = 0.5$ ($p = 2$), $\gamma_{min} = 10$,
$\gamma_{break} = 4.4\times10^4$, $\gamma_{max} = 5\times10^9$.



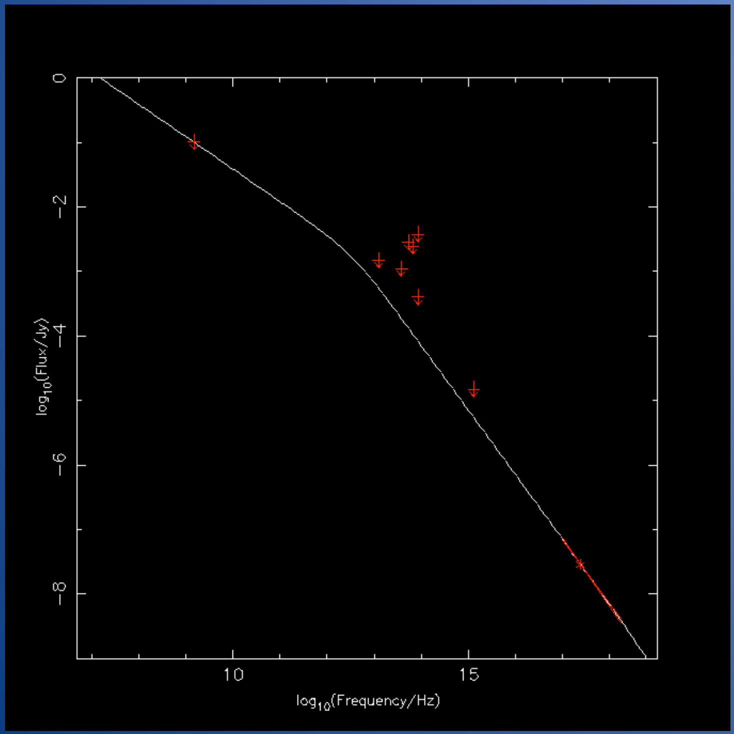

$\alpha = 0.5$ ($p = 2$), $\gamma_{min} = 10$,
no break, $\gamma_{max} = 3\times10^8$.



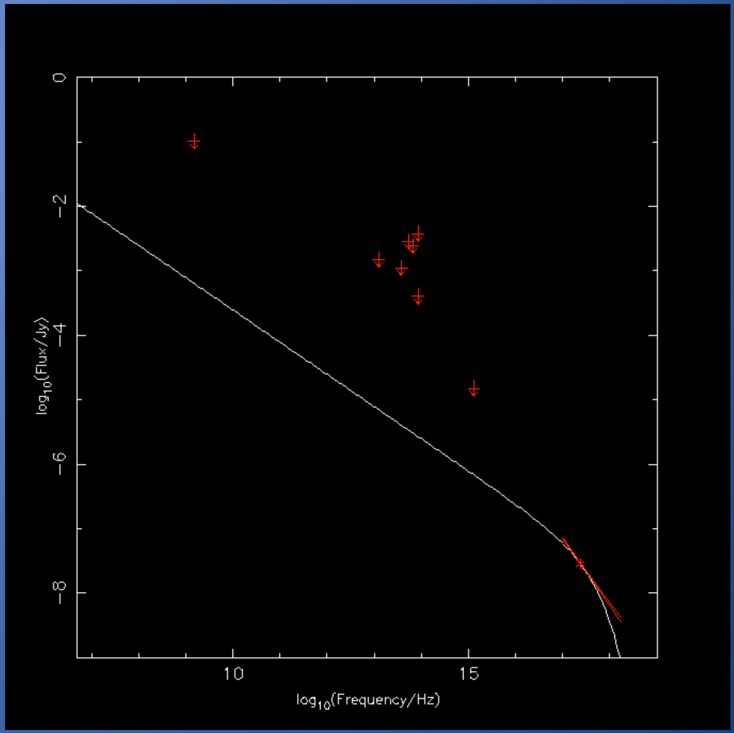
# Synchrotron Shock Model

Models for diffusive shock acceleration, where $\gamma_{max}$ is determined by competition between acceleration timescale and radiative losses (eg Reynolds 1996), imply $\gamma_{max} \sim 10^8$ at the tip of SW lobe (where the shock is strongest). Variation of shock speed may then account for the lack of non-thermal X-ray emission from the shock nearer the AGN.

(Upper limit) $\alpha = 0.5$ ($p = 2$), $\gamma_{min} = 10$, $\gamma_{break} = 4.4\times10^4$, $\gamma_{max} = 5\times10^9$.




$\alpha = 0.5$ ($p = 2$), $\gamma_{min} = 10$, no break, $\gamma_{max} = 3\times10^8$.



# Jet Power

Behind the thermal shock in north:

Proton density $n_p$ = 0.033 $cm^{-3}$ and kT = 0.95 keV => pressure = $1.1\times10^{-10}$ cgs.

High sound speed =>pressure nearly uniform in lobe, so same pressure drives SW shock .

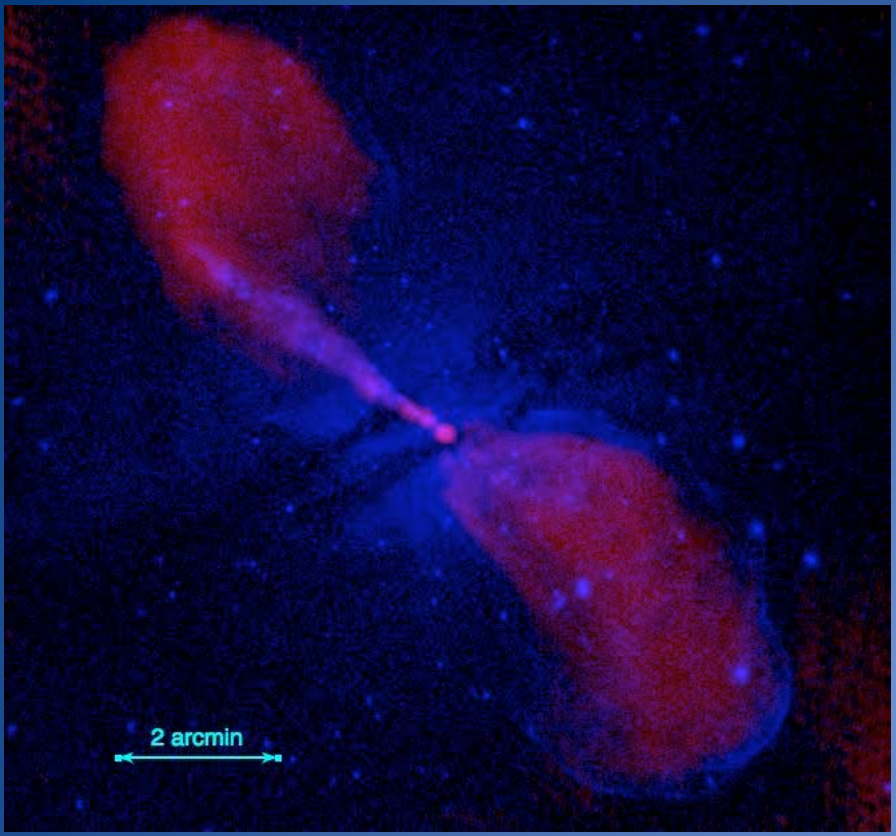
Outside shock, $n_e \approx 0.001$ $cm^{-3}$, kT = 0.35 keV (Kraft et al 2003), so pressure jump at shock ≈ 87 => shock Mach number of ≈ 8.4, or $v_{shock} \approx 2600$ km $s^{-1}$.

Thermal emission from the shocked gas is negligible compared to the non-thermal emission observed.

Integrating over energy distribution of non-thermal electrons and including equipartition magnetic field (no protons) gives their contribution to the pressure as no more than ≈ $2\times10^{-12}$ cgs – negligible compared to the thermal pressure.

Shock age, $2a/v_{shock} \approx 2\times10^6$ y => average power ≈ 4pV/age ≈ $10^{43}$ erg $s^{-1}$.

"Instantaneous" power, $P = p\, dV/dt = pV(1/a\, da/dt + 2/b\, db/dt) = 3pV\, 1/a\, da/dt$
$= 4\pi p b^2\, da/dt = 2\pi p b^2 v_{shock} \approx 6.6\times10^{42}$ erg $s^{-1}$.




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

# NE Jet Flow Model

Like Laing & Bridle (2002):

Gas temperature (kT ≈ 0.55 keV), density profile ($n_e \sim r^{-1.26}$), pressure from Chandra data . **Equate to internal pressure.

Steady, near 1-d flow. Area of cross, A, varies with radius, R.

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

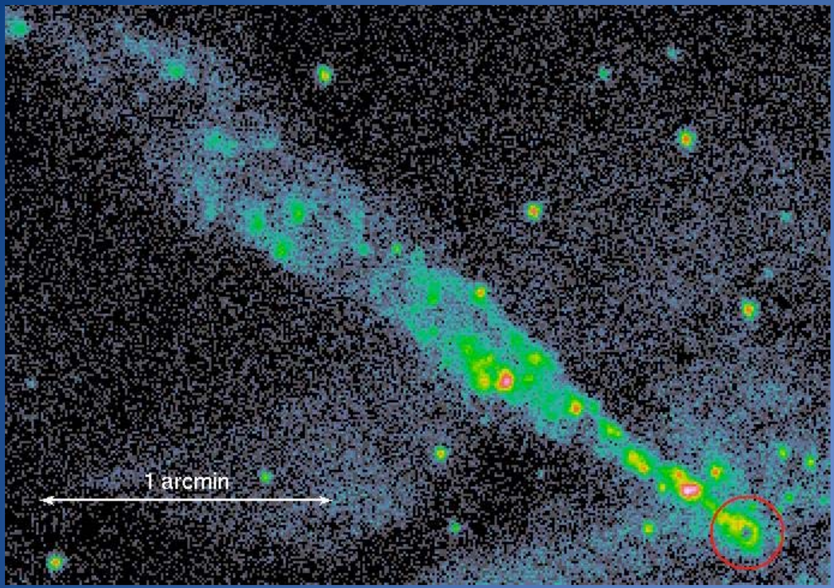
Allowing for entrainment α is rate of mass injection $\dot{M}\Big|_1^2 = \int_1^2 \alpha A dR$

Power through jet assumed constant: $P = (\gamma - 1)\dot{M}c^2 + hAc\beta\gamma^2$

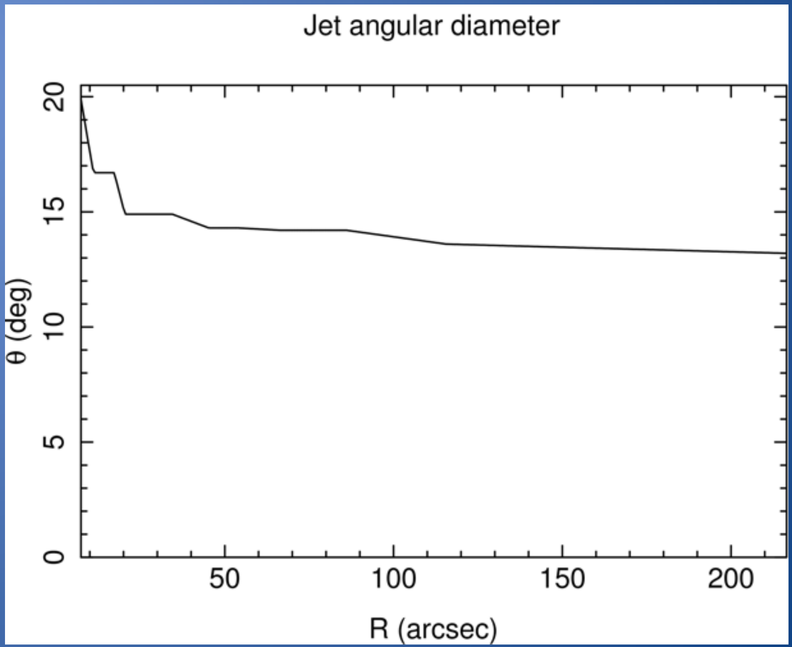
h = enthalpy per unit volume, h = p + e = Γp/(Γ-1), for pressure p. Here Γ = 13/9.

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

# Jet Width




Knots complicate measurement of jet width




Plot shows angle subtended by jet at the AGN

# Flow Parameters

Fiducial values:

Jet power, $P = 6\times10^{42}$ erg $s^{-1}$ (cf $6.6\times10^{42}$ erg $s^{-1}$ for power into SW lobe, Croston et al 2009).

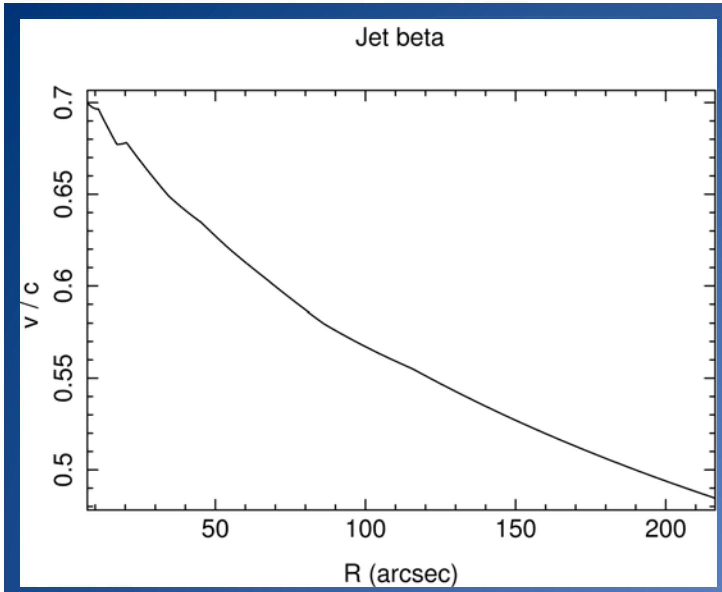
Initial speed, $\beta = 0.7$: radio knot proper motions of $\approx 0.5c$ near start of jet (Hardcastle et al 2003).

Mass injection:
Star density is expressed as a fraction, f, of gravitating mass density (determined from hydrostatic equilibrium). Expect $f \approx 1$ at $R = 100$ arcsec (1.8 kpc; also consistent with photometry). Then $\alpha = f \rho_{grav} / \tau$, with $\tau = 10^{12}$ yr (Faber & Gallagher 1976).

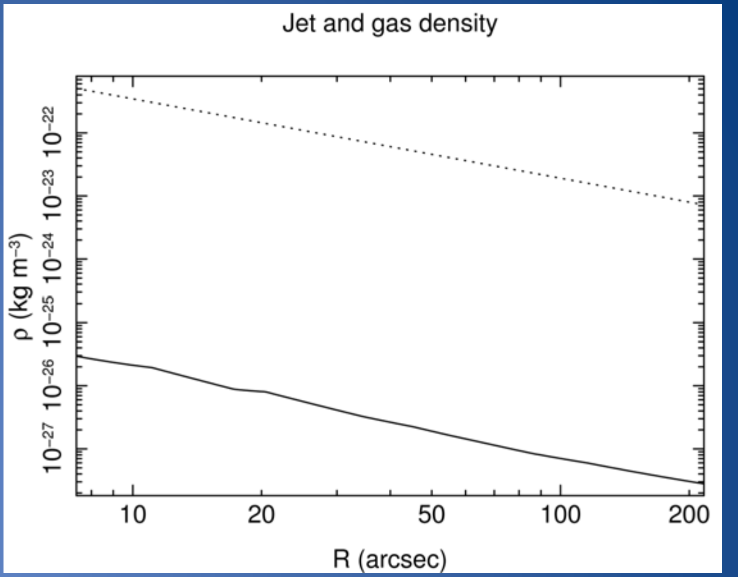
Allow for other entrainment by varying f.

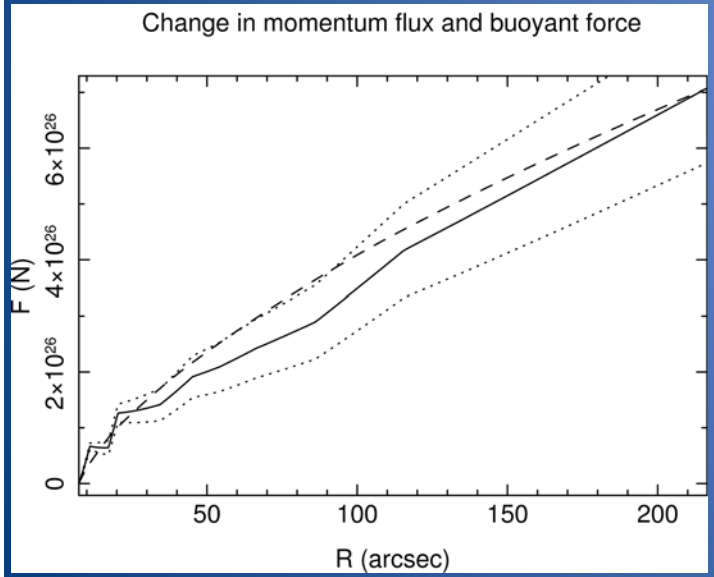
In fact, solution is over-determined, so we adjust f to make change in momentum flux match the buoyant force.

# Fiducial Model



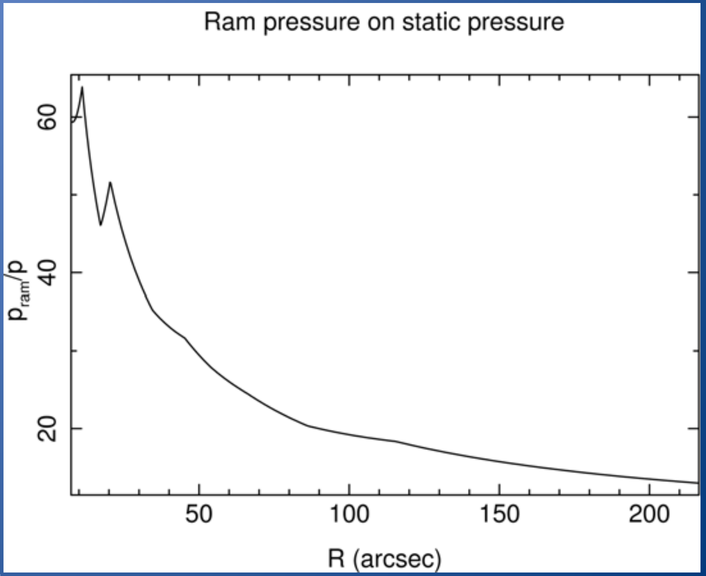

Non-dissipative flow would obey Bernoulli's theorem: pressure decrease => speed increase – inconsistent with data.



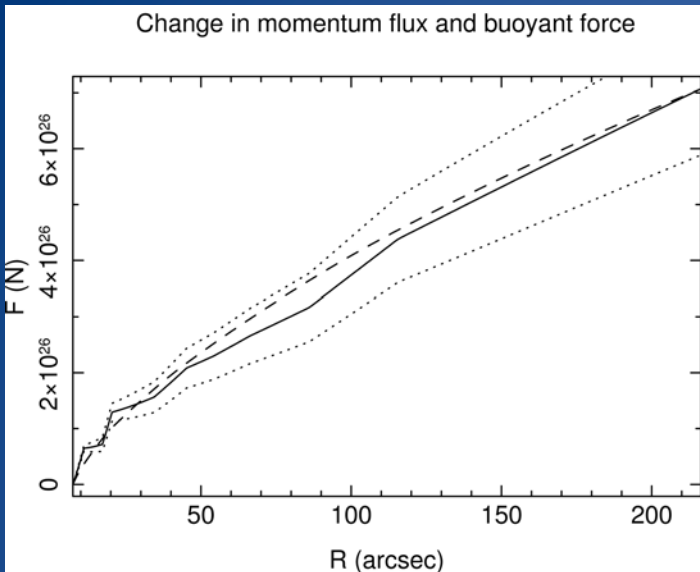



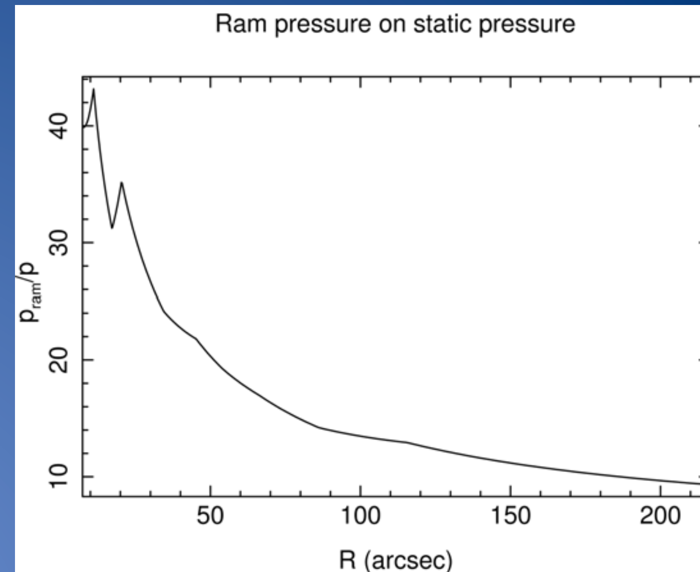

Need f = 0.60 to make ΔΠ = buoyant force -

ie, stellar mass loss within the jet can account for all dissipation.



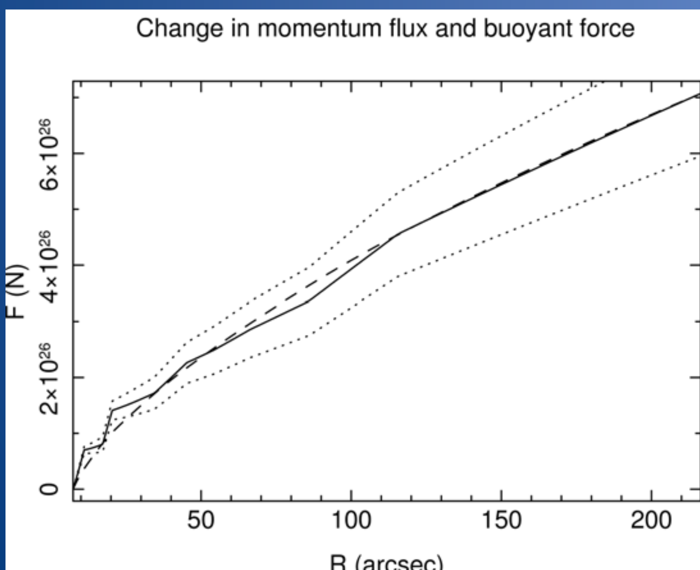
# Variations

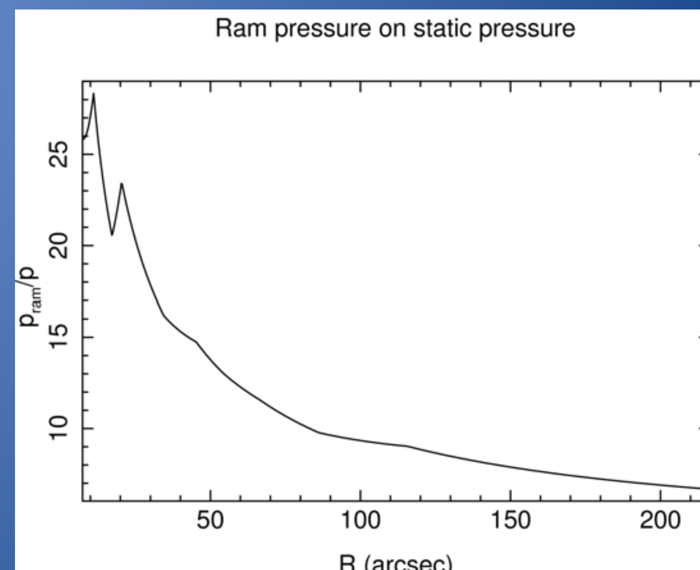



Initial β = 0.85
need f = 0.42

(for β = 0.5, f = 0.93)



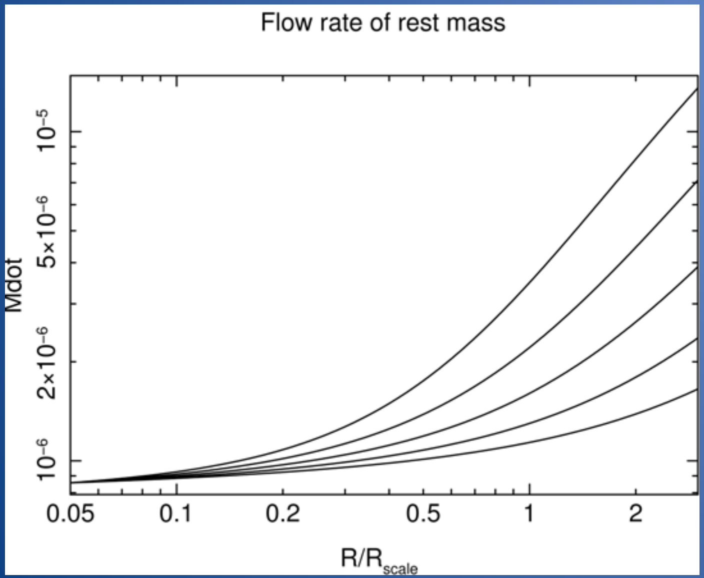

$P = 3\times10^{42}$ erg $s^{-1}$
need f = 0.61

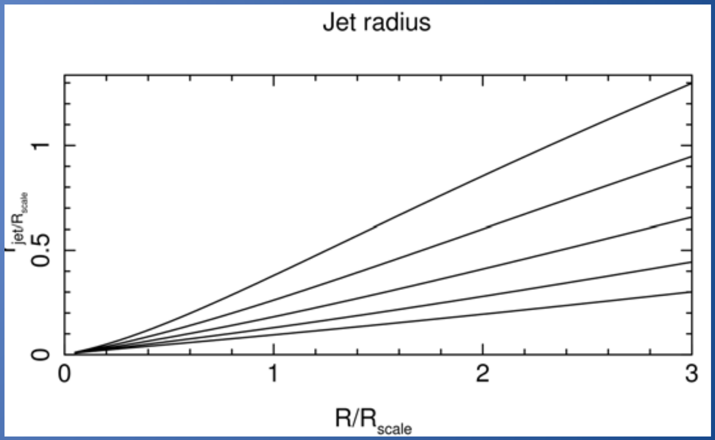
# Effect of Environment

If dissipation is governed by stellar mass injection, the jet is unstable:
larger cross section => more stars in jet, hence more dissipation => more broadening

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

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




Moderate (transient) asymmetry in environment may make the difference between a jet and a lobe.

# Effect of Environment

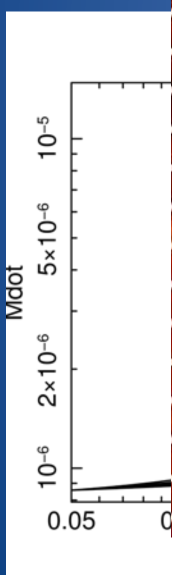
If dissipation is governed by stellar mass injection, the jet is unstable:

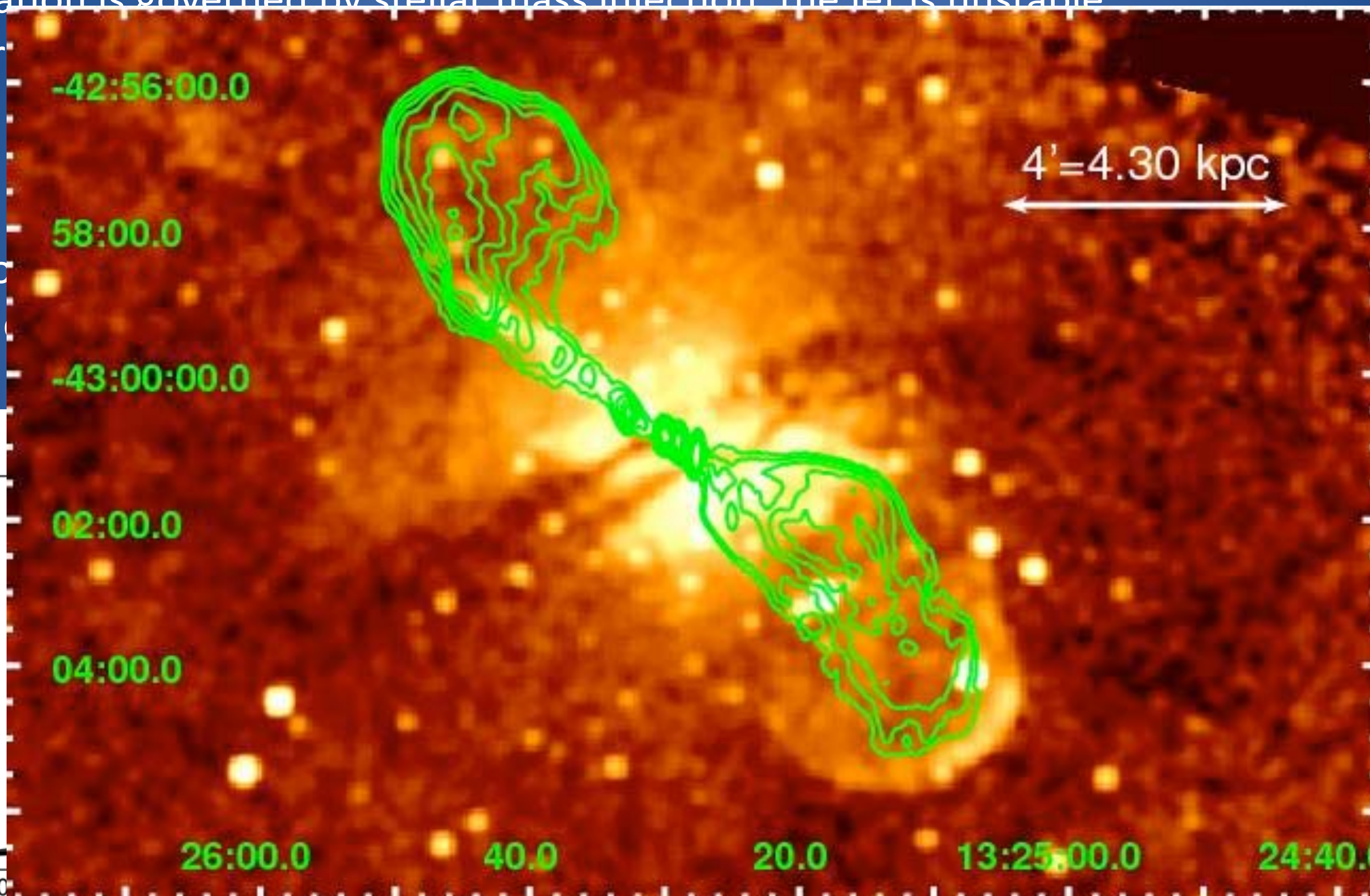
larger cr … g

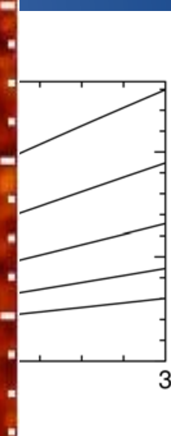
Model:

Same pc … re is

scaled d…

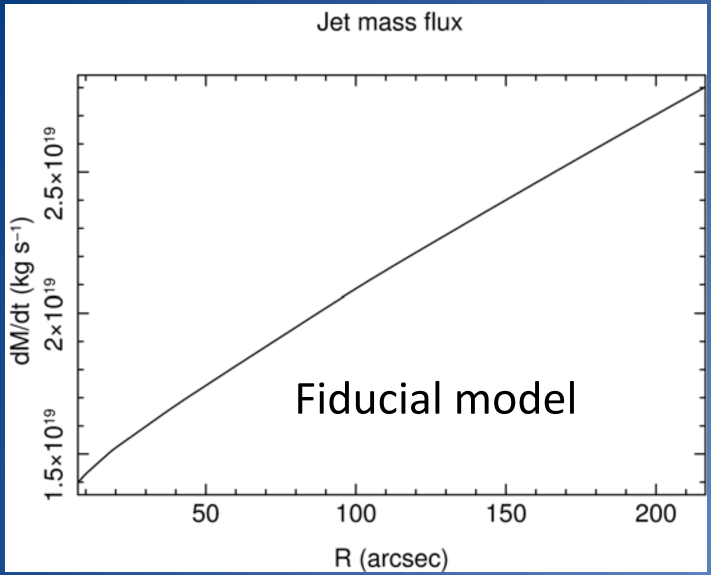


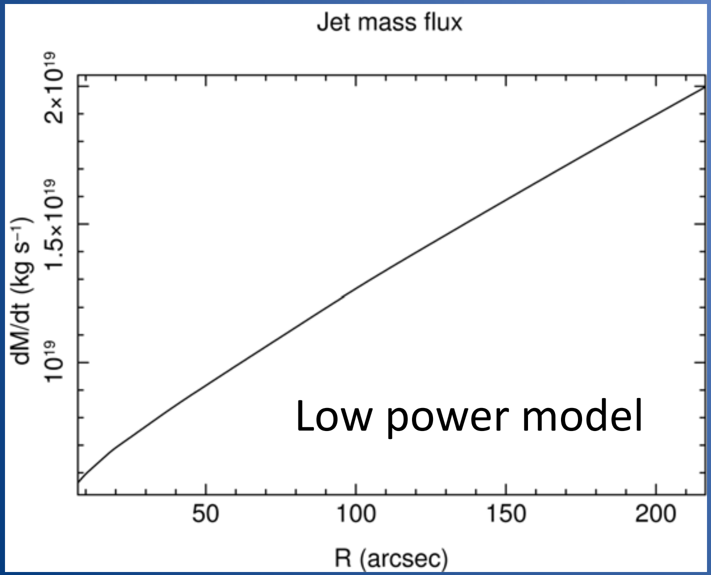




Moderate (transient) asymmetry in environment may make the difference between a jet and a lobe.

# Stellar Mass Loss




Total mass injection ≈ 2×10$^{-4}$ $M_{\odot}$ yr$^{-1}$, comparable to mass loss rate of ~100 AGB stars.

Comparable to the number of knots in the jet (eg Hardcastle et al 2007), suggesting that each knot may be caused by a single star.

Ram pressure stops wind where $p_{ram} \approx \rho_{wind}\, v_{wind}^2$, ie for a star losing 10$^{-6}$ $M_{\odot}$ yr$^{-1}$, with $v_{wind}$ = 10 km s$^{-1}$, at 20” from the AGN, only ≈ 0.009 pc from the star. (cf. ~3 pc, Tingay & Lenc 2009).

A wind of ≈ 10$^{-6}$ $M_{\odot}$ yr$^{-1}$ must intercept ≈ 1% of jet (mass flux ≈ 10$^{-4}$ $M_{\odot}$ yr$^{-1}$) to be accelerated to jet speed

⇛ long trails behind AGB stars where wind gas is accelerated and mixed with jet gas

⇛ supersonic, turbulent wake?

# Conclusions

- X-ray emission from shock surrounding SW radio lobe is predominantly synchrotron
- The shock speed ≈ 2600 km $s^{-1}$ and the jet power ≈ $6.6 \times 10^{42}$ erg $s^{-1}$
- Stellar mass loss may be the primary source of mass entrained by the Cen A jet
- Modest asymmetry in the environment can make the difference between a jet and a lobe
- Many jet knots may be due to individual AGB stars within the jet