Jets from variable sources

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VLT-FORS2

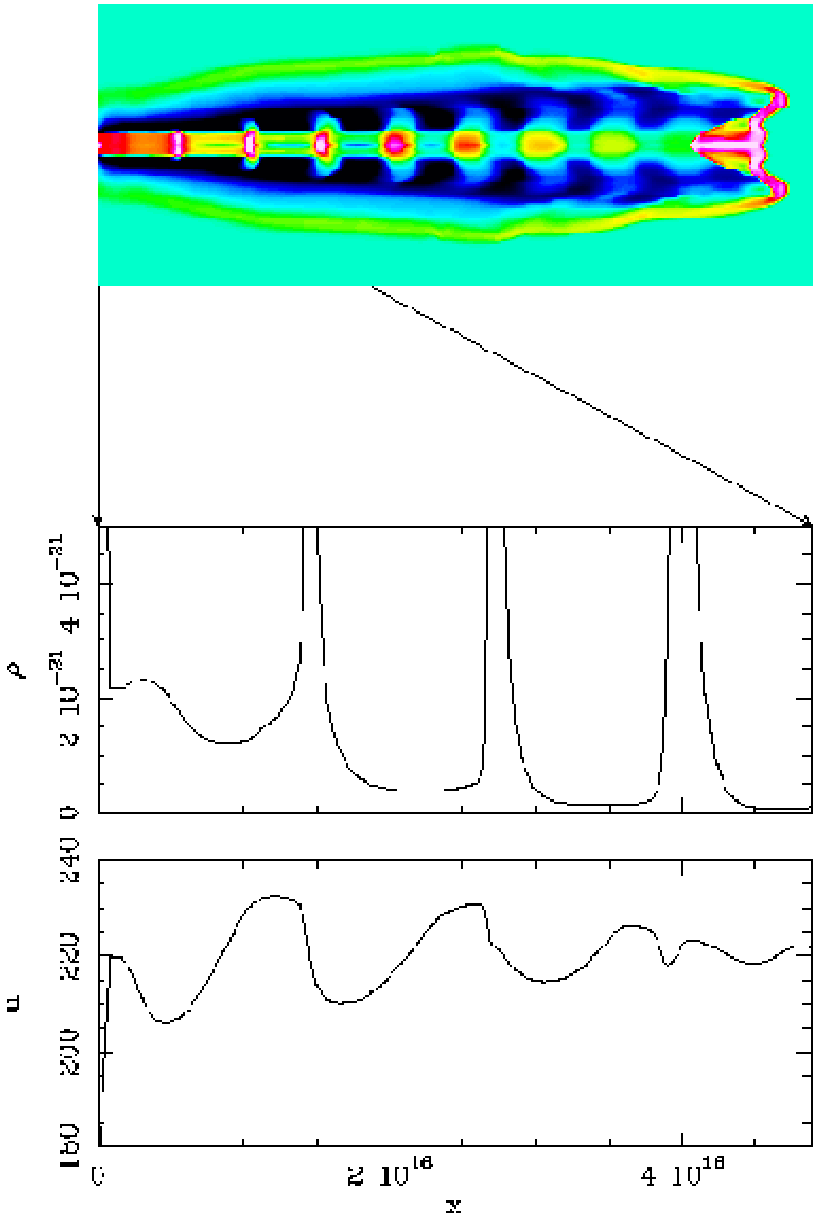
(1999)

Ejectionvelocityvariability

→Leads to the formation of “internal working surfaces”

Density variability

Leads only to the formation of weak shocks



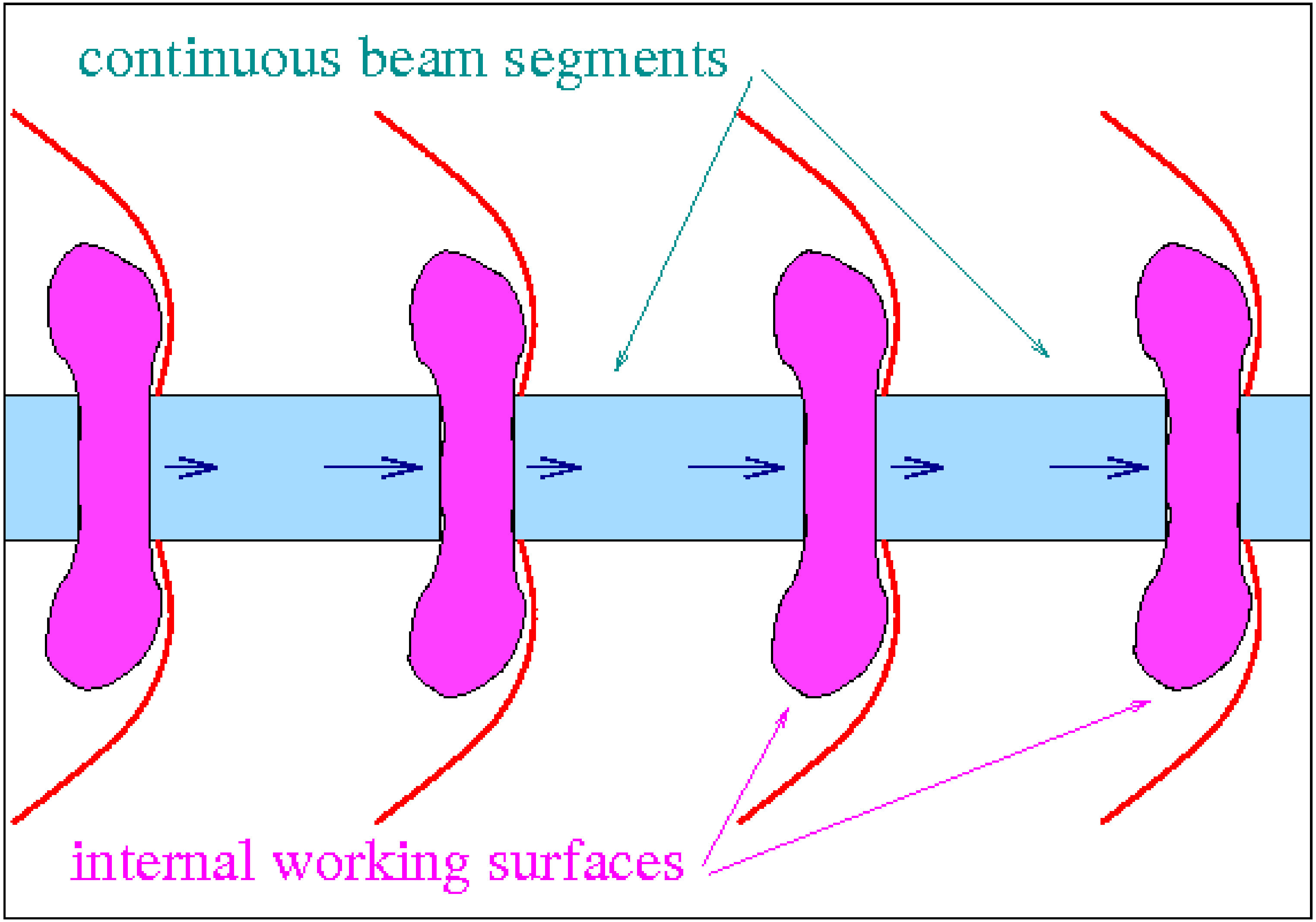
Jet with variable ejection velocity

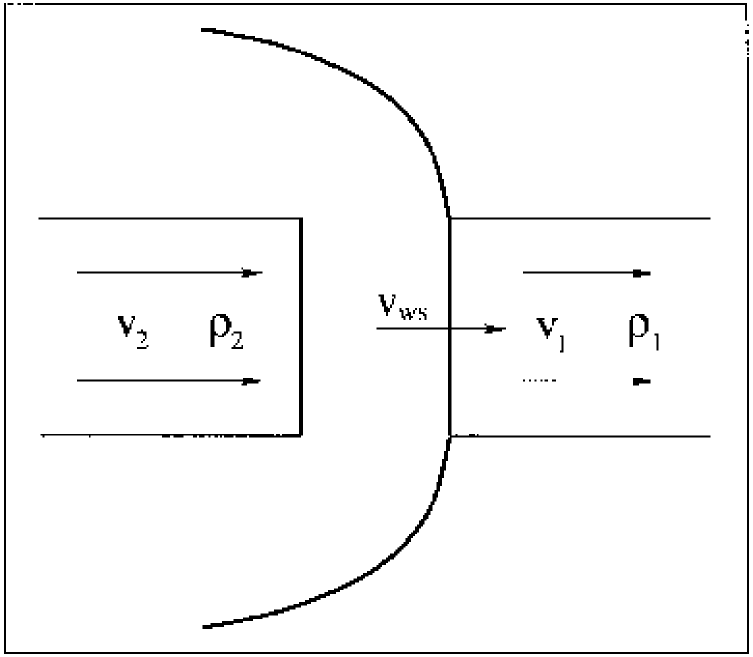
$$v_j = v_0 + \Delta v \sin(2\pi t/\tau)$$

v_0 = 200 km/s, Δv = 40 km/s, τ = 20 yr

n_j = 1000 cm^{-3}, T_j = 1000 K, r_j = 2x10^{15} cm

n_{env} = 100 cm^{-3}, T_{env} = 1000 K


continuous beam segments
internal working surfaces



Free-streaming continuous beam segments

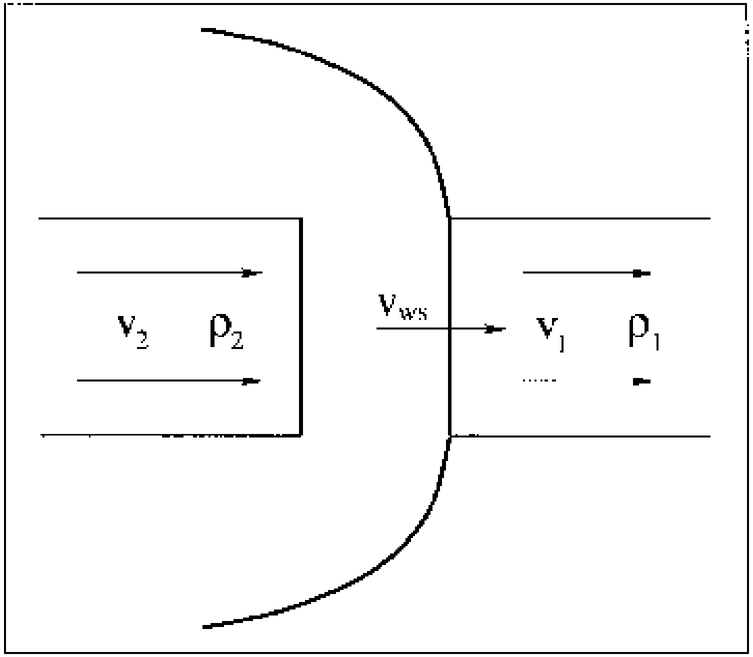
$$u(x, t) = u_0(\tau) = \frac{x}{t - \tau}$$

$$\sigma(x) = \sigma_0 \left(\frac{x_0}{x + x_0} \right)^p$$

pos-dep cross section

$$\rho(x, t) = \rho_0(\tau) \left(\frac{x_0}{x + x_0} \right)^p \left[1 - (t - \tau) \frac{d \ln u_0}{d\tau} \right]^{-1}$$

E.O.M. for internal working surface



Ram pressure balance:

$$v_s = \frac{dx_s}{dt} = \frac{u_1 + \beta u_2}{1+\beta}, \quad \beta = \sqrt{\frac{\rho_2}{\rho_1}}$$

Centre of mass formalism:

$$v_{\rm ws} = \frac{1}{m}\int_{\tau_1}^{\tau_2} \dot{m}(\tau) v_0(\tau)\,{\rm d}\tau.$$

$$x_{\rm ws} = (t - \tau_2)v_{\rm ws} + \frac{1}{m}\int_{\tau_1}^{\tau_2} \dot{m}(\tau) v_0(\tau)(\tau_2 - \tau)\,{\rm d}\tau,$$

$$m = \int_{\tau_1}^{\tau_2} \dot{m}(\tau)\,{\rm d}\tau.$$

Ram-pressure balance eom:

→Asymptotic solution for large distances from the source

(Kofman, Raga 1998)

Centre of mass eom:

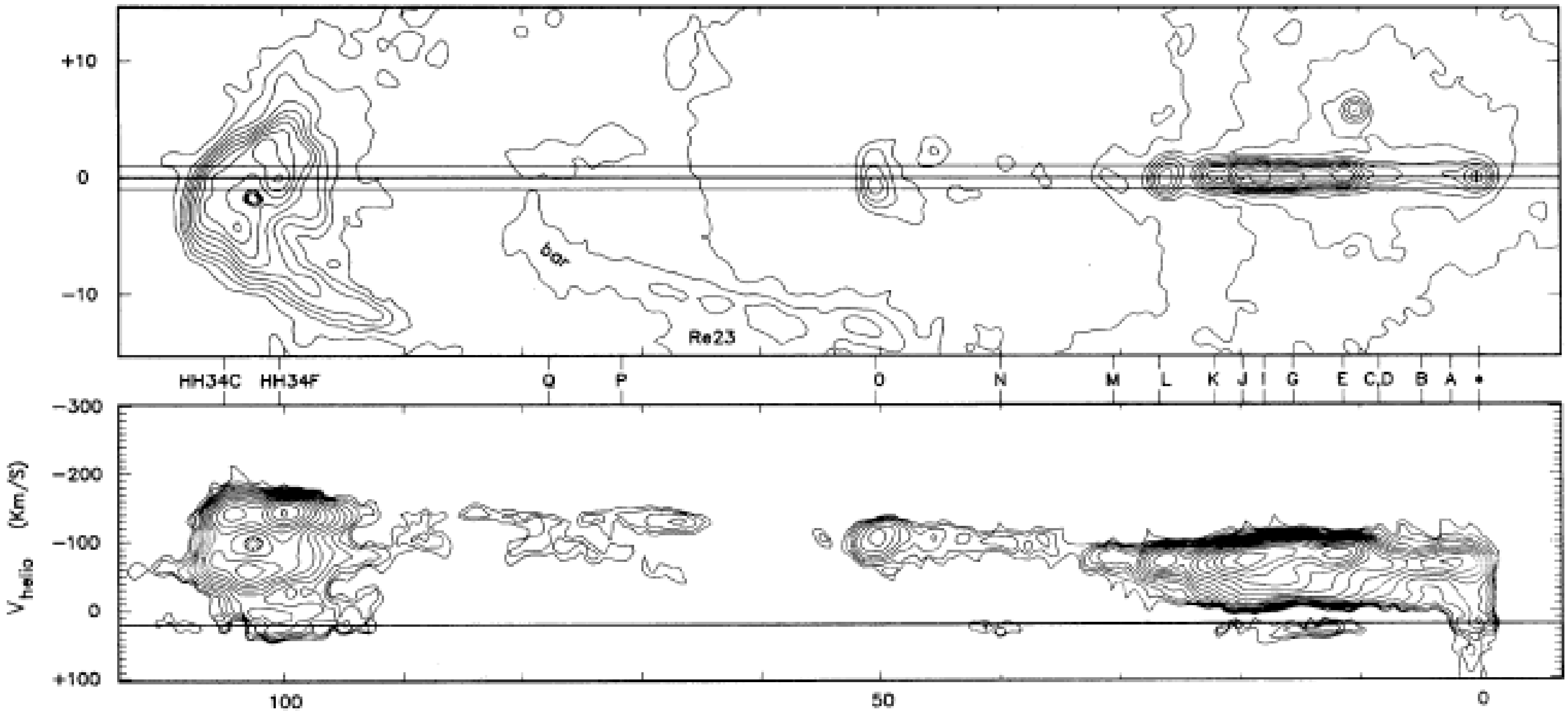
→All kinds of analytic solutions

(Canto et al. 2000)

2 – 3D numerical simulations produce results which lie between these two analytic approximations

Observational evidence for ejection time-variability:

1. “acceleration” observed along some HH jets



HH 34: Heathcote and Reipurth (1992)

Initial jet velocity□ 200 km/s
Initial jet sound speed□ 10 km/s
Final jet speed□ 300 km/s

$$v^2/2 + c_s^2/(\gamma - 1) = \text{const.}$$

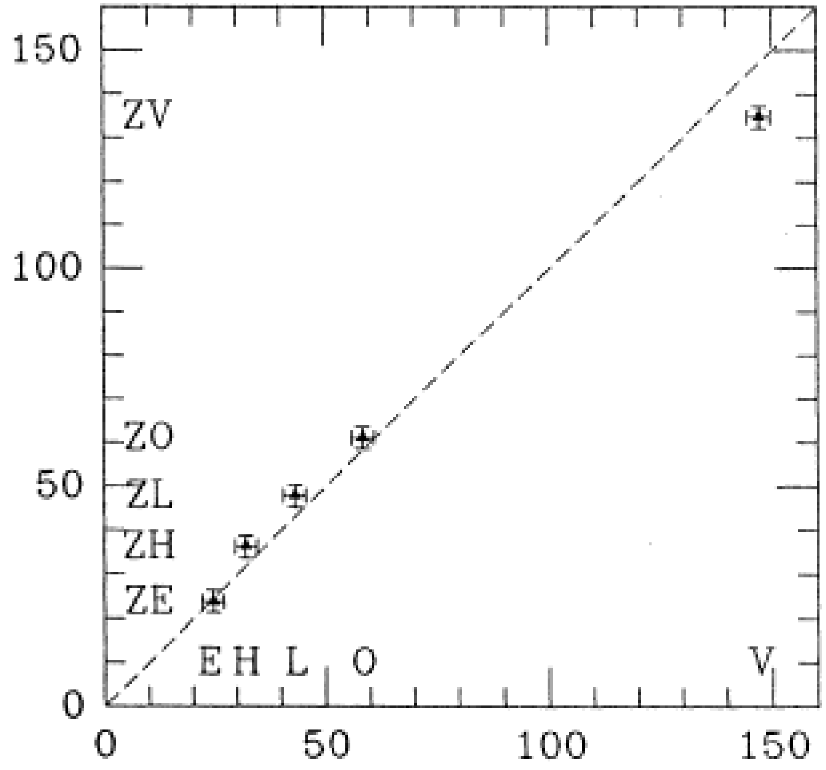
$$M_0 = v_0/c_{s,0} \approx 20$$

→Impossible to produce the observed acceleration in a steady jet

□ejection velocity varies with time

Observational evidence for ejection time-variability:

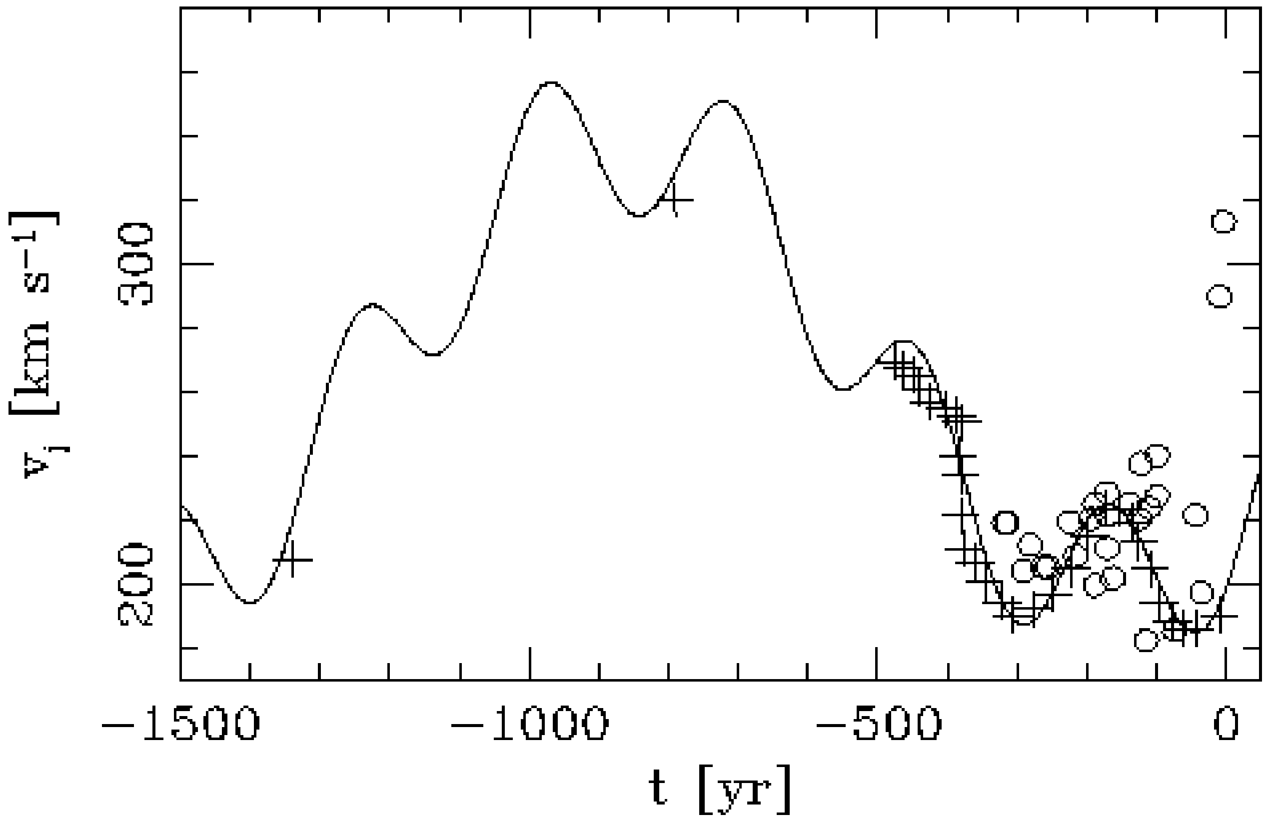
2. "point symmetry" between knots in jet and counterjet



HH 111: Gredel and Reipurth (1994)

(HH 34 Panoglou et al. 2009)

Free-streaming flow can be used to reconstruct ejection velocity history

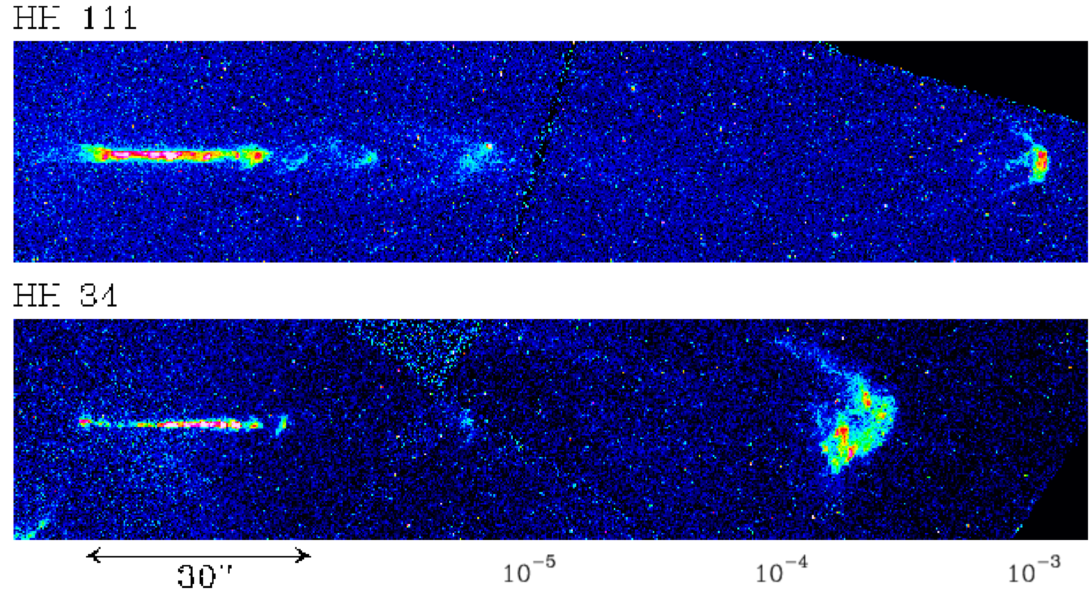


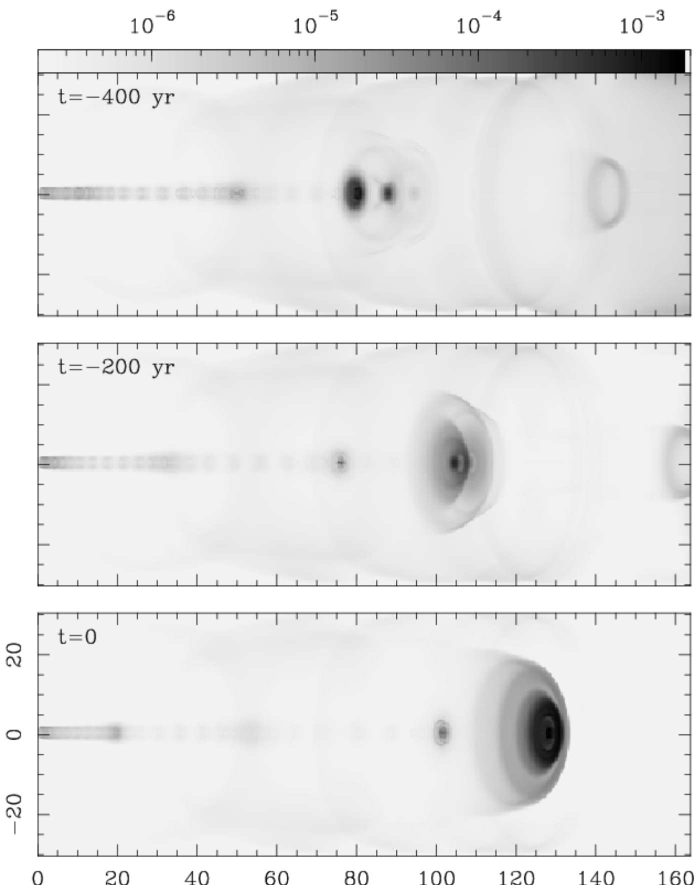
HH 34: Raga et al. (2002)

$$u(x, t) = u_0(\tau) = \frac{x}{t - \tau}$$

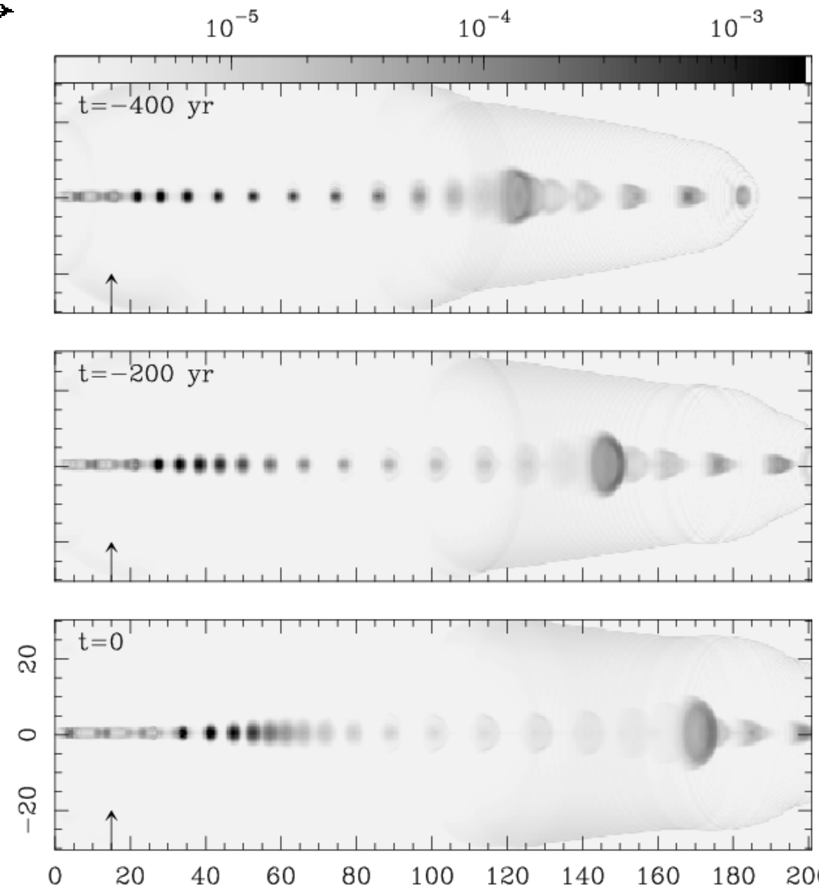
Reconstructed ejection velocity variability

→Fed into a numerical simulation





Raga et al. (2002)



Ejection velocity variability + precession

3D: $1024 \times 512 \times 512$

$\rightarrow$ size of domain along axis: 4×10^{17} cm

$\rightarrow$ jet radius: $r_j = 7 \times 10^{15}$ cm

$\rightarrow$ jet radius resolved with 18 grid points

$\rightarrow$ $v_j = 200$ km s^{-1}, $n_j = 1000$ cm^{-3}, $T_j = 1000$ K

$\rightarrow$ $n_{env} = 100$ cm^{-3}, $T_{env} = 100$ K

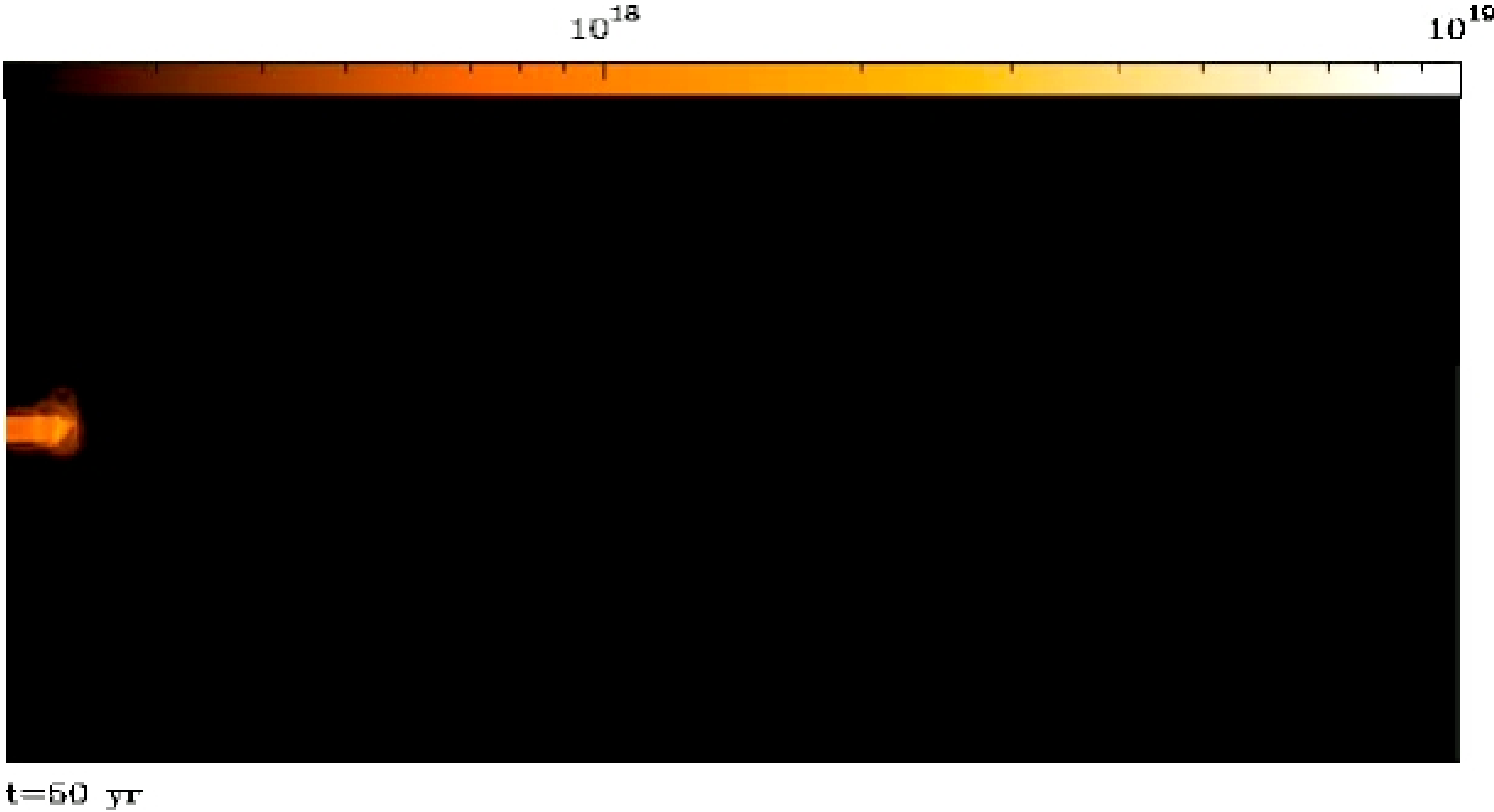
$\rightarrow$ **two sinusoidal modes:**

$$\Delta v = 20 \text{ km s}^{-1},\ \tau = 30 \text{ yr}$$

$$\Delta v = 100 \text{ km s}^{-1},\ \tau = 230 \text{ yr}$$

$\rightarrow$ **precession:** $\tau_{prec} = 1000$ yr, half-angle: $5°$

“modern” 3D numerical simulation



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Summary:

Evidence that HH jets are the result of a time-dependent ejection

→Multiple “heads” (e. g. in giant jets)
→“point symmetric” chains of knots
→“accelerations”

Theoretical work

→Analytic models (ram pressure balance, centre of mass)
→Numerical simulations (1,2,3D; multiple mode, precession, sidewind, orbital motion, externally photoionized jets, stratified medium, interaction with clumps, clumpy jet)

Combining theory+observations

1.Observed kinematics→reconstruction of ejection history through analytic model

2. Numerical simulation→prediction of observed emission