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ALMA, Charlottesville
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Physical Conditions in YSO Jets

OVERVIEW
(Focus on atomic lines)

I. Radiative Shocks

II. Electron Densities, Temperatures, Ionization Fractions

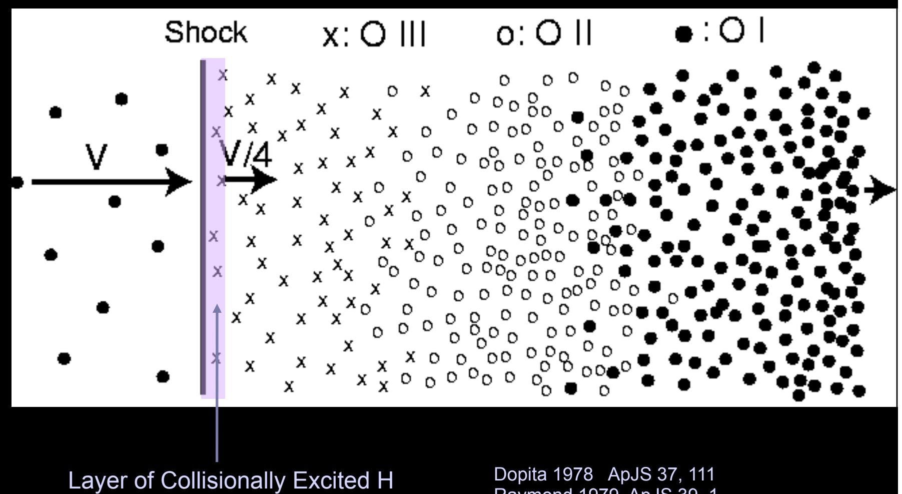
III. Proper Motions, Velocity Structure

IV. Collimation, Opening Angles

V. Magnetic Fields

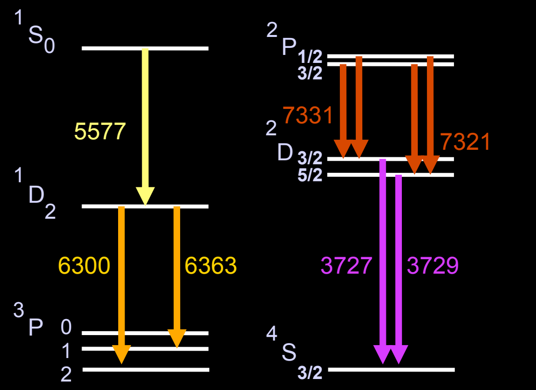
VI. Internal Dynamics

I. Cooling Zones Behind A Radiative Shock



Dopita 1978 ApJS 37, 111
Raymond 1979 ApJS 39, 1

II. Density, Temperature, Ionization Fraction
What to do with the observed line ratios?



O I ($1s^22s^22p^4$)
C I, N II, O III, Ne III, Ar III

O II ($1s^22s^22p^3$)
N I, S II, Ne IV, Ar IV

II. Many Lines, Te and Ne

1956 ApJ 123 379

A SPECTROPHOTOMETRIC ANALYSIS OF THE BRIGHTEST HERBIG-HARO OBJECT*

KARL-HEINZ BÖHM†
Lick Observatory, University of California
Received December 23, 1955

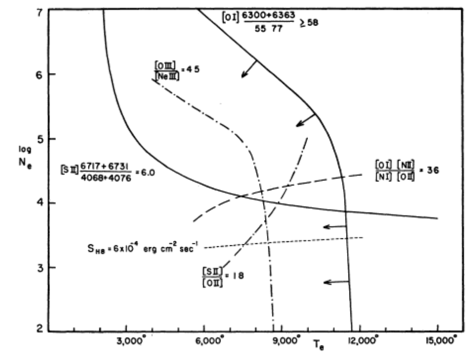
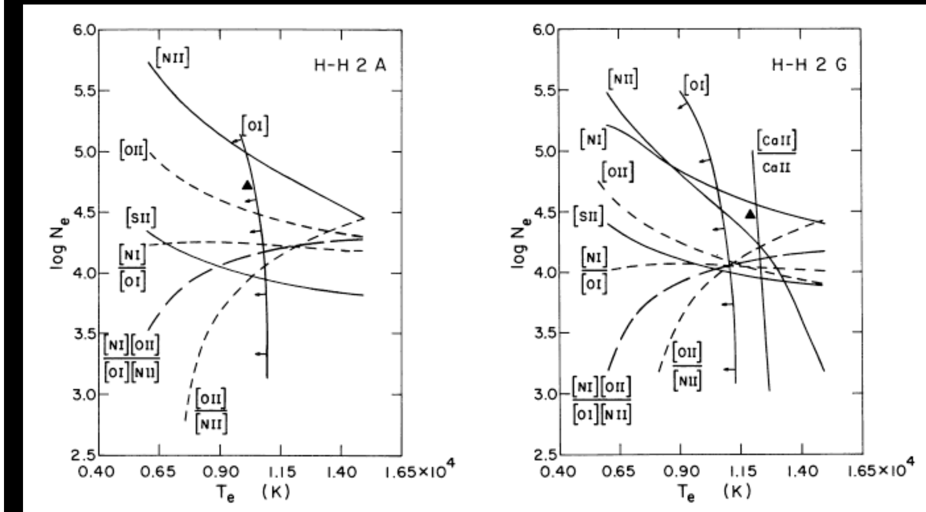


FIG. 1.—The relationships between log N_e and T_e that correspond to the observed intensity ratios of forbidden lines and to the observed surface brightness in H8.

II. Many Lines, Te, Ne

Brugel, Bohm and Mannery 1981

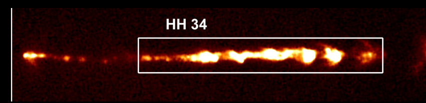


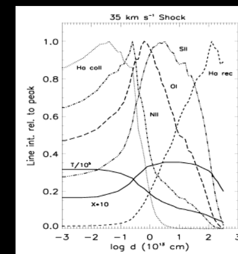
No single density or temperature describes HH objects

Filling factor is low

II. Many Lines, Range of Te, Ne, X

Hartigan, Morse and Raymond 1994, ApJ 436, 125





Fit a single shock model to the observed line ratios integrated over a section of the jet

Find: V_s ~ 25 – 40 km/s

<< V_{jet}, so must have multiple bows, Dopita 1976!

Mass Loss Rate: = MV/L; M=emitting mass, V=velocity, L=length
use luminosity to get M in beam [problems: gas that does not emit; L to M conversion requires T_e, N_e, abundances; need dereddened luminosities]

… or = ρVA = $(m_H N_e/X_H)$VA, A=area, N_e=electron density, X_H= H ionization fraction
[problems: single N_e, X_H, what is A for a real jet (not a cylinder)?, what is 'average' density in a clumpy shocked flow – some average of preshock and postshock?]

Find $\langle X_H \rangle_{SII}$ ~ 0.03

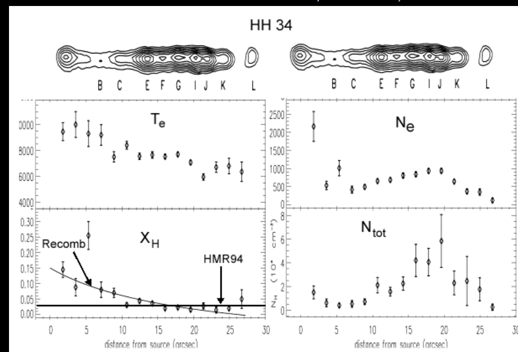
M-dot ~ 3×10^{-7} $M_{\odot}yr^{-1}$

B field hard to get from line ratios, but dramatically affects compression

II. A Few Lines, Single Te, Ne, X at each spatial point

Solve for (T_e,N_e,X_H) at each point in the jet from line ratios
Charge exchange ties X_N = NII/NI and X_O = OII/OI to X_H

Bacciotti and Eisloffel 1999, A&A 342, 717



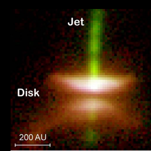
Decline of X_H with distance

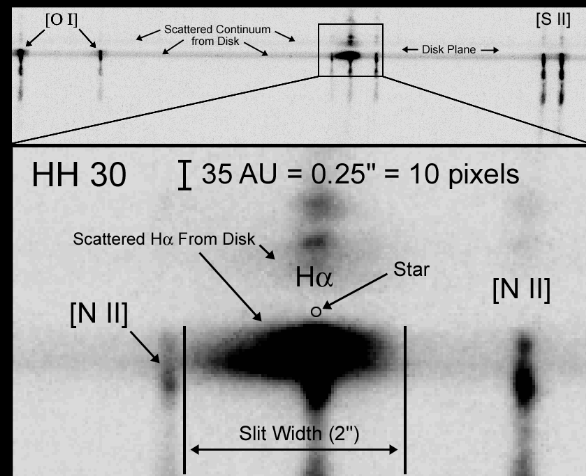
X_H = 0.025 – 0.25,
depending on jet

M-dot = ρVA,
Same problem, clumpy flows

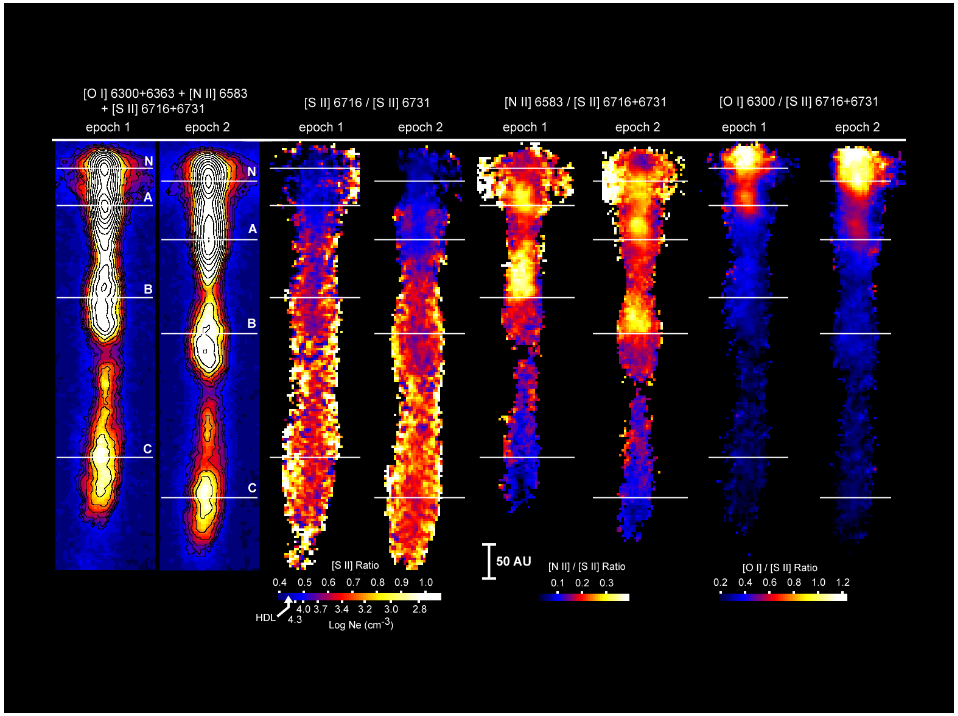
Nisini et al 2005 A&A 441, 159 (also Podio et al 2006) use more lines,
find scatter of T_e (8K – 20K), N_e (10^3 – 10^5 cm^{-3}) like BBM81
Moral: Single N_e,T_e,X_H model works best when cooling zones resolved

II. Multiple Lines, Single Te, Ne, X at each spatial point

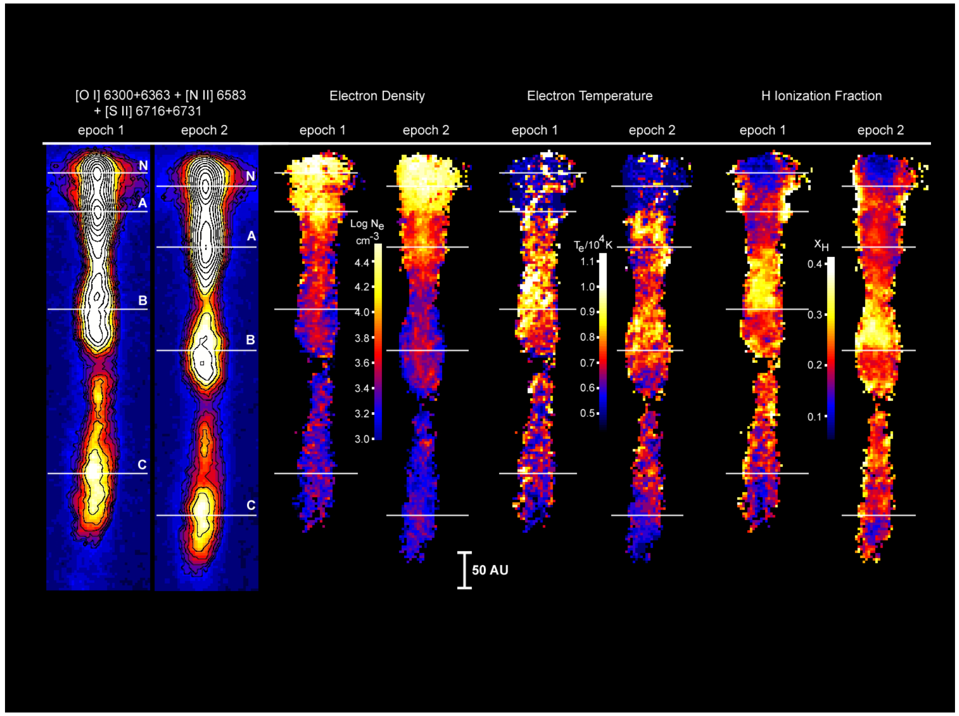




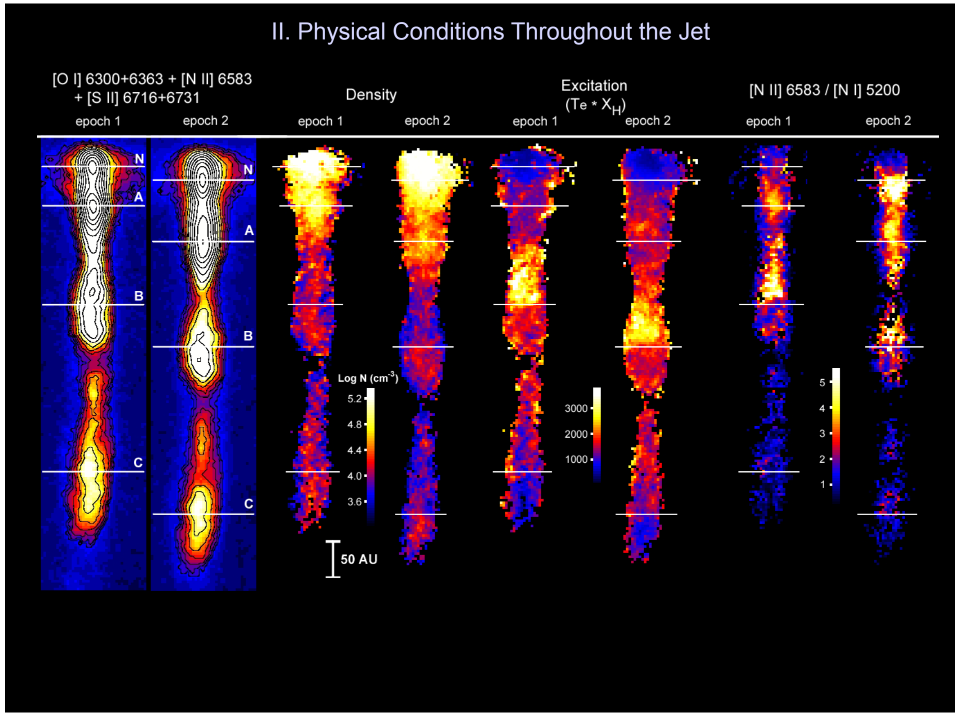
Hartigan & Morse 2007 ApJ 660, 426



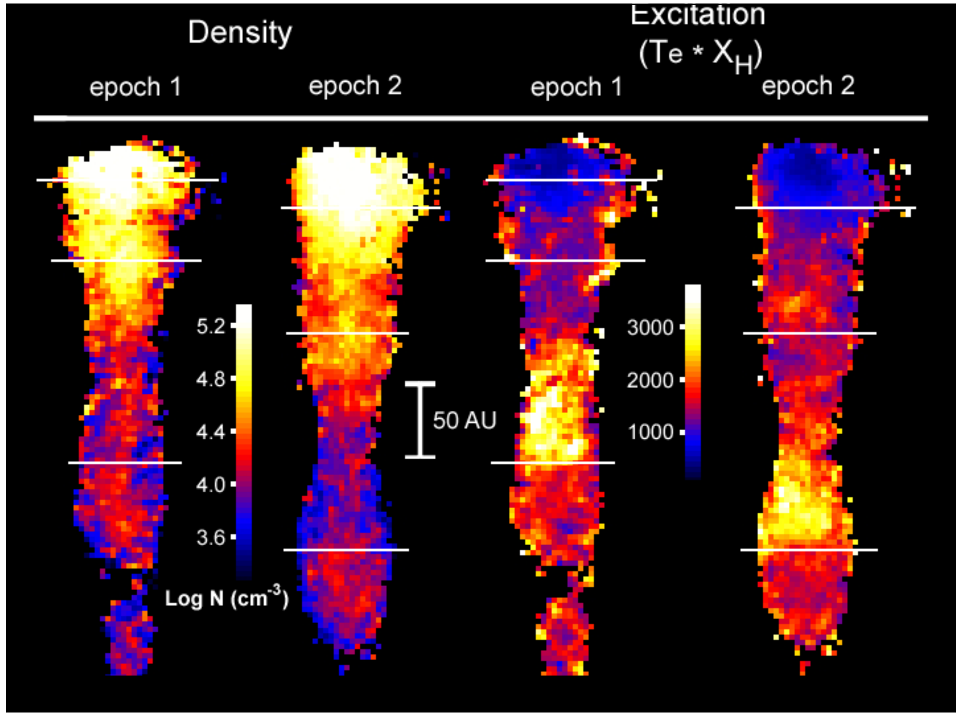
[O I] 6300+6363 + [N II] 6583 + [S II] 6716+6731
[S II] 6716 / [S II] 6731
[N II] 6583 / [S II] 6716+6731
[O I] 6300 / [S II] 6716+6731
epoch 1
epoch 2
N
A
B
C
50 AU
[S II] Ratio
0.4 0.5 0.6 0.7 0.8 0.9 1.0
HDL
4.3 4.0 3.7 3.4 3.2 3.0 2.8
Log Ne (cm-3)
[N II] / [S II] Ratio
0.1 0.2 0.3
[O I] / [S II] Ratio
0.2 0.4 0.6 0.8 1.0 1.2



[O I] 6300+6363 + [N II] 6583
+ [S II] 6716+6731
Electron Density
Electron Temperature
H Ionization Fraction
epoch 1
epoch 2
N
A
B
C
Log N_e cm^{-3}
$T_e/10^4$ K
x_H
50 AU



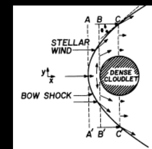
II. Physical Conditions Throughout the Jet
[O I] 6300+6363 + [N II] 6583 + [S II] 6716+6731
Density
Excitation (Te * X_H)
[N II] 6583 / [N I] 5200
epoch 1
epoch 2
N
A
B
C
Log N (cm^-3)
5.2
4.8
4.4
4.0
3.6
3000
2000
1000
5
4
3
2
1
50 AU

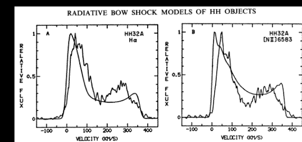


Density
Excitation
(Te * X_H)
epoch 1
epoch 2
epoch 1
epoch 2
5.2
4.8
4.4
4.0
3.6
Log N (cm-3)
50 AU
3000
2000
1000

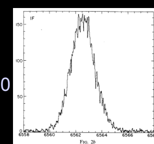
III. Proper Motions, Velocity Structure

Linewidths > 100 km/s
Suggest Bow Shocks
Schwartz 1978 ApJ 223, 884





Initial Bow Shock Models
Account for Large Linewidths
Hartmann & Raymond 1984, Ap J 276, 560



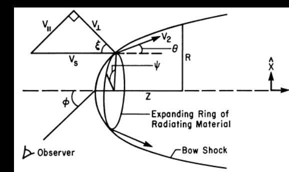
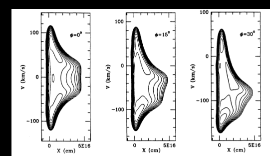


FIG. 1.—Bow shock geometry

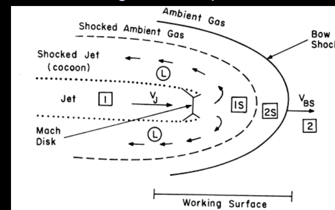
Hartigan, Raymond, Hartmann
1987, ApJ 316, 323



Raga & Bohm 1986, ApJ 308, 829

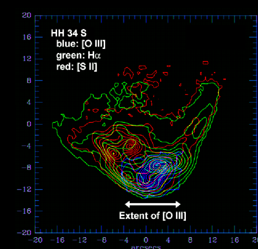
III. Bow Shock/Mach Disk Structures

Hartigan 1989 ApJ 339, 987



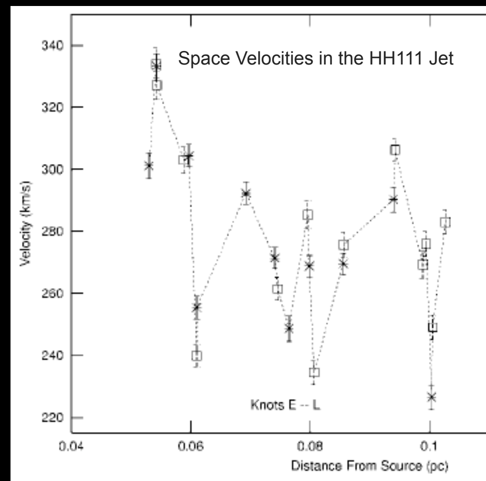
This paper uses a simple model to determine which of the two principal shocks at the end of a stellar jet, the bow shock or the Mach disk, emits more light at Hβ. We find that the two shocks should have comparable surface brightness provided the jet and ambient medium densities do not differ by more than one to two orders of magnitude, and both shocks are radiative.

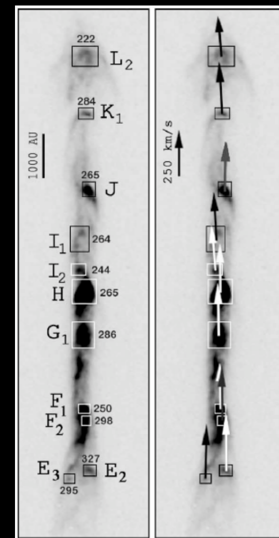
Reipurth & Heathcote
1992 A&A 257, 693



Morse et al 1992, ApJ 399, 231

III. Errors in HST Proper Motions Small Compared to Differential Motions

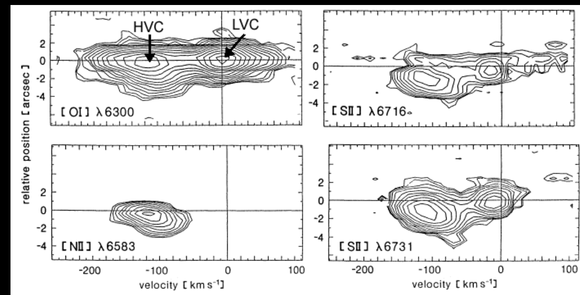




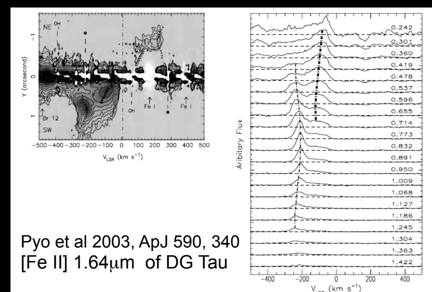
…and differential motions agree with shock models

Hartigan et al 2001

III. Close to the Source: Position/Velocity Diagrams



Hirth, Mundt, & Solf
1994, A&A 285, 929
(CW Tau)

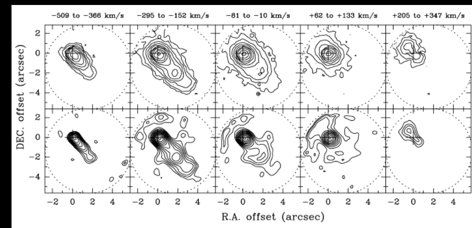


Pyo et al 2003, ApJ 590, 340
[Fe II] 1.64μm of DG Tau

Connection to Disk Wind/X-wind Models
Cabrit, Ferreira, & Raga 1999, A&A 343, 61
Shang, Shu, & Glassgold 1998, ApJ 493, L91

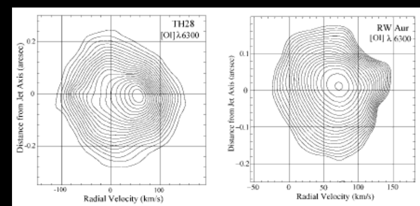
Need to know how & where jet is heated

III. Close to the source: Slit Mapping, Image Slicers



Jet is fastest along the axis

Lavalley et al 1997, A&A 327, 671



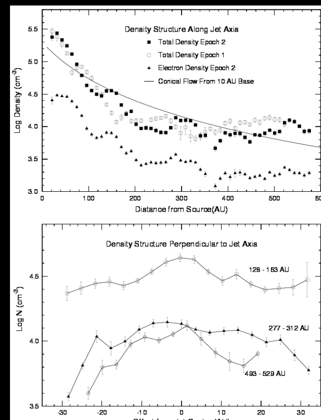
… and may even be rotating

Coffey et al 2004, ApJ 604, 758

Woitas et al. 2005 A&A 432, 149

III. Density and Velocity Structure Near Source

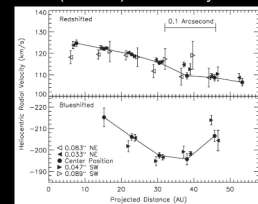
Density Structure on 10 AU Scales [HST; HH 30]



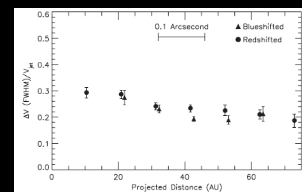
VLT: H_2 usually on sides but sometimes in jet
(Davis et al 2011, A&A 528, A3)

Velocity Structure on 10 AU Scales [Keck AO; RW Aur]

(Hartigan & Hillenbrand 2009 ApJ [Fe II] 1.64μm
Spatial = 0.06" (8.4 AU) Velocity res= 20 km/s

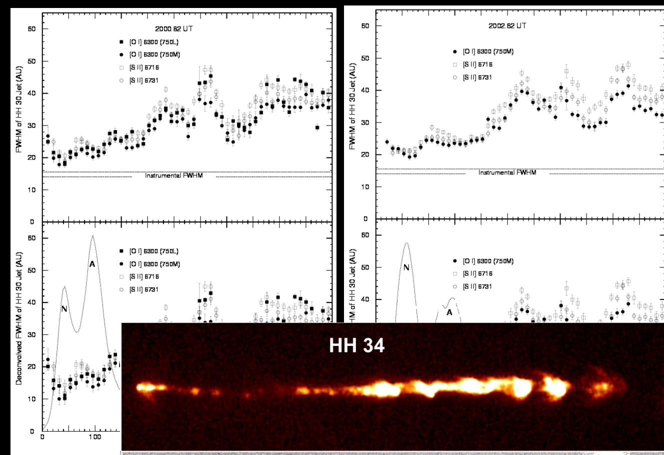


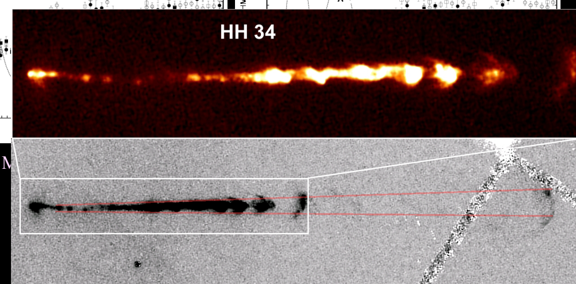
Note: blueshifted twice as fast as redshifted



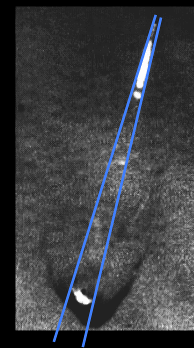
But ratio of FWHM to velocity is the same for both

IV. Jet Collimation





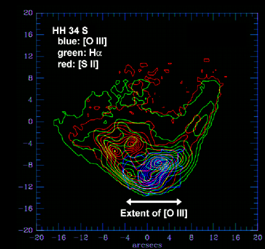
Hartigan & M



Reipurth et al. 1986

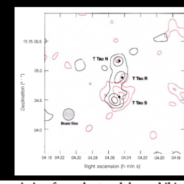
V. Magnetic Fields

- The fact that there are shocks limits B (Hartigan et al. 2007 ApJ)
- Use observed compression: weak preshock B amplifies in cooling zone (Morse et al 1992)
- Radio continuum polarization (Ray et al 1997; Carrasco-Gonzalez et al 2010)



Morse et al. 1992, ApJ 399, 233

Fairly easy to measure compression
Several spatially-resolved emission lines and ratios give V_{shock}
→ Together give B ~ 30 μG in front of bow shock



The radio emission from the two lobes exhibits strong circular polarization of opposite helicity, implying the existence of a strong, ordered magnetic field at a surprisingly large distance from the source.

Ray et al 1997 Nature 385, 415 B = several G

Carrasco-Gonzalez et al. 2010, Science 330, 1209 B=0.2mG

VI. Dynamics