The Interaction of Jets with the Interstellar Medium of Radio Galaxies

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Outline

- Evolution of powerful radio sources from initial stages
- Effect of inhomogeneous interstellar medium – three dimensional effects
- X-ray emission linking radio and optical structure
- Supersonic turbulent disks in radio galaxies
- Restarting jets in Mpc-scale radio galaxies

Axisymmetric simulations

$$\text{Mach Number} = 50$$

$$\eta = \frac{\text{Jet density}}{\text{ISM density}} = 10^{-3}$$

QuickTimeŞ and a
Photo - JPEG decompressor
are needed to see this picture.

Hot spot

Bow shock

Jet shocks

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Jets constrained to be straight

Slab jets in clumpy medium

(Saxton, Sutherland & GB)

QuickTime and a
Animation decompressor
are needed to see this picture.

Developments and additions

- 3D (with thermal cooling via MAPPINGS shock and photoionization code)
- Potential of luminous and dark matter
- Hot isothermal ISM consistent with potential
- Clumpy ISM described by log-normal + power-law energy spectrum
- In some cases the warm ISM is distributed in a turbulent equilibrium disk
- In other cases an adhoc distribution of warm clumpy matter is used for the initial data

Turbulent disk

Near Keplerian, isothermal disk:

Mean temperature

Turbulent velocity dispersion

$$\sigma_g^2 = k\tilde{T}/\mu m_p + \sigma_t^2 = \text{constant}$$

$$\tilde{v}_\phi(r) = e_{\mathrm{K}} \left[r \frac{\partial \phi}{\partial r} \right]^{1/2} \qquad e_{\mathrm{K}} = \text{constant} < 1$$

Density distribution:

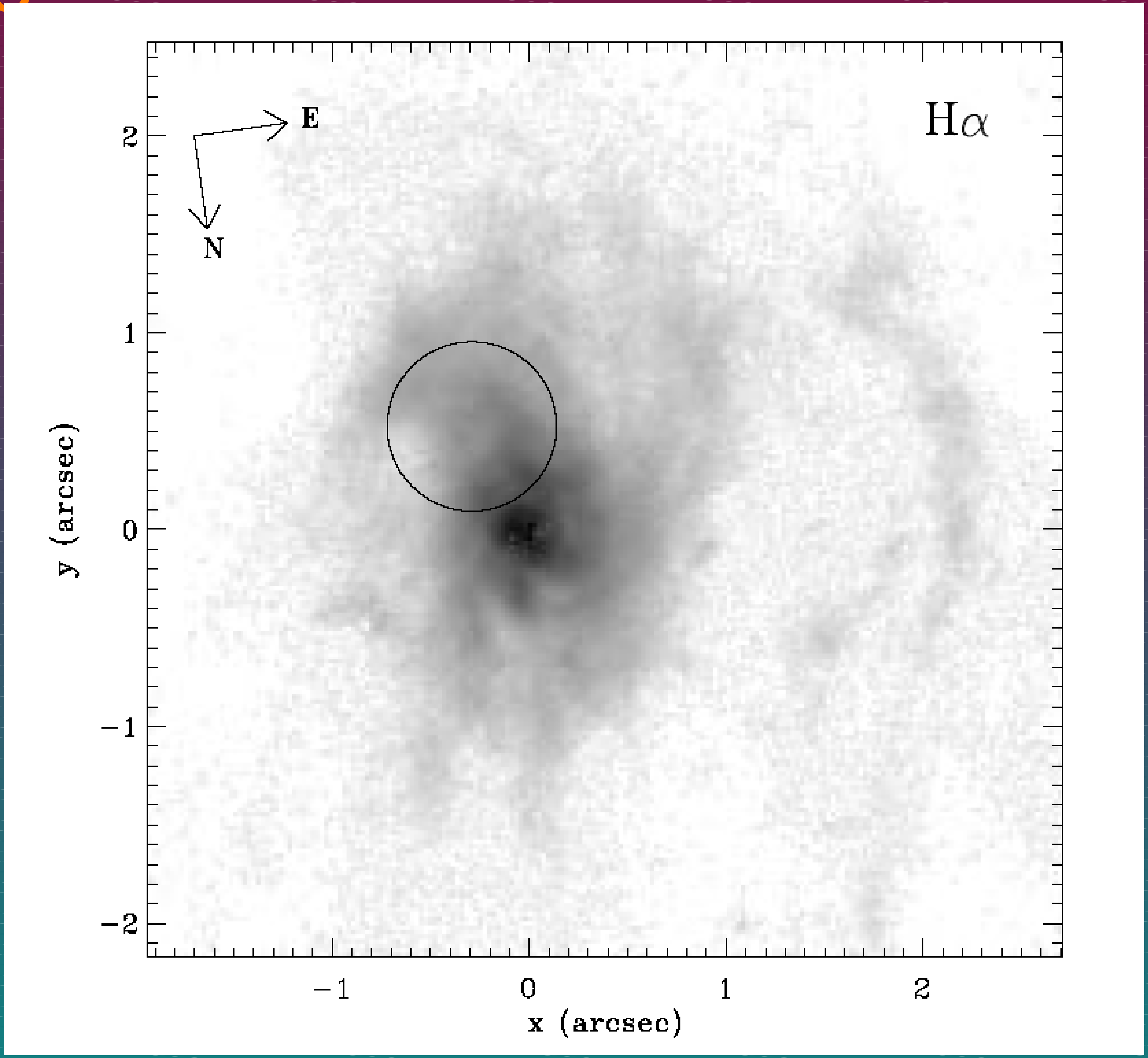
$$\frac{\bar{\rho}(r,z)}{\bar{\rho}(0,0)} = \exp - \left[\frac{\phi_G(r,z) - e_{\mathrm{K}}^2 \phi_G(r,0) - (1 - e_{\mathrm{K}}^2)\phi_G(0,0)}{\sigma_g^2} \right]$$

Supersonic turbulent disks

$$\frac{\bar{\rho}(r,z)}{\bar{\rho}(0,0)} = \exp - \left[\frac{\phi_G(r,z) - e_{\mathrm{K}}^2 \phi_G(r,0) - (1 - e_{\mathrm{K}}^2)\phi_G(0,0)}{\sigma_g^2} \right]$$

In order to achieve a scale height of order the luminous core radius the turbulent velocity dispersion has to be supersonic.

Supersonic turbulent disks in radio galaxies

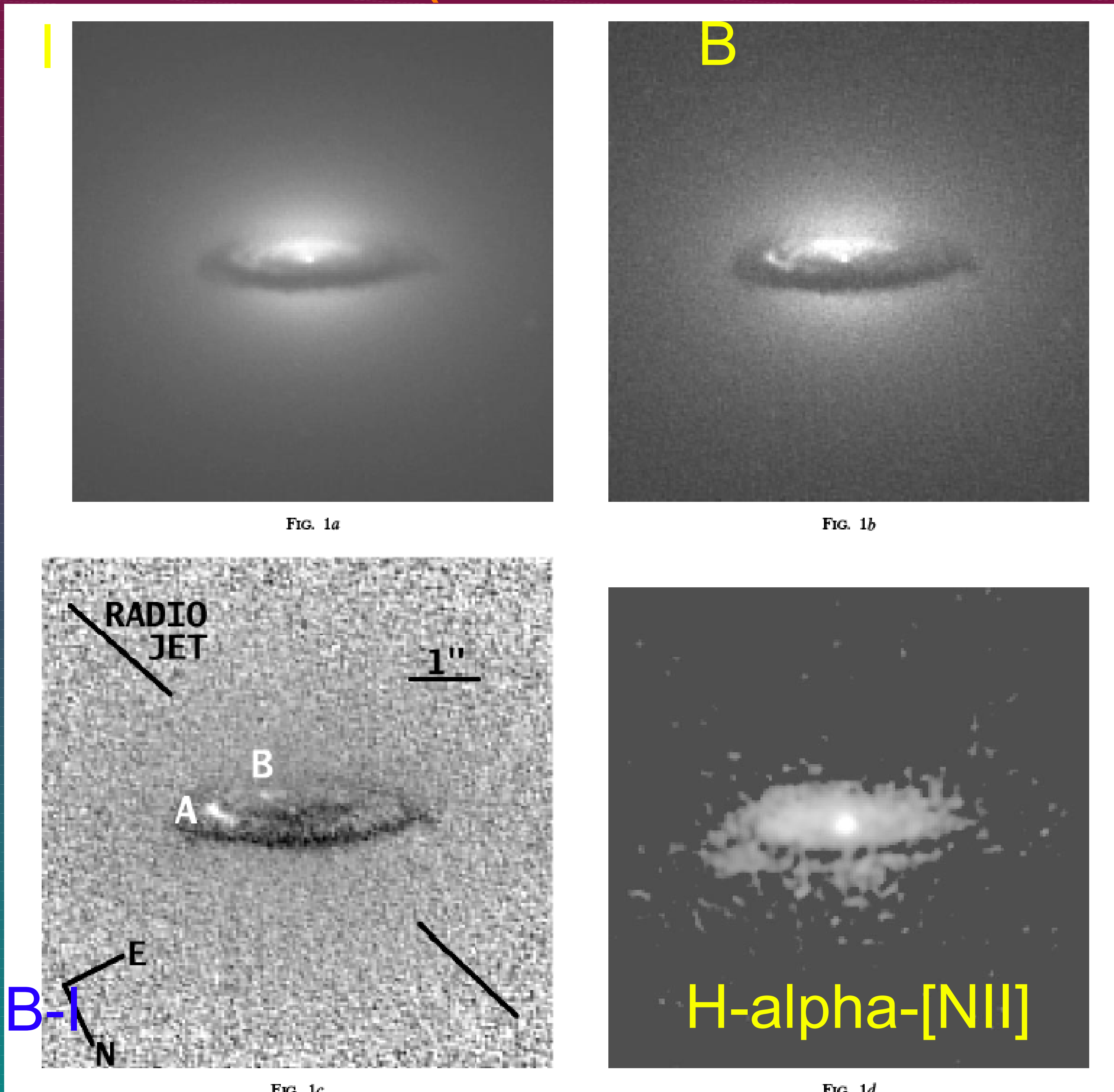


Disk in M87 (Dopita et al., 1997)

Turbulent velocity ~ 250 km/s

Shock velocity required to reproduce emission line flux = 265 km/s

NGC 7052 (van der Marel et al. 98)



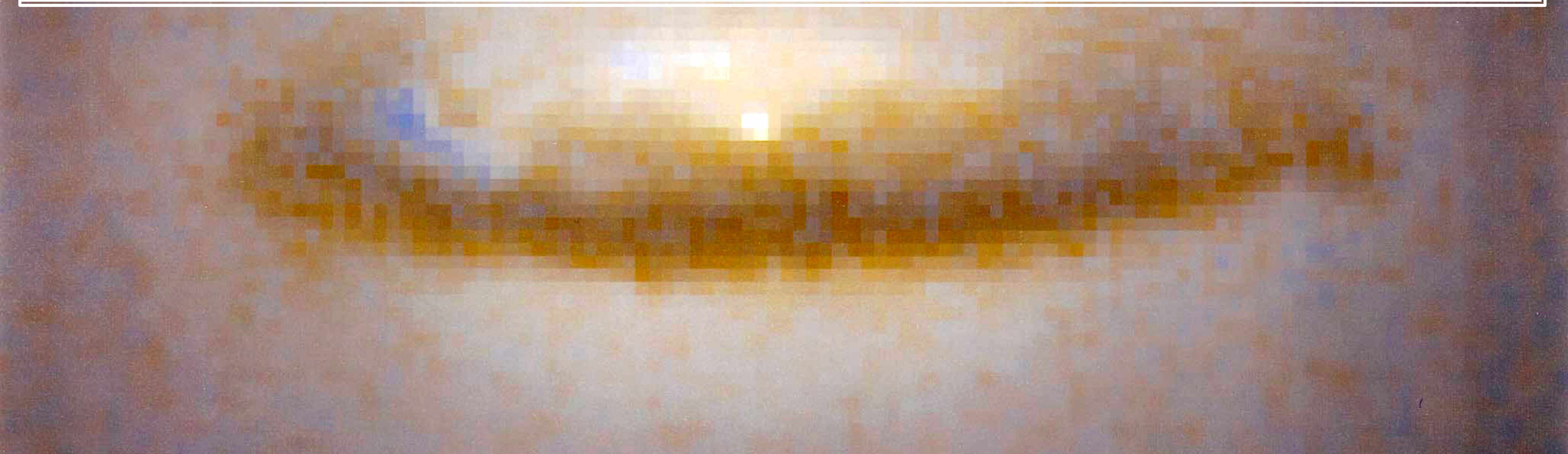
HST images of NGC 7052

Velocity dispersion ~ 70 - 400 km/s

TABLE 2

HST/FOS Spectra: Observational Setup and Gas Kinematics

ID (1)	Date (2)	*HST*-ID (3)	Position x (arcsec) (4)	Position y (arcsec) (5)	T_{exp} (s) (6)	V (km s^{-1}) (7)	ΔV (km s^{-1}) (8)	σ (km s^{-1}) (9)	$\Delta\sigma$ (km s^{-1}) (10)
1......	1996 Aug	b	−0.20	−0.02	2380	−147	36	184	31
2......	1995 Sep	d, f	−0.20	0.01	3830	−156	21	209	17
3......	1996 Aug	d	−0.04	−0.02	2380	−39	22	379	20
4......	1995 Sep	7	0.00	0.01	2370	−42	24	421	23
5......	1996 Aug	7, 9, f	0.12	−0.02	6220	138	21	315	19
6......	1995 Sep	9, b	0.20	0.01	4770	164	54	235	44



Van der Marel et al. “true colour” image of NGC 7052

3D simulations

- ppmlr - <u>Piecewise Parabolic Method Lagrangian Remap</u>: VH1 + local enhancements for cooling & shock stability
- Non-relativistic parameters (density, Mach no) chosen to correspond with relativistic jet with same energy flux
- Synchrotron emissivity

$$
\begin{aligned}
\frac{B^2}{8\pi} &\propto p \\
j_\nu &\propto p^{(3+\alpha)/2}\nu^{-\alpha}
\end{aligned}
$$

Double isothermal potential

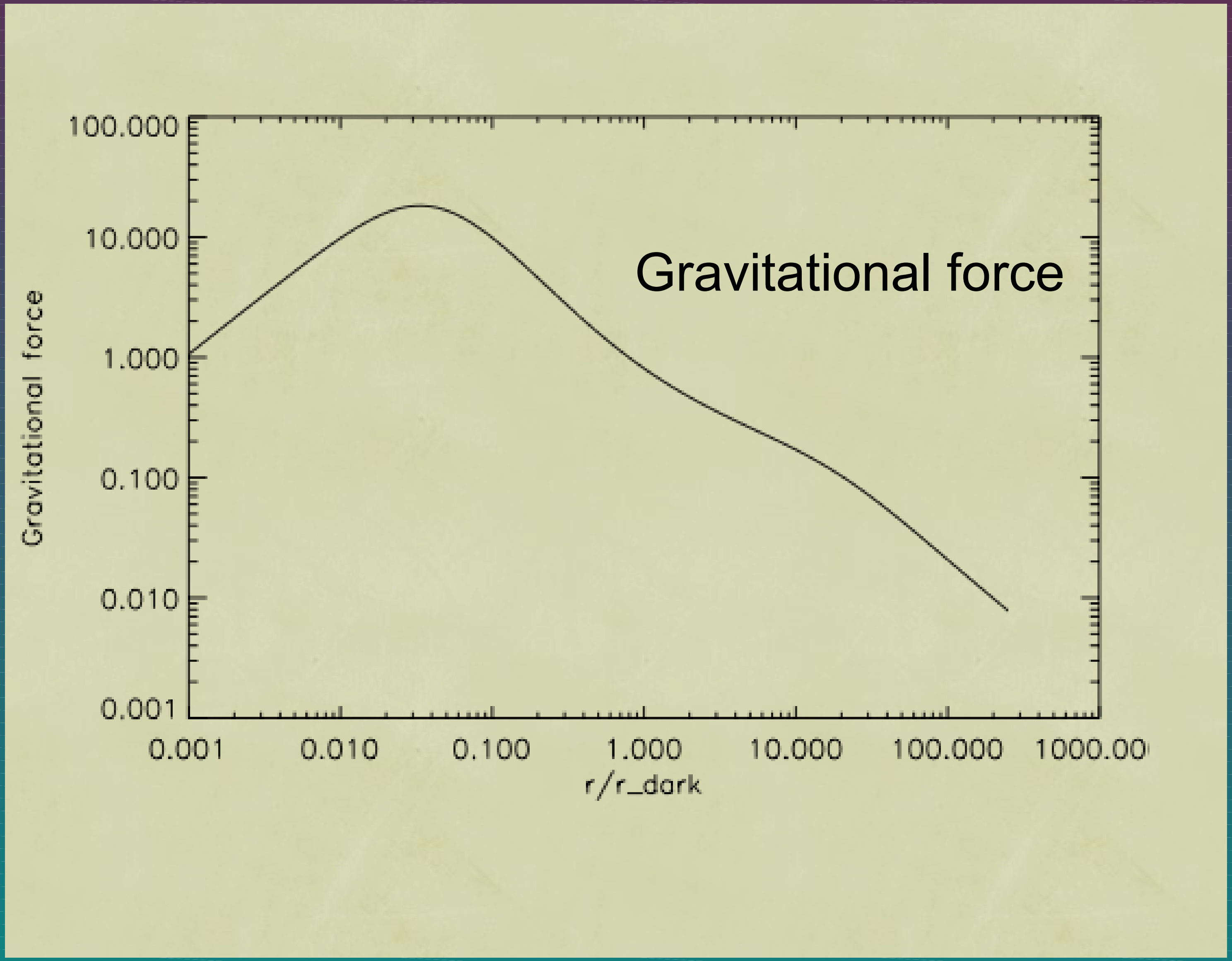
$$
\begin{aligned}
f_{\rm lum}(E) &\propto \exp(-E/\sigma^2_{\rm lum}) \\
f_{\rm dk}(E) &\propto \exp(-E/\sigma^2_{\rm dk})
\end{aligned}
$$

Solve for dark and luminous matter self-consistently using Poisson's equation

Parameters of distribution:

- Dark and luminous core radii
- Dark and luminous velocity dispersions

Sample dark and luminous matter distribution



$$\frac{r_{\rm lum}}{r_{\rm dark}} = 0.1$$

$$\frac{\sigma_{\rm lum}}{\sigma_{\rm dark}} = 0.5$$

3D jet and disk simulation

$$\Gamma = 5$$
$$\chi = \frac{\rho c^2}{4p} = 5$$
$$\xi = \frac{p_{\rm jet}}{p_{\rm ism}} = 1$$

$$p/k = 10^6$$
$$T \approx 1.2 \times 10^7$$

$$\eta \approx 2 \times 10^{-3}$$
$$M \approx 26$$
$$D = 40 \text{ pc}$$
$$L_{\rm jet} \approx 3 \times 10^{43} \text{ ergs s}^{-1}$$

10 cells

512 cells = 1.024 kpc

$$r_{\rm dark} = 4 \text{ kpc}$$
$$\sigma_{\rm dark} = 400 \text{ km s}^{-1}$$
$$r_{\rm lum} = 0.5 \text{ kpc}$$
$$\sigma_{\rm lum} = 200 \text{ km s}^{-1}$$

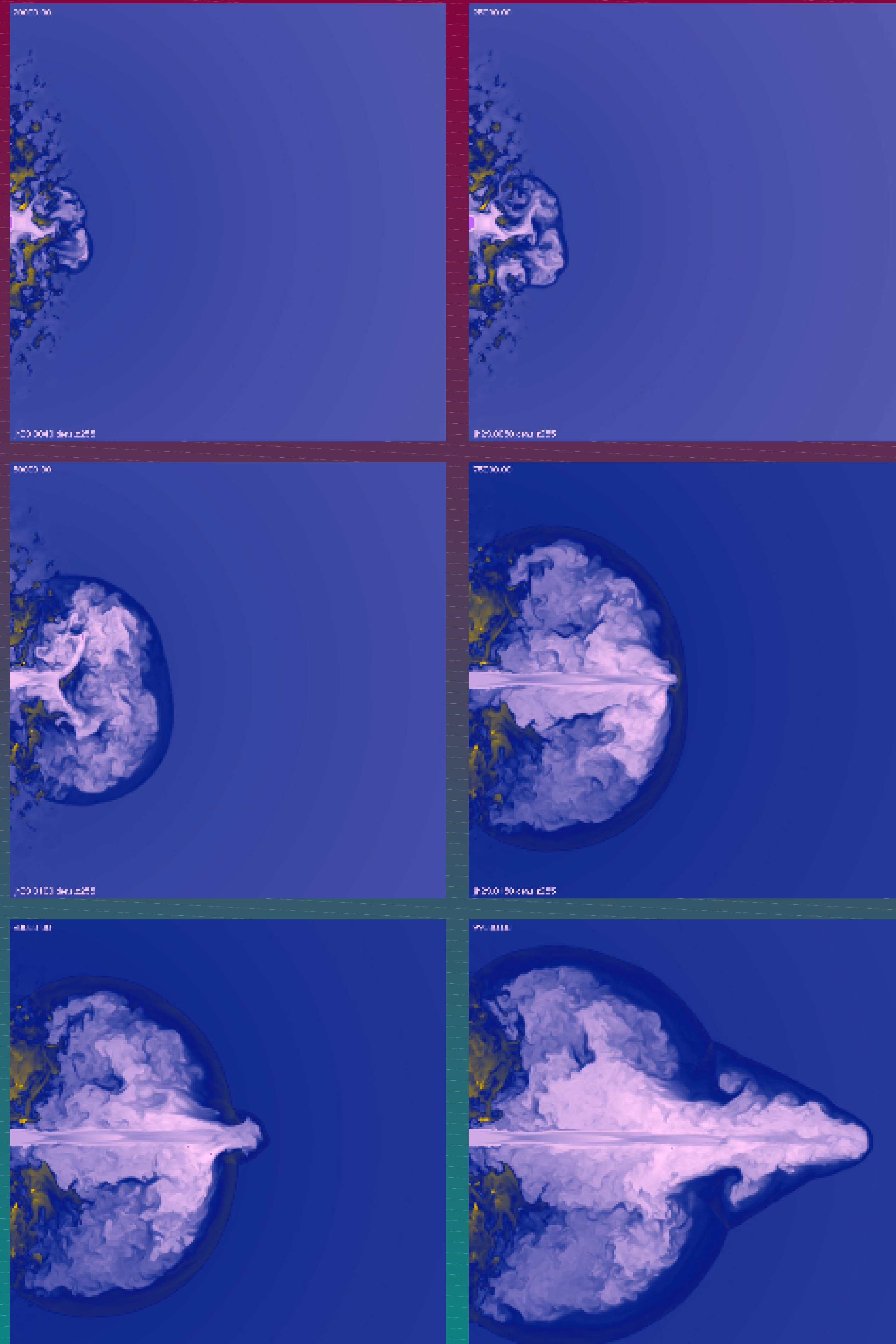
QuickTime and a Graphics decompressor are needed to see this picture.

Warm disk

$$n_{\rm warm} = 10 \text{ cm}^{-3}$$
$$T_{\rm warm} = 10^4 \text{ K}$$
$$\sigma_{\rm g} = 40 \text{ km s}^{-1}$$

512 cells = 1.024 kpc

Evolutionary phases



Disk interaction phase

Jet-driven bubble; bifurcated jet

End of bubble phase

Jet breakout

CSS => Classical radio galaxy

Log density

x=5

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Graphics decompressor
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Graphics decompressor
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z=255

Radio and thermal surface brightness

Viewed at 30 degrees to the jet axis

QuickTime™ and a
Graphics decompressor
are needed to see this picture.

QuickTime™ and a
Graphics decompressor
are needed to see this picture.

More powerful jet; more holey disk

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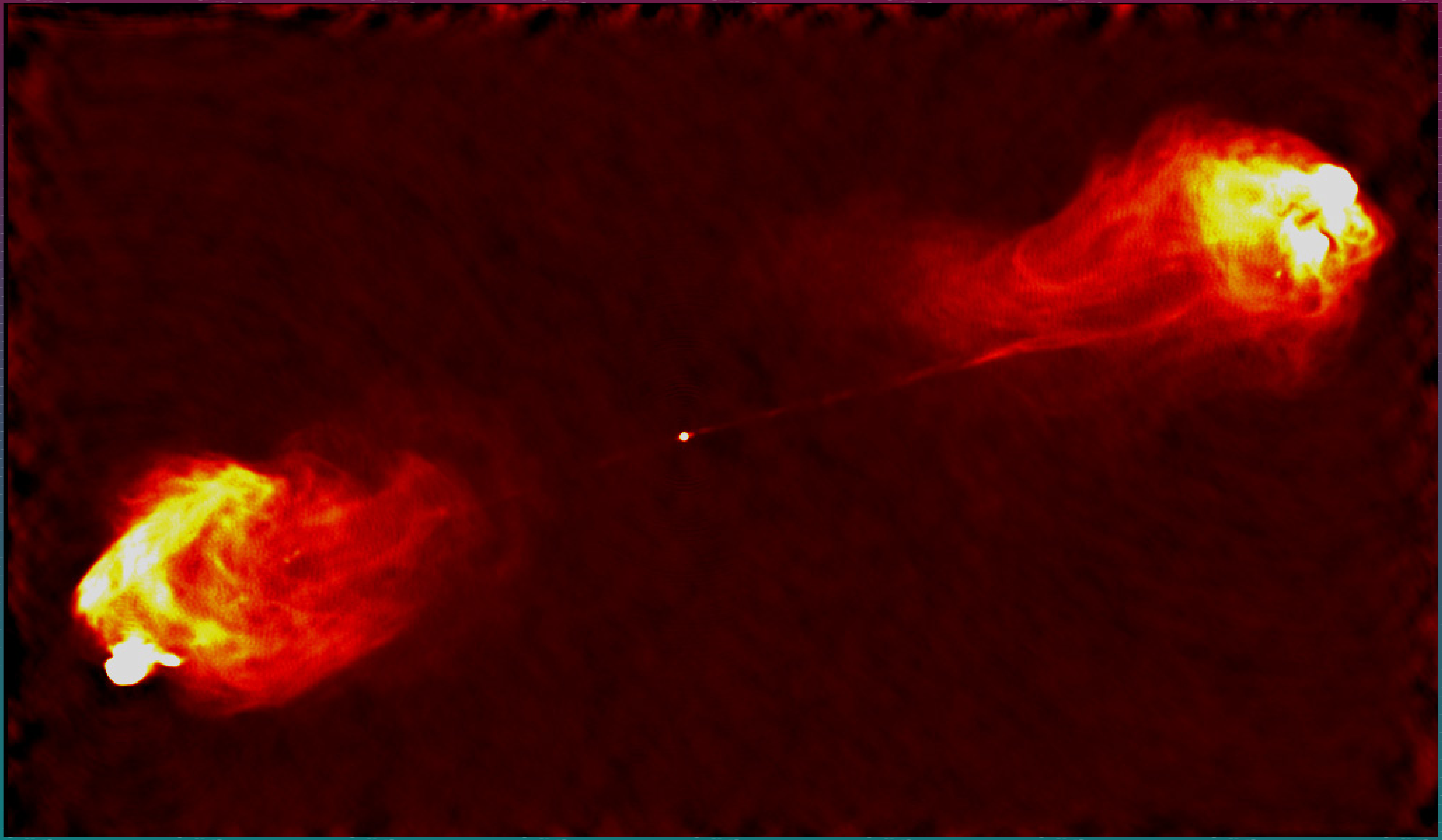
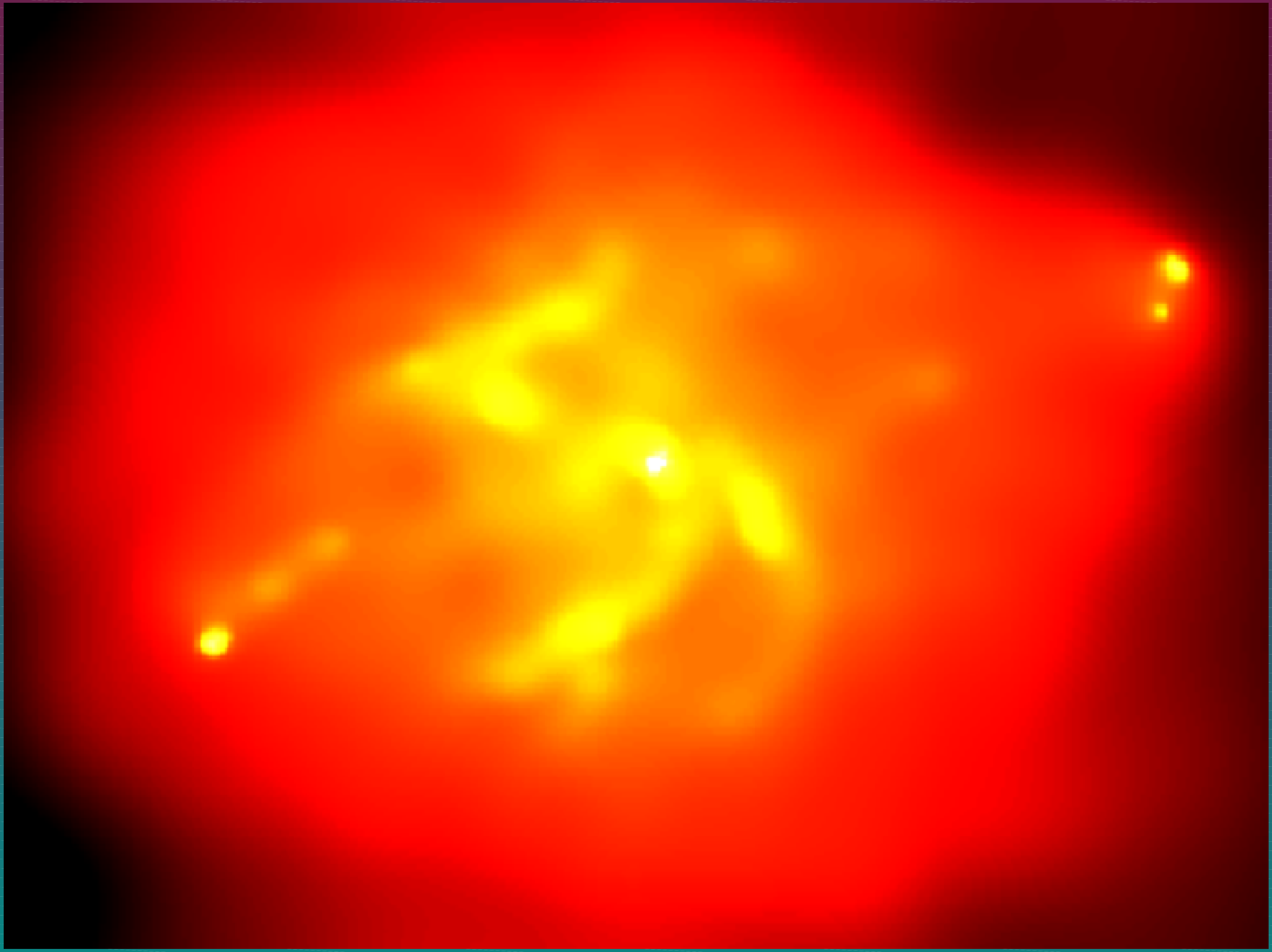
$$L_{\rm jet} \approx 3.8 \times 10^{44}\,{\rm ergs\,s^{-1}}$$

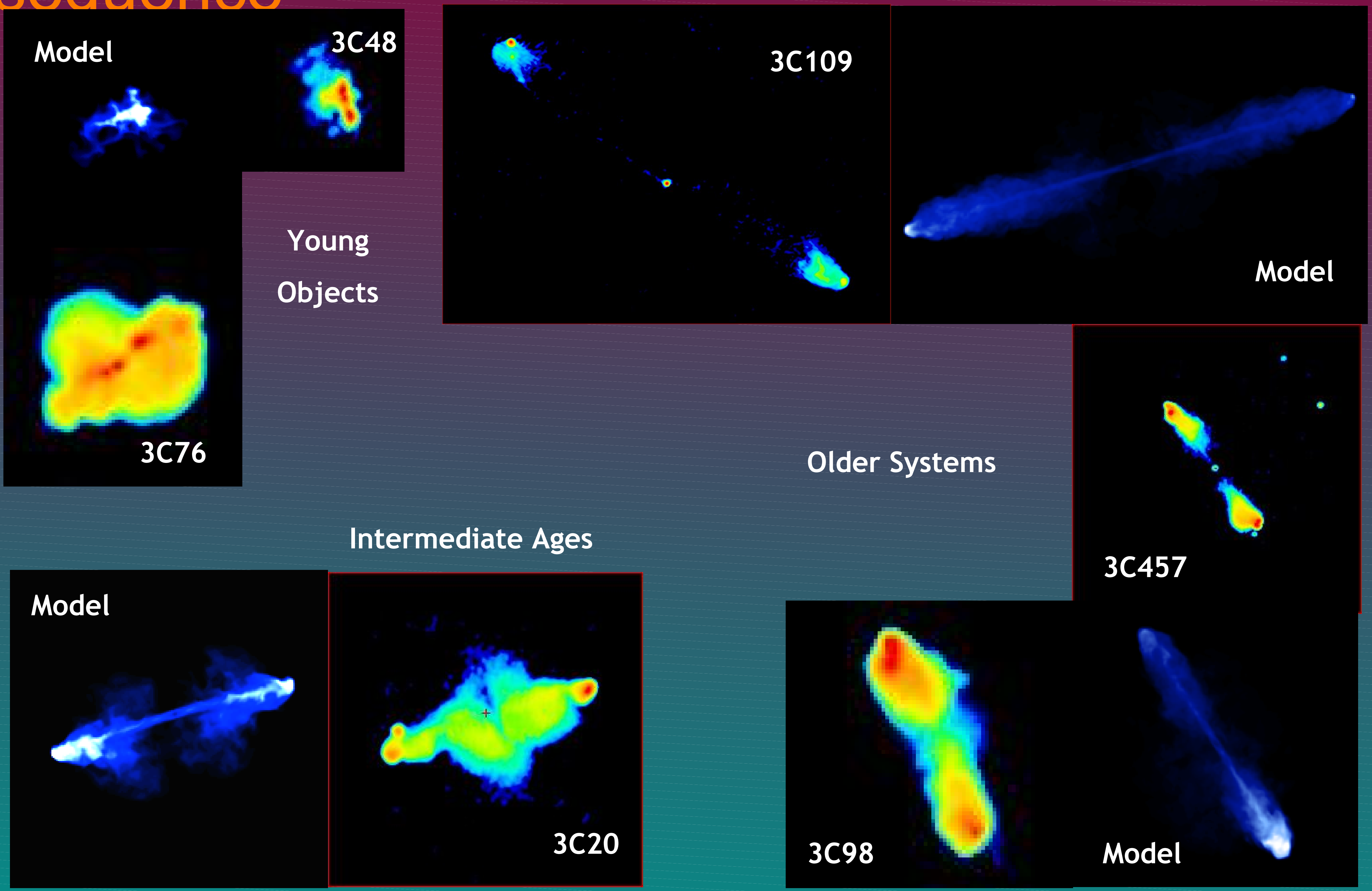
Cygnus A Radio - extent 60 kpc



Cygnus A X-ray



Evolutionary sequence



Extended distribution of warm clumpy matter

Log-normal distribution of gas with scale height 2 kpc

η	$=$	0.002
M	$=$	10
$D_{\rm jet}$	$=$	$1.2\,{\rm kpc}$
$L_{\rm K}$	$=$	1.4×10^{46}
$r_{\rm lum}$	$=$	$1\,{\rm kpc}$
$r_{\rm dk}$	$=$	$10\,{\rm kpc}$
$\sigma_{\rm lum}$	$=$	$400\,{\rm km\,s^{-1}}$
$\sigma_{\rm dk}$	$=$	$800\,{\rm km\,s^{-1}}$
$n_{\rm hot}$	$=$	0.1
$T_{\rm hot}$	$=$	$4.8 \times 10^7\,{\rm K}$
p/k	$=$	4.8×10^6
$\bar{n}_{\rm warm}$	$=$	500
$\tilde{T}_{\rm warm}$	$=$	$10^4\,{\rm K}$

QuickTimeŞ and a
Graphics decompressor
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256 cells = 25.6 kpc

Evolution of radio surface brightness

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Graphics decompressor
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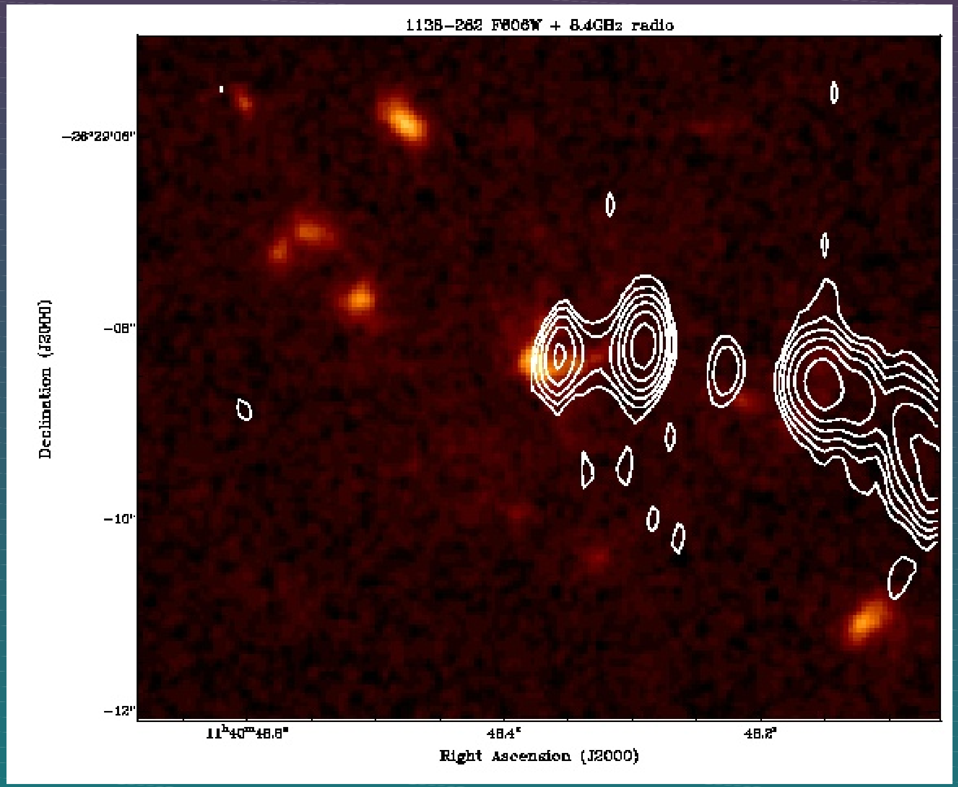
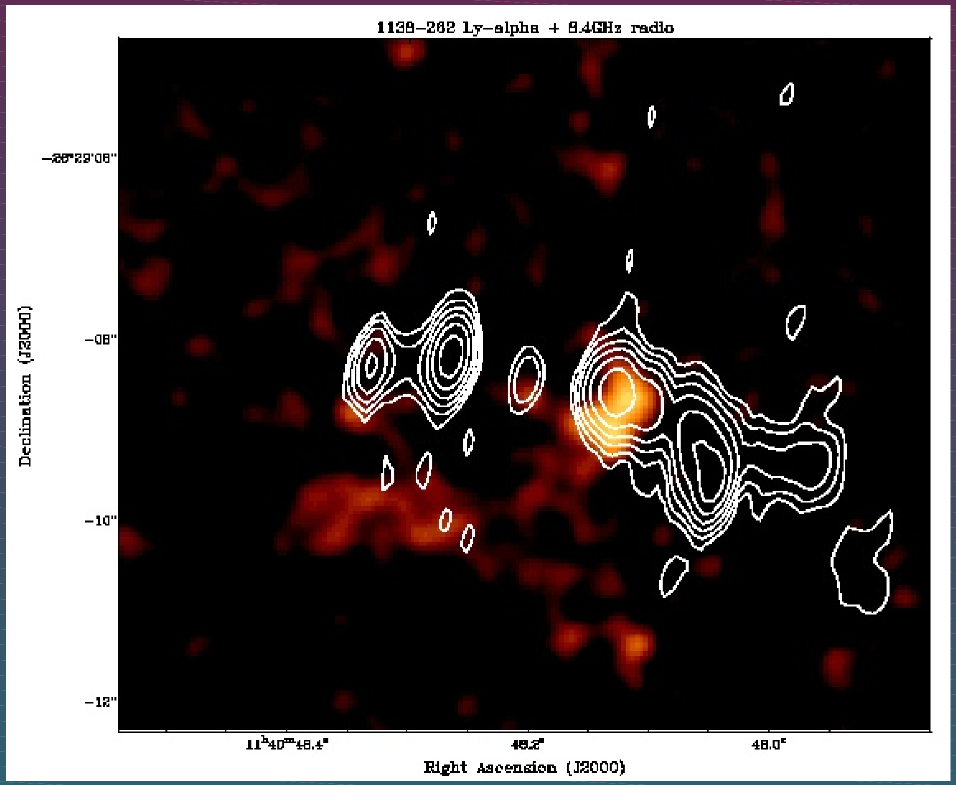
PKS 1138-262 (De Vries, Van Breugel et al. 2005)

z=2.16



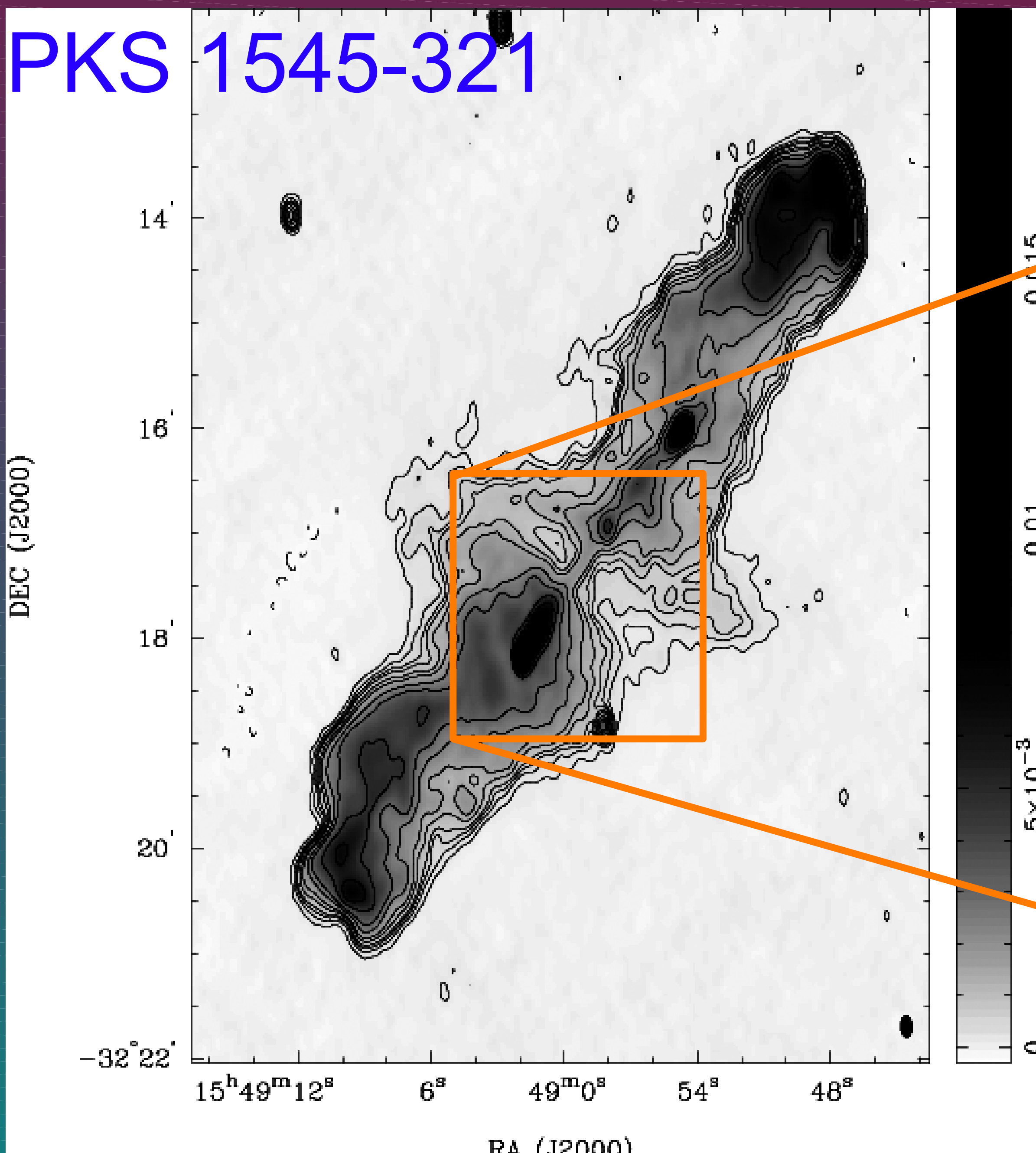
HST continuum



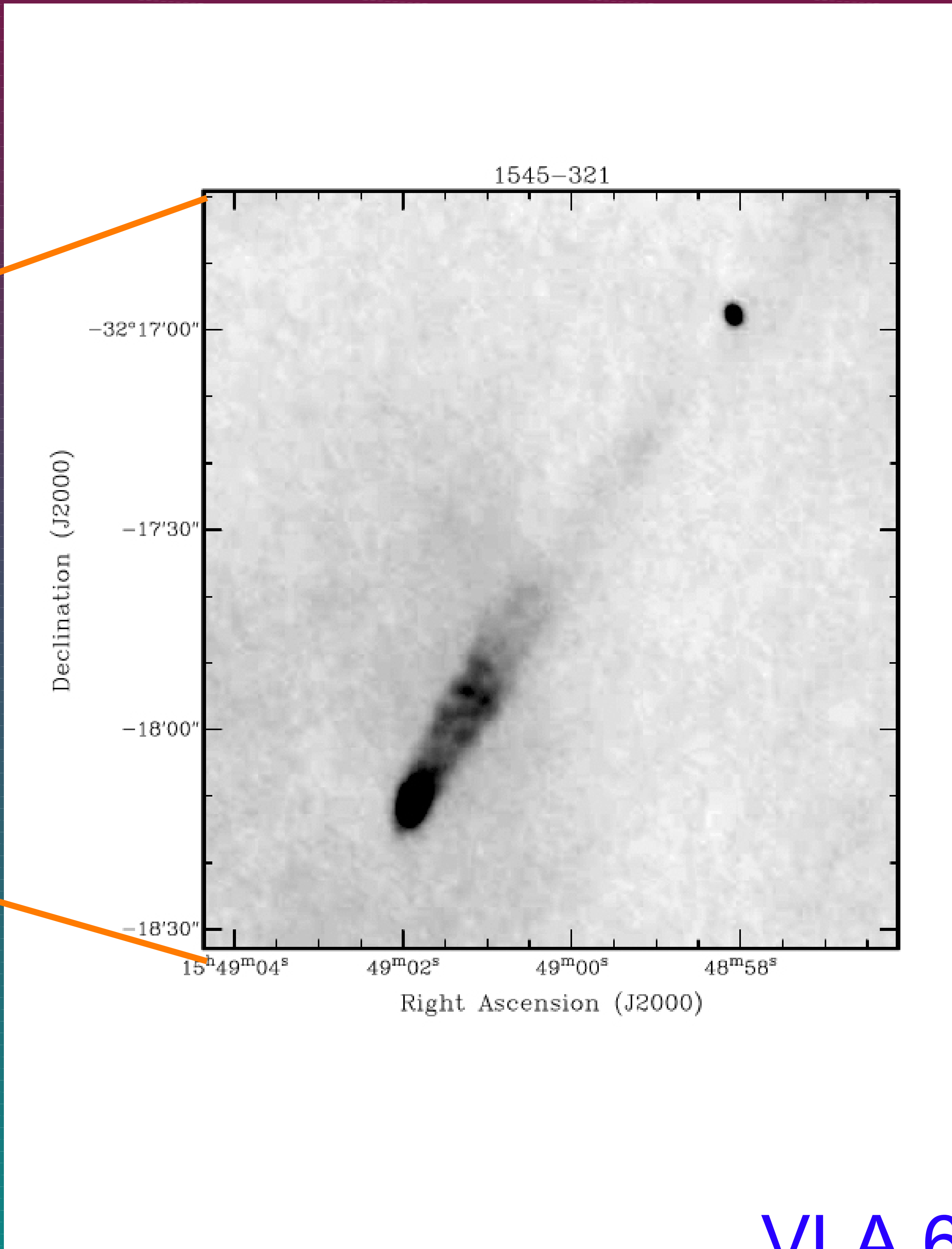
No HST Ly-alpha near AGN
Bright double knot where jet splits
Faint emission outside radio sourc

Restarting jets: A different medium

(Safouris, Subrahmanyan, Saripalli, GB, RS)



VLA + ATCA 20 cm



VLA 6cm

Previous work and ideas

- Clarke & Burns 1991: Simulations of restarting jet show that new jet is overdense

- Low Mach number of the leading bow shock

- Lack of prominent hot spot

Kaiser, Schoenmakers & Rottgering 2000

- Argue for entrainment of material into the existing lobe

- Produces higher Mach number bow-shock

Simulations of restarting jet

$$\eta = 1.5 \times 10^{-3}$$
$$M = 11.5$$
$$\xi = \frac{p_{\mathrm{jet}}}{p_{\mathrm{IGM}}} = 42.9$$
$$D = 3\,\mathrm{kpc}$$
$$L_{\mathrm{jet}} = 1.3 \times 10^{44}\,\mathrm{ergs\,s^{-1}}$$

Equivalent rel. jet

$$\Gamma = 5$$
$$\chi = \frac{\rho c^2}{4p} = 1$$

Background medium

$$n_{\mathrm{IGM}} = 10^{-4}\,\mathrm{cm^{-3}}$$
$$\frac{\rho_{\mathrm{IGM}}}{\rho_{\mathrm{crit}}} = 11.2$$

log(density)

QuickTimeŞ and a
Graphics decompressor
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$t_{\mathrm{off}} = 10^7$ yrs $\quad$ $t_{\mathrm{on}} = 2 \times 10^7$ yrs

Surface brightness

QuickTimeŞ and a
Graphics decompressor
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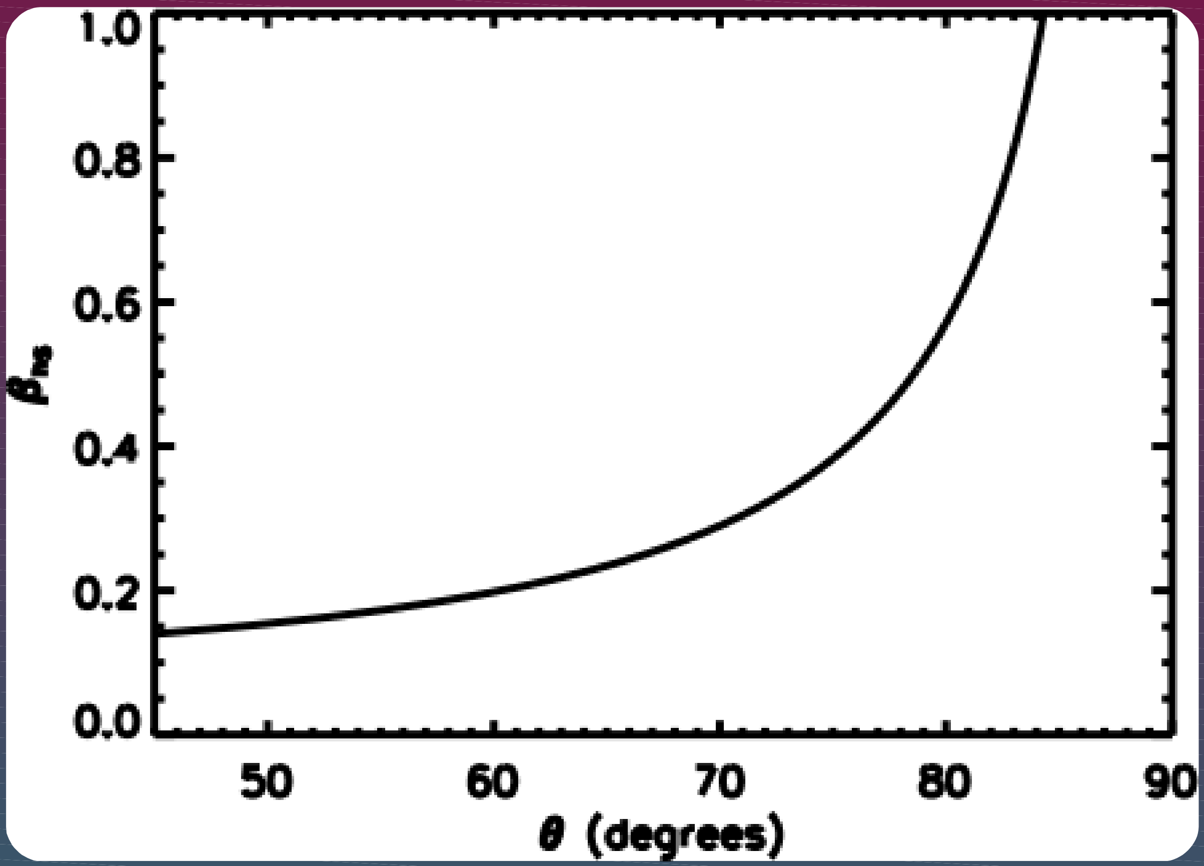
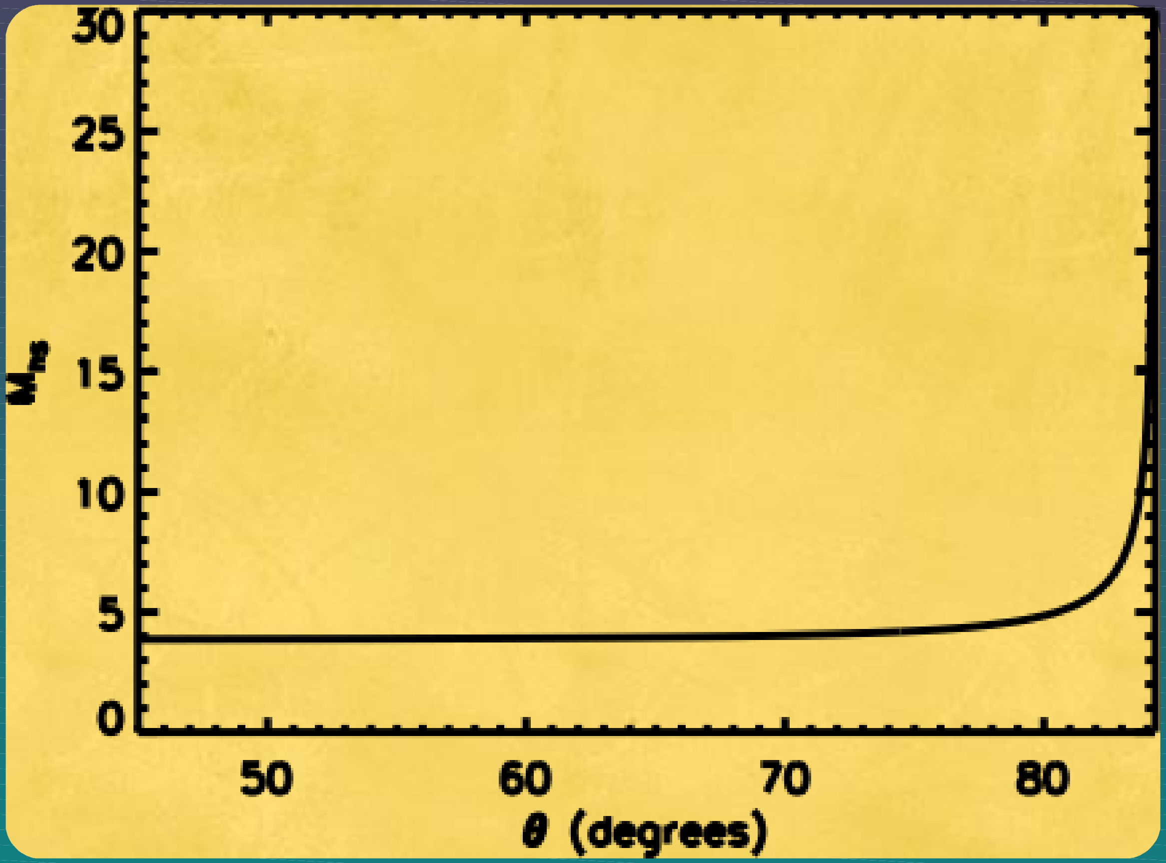
Analysis of PKS 1545-321 data



Use arm-length ratio of inner hot spots to estimate hot spot velocity

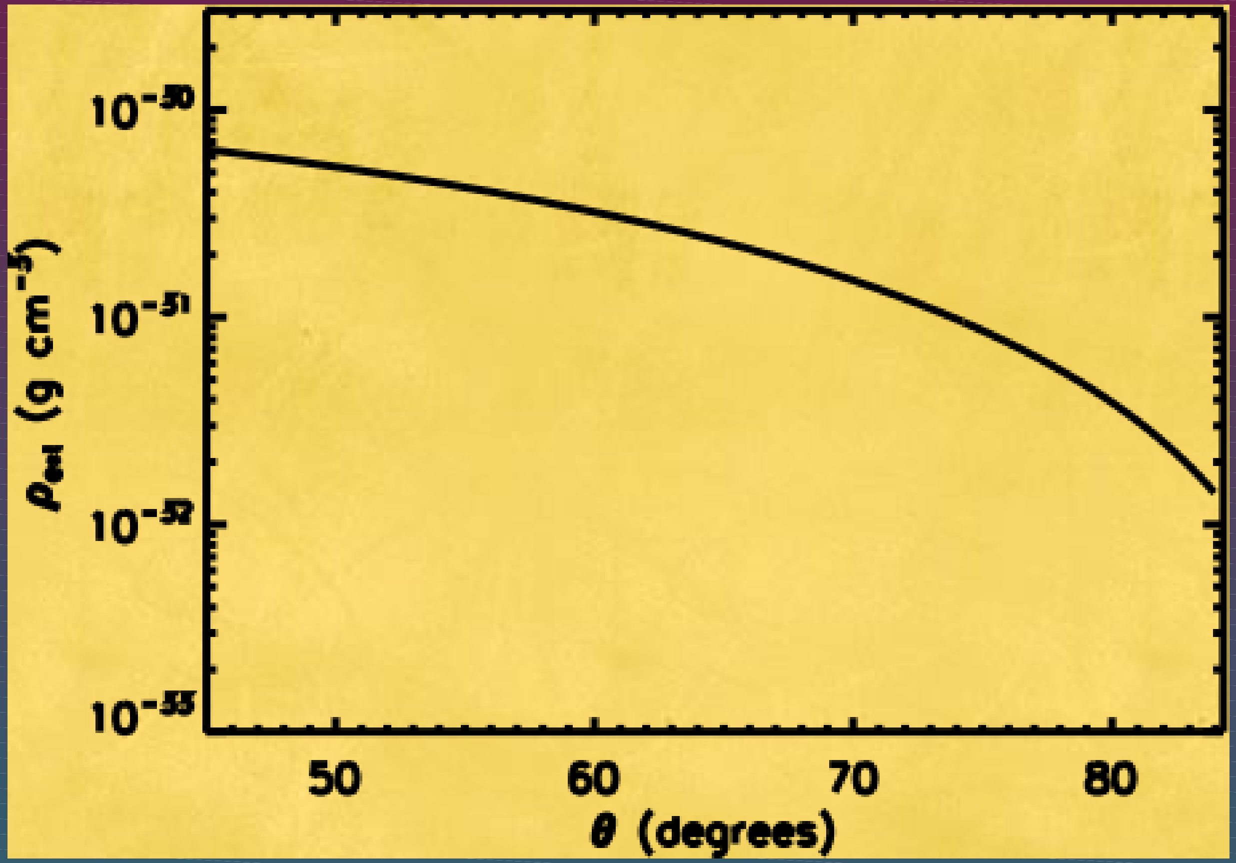
$$p_{\rm hs} = \frac{3}{4}\rho_{\rm ext}c^2\,\Gamma_{\rm hs}^2\beta_{\rm hs}^2$$

=> Density of lobe and hot spot Mach number



Jet power

Inner hot spots due to jittering jet



$$\rho_{\rm ext}\, c^2\, \beta_{\rm hs}^2 \times \text{Hot spot Area}$$
$$\approx \text{Jet Force in Hot-spot frame}$$

$$P_{\rm jet} \approx \rho_{\rm ext} c^2 \left(\frac{\beta_{\rm hs}}{\beta_{\rm jet} - \beta_{\rm hs}}\right)^2 c\beta_{\rm jet}\, A_{\rm hs}$$
$$\approx 3 \times 10^{44}\,{\rm ergs\,s^{-1}}$$

– consistent with energy budget of inner lobe

Summary

- A clumpy interstellar medium significantly influences the early evolution of radio galaxies
- Disk + Jet => 3 phases of evolution
- Memory of early phase in late-time structure
- More extended clumpy medium => highly disrupted structure typical of high redshift radio galaxy
- Thermal X-ray emission the link between radio and optical structure
- Feasible that inner doubles in radio galaxies are the result of jet propagation in a polluted