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Jetset, Rhodes
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Magnetic Fields in Stellar Jets

OVERVIEW OF TALK

I. PHYSICS BEHIND FIELD MEASUREMENTS

- Zeeman Splitting
- Synchrotron Emission
- Emission Lines in Shocked Cooling Zones

II. IMPLICATIONS OF PULSED MAGNETIC FLOW

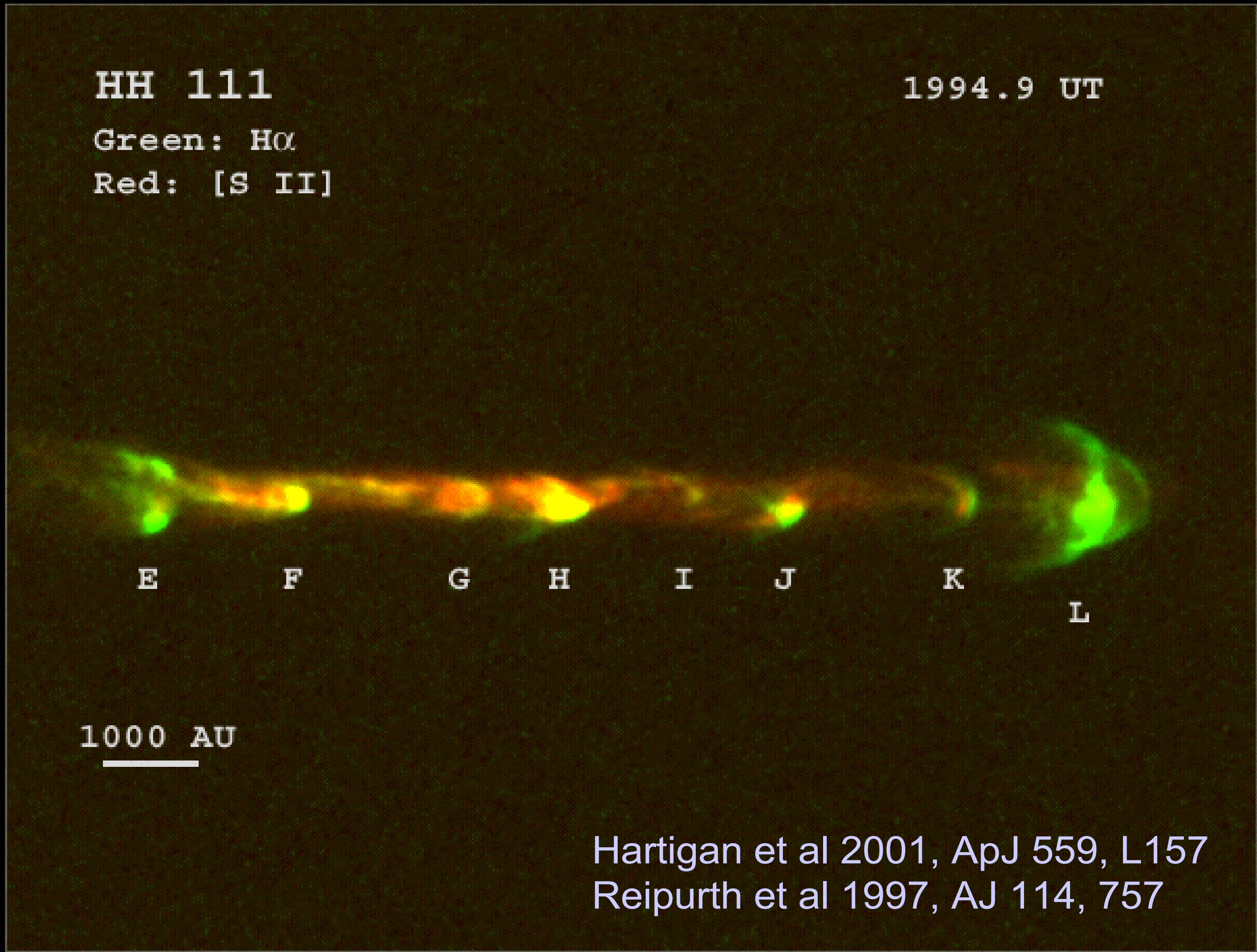
- Numerical Models

III. INFORMATION ABOUT JET LAUNCHING RADII

- LVC HVC Measurements

IV. A FUN SURPRISE (Only sort of related to B fields)

What field tracers to use – roughly, how strong is the field?



So, V_A <~ 30 km/s, $n_{preshock}$ ~ 100 cm^{-3}, So $B_{preshock} < 140\ \mu G$
Want tracers sensitive in 10μG – 10 mG regime

Non-relativistic Hamiltonian Magnetic Perturbation Terms

Electron in Atom, Nonrelativistic Quantum, No Spin

$$\mathbf{H} = \frac{(\mathbf{p} - e\mathbf{A}/c)^2}{2m} + \text{electrostatic terms (e-nucleus, e-e)}$$

Uniform external $\mathbf{B} = \mathrm{B}_\circ\,\hat{\mathbf{z}} \longrightarrow \mathbf{A} = -\frac{1}{2}\mathbf{r} \times \mathbf{B}$

$$\mathbf{H} = \frac{p^2}{2m} + \frac{e}{4mc}[\mathbf{p}\cdot(\mathbf{r} \times \mathbf{B}) + (\mathbf{r} \times \mathbf{B})\cdot\mathbf{p}] + \frac{e^2}{8mc^2}(\mathbf{r} \times \mathbf{B})^2 + \text{es-terms}$$

$$= \frac{p^2}{2m} + \frac{e}{4mc}[\mathbf{B}\cdot(\mathbf{p} \times \mathbf{r}) + (\mathbf{p} \times \mathbf{r})\cdot\mathbf{B}] + \frac{e^2}{8mc^2}\left[r^2 B^2 - (\mathbf{r}\cdot\mathbf{B})^2\right] + \text{es- terms}$$

$$= \text{es-terms} + \frac{p^2}{2m} \quad - \frac{e}{2mc}\mathbf{L}\cdot\mathbf{B} \quad + \frac{e^2 B^2}{8mc^2}\left(x^2 + y^2\right)$$

$\mathrm{H}_\circ$

H_1 paramagnetic

H_2 diamagnetic

$\mathrm{H}_1 >> \mathrm{H}_2$

Consider H_1

$\mathbf{L}\cdot\mathbf{B} = \mathbf{L}\cdot\mathrm{B}_\circ\hat{\mathbf{z}} = \mathbf{L}_Z\mathrm{B}_\circ = m_l\hbar B_\circ$

$\mathrm{H}_1 = -\frac{e\hbar}{2mc}B_\circ m_l = -\mu_B B_\circ m_l$

where μ_B = Bohr Magneton $= \frac{e\hbar}{2mc} = 9.26 \times 10^{-21}$ cgs.

$\mathrm{H}_1 = -\frac{\mu_B}{\hbar}\mathbf{L}\cdot\mathbf{B}$

For spin, $\overrightarrow{\mu_S} = -\mathrm{g}_S\mathbf{s}\mu_B$, $\mathrm{g}_S = 2.0023 \sim 2.$

So, $\overrightarrow{\mu_i} = -\mu_B\left(\mathbf{l_i} + 2\mathbf{s_i}\right)$ for each electron

Magnetic Perturbation in L-S Coupling

For L-S coupling, $\mathbf{J}$ specifies the quantum state

$$\mathrm{H}_1 = -\frac{\mu_B}{\hbar}\mathrm{g}_J \mathbf{J}\cdot\mathbf{B} \; ; \; \mathrm{g}_J = \frac{\mathbf{L}\cdot\mathbf{J}}{J^2} + \frac{2\mathbf{S}\cdot\mathbf{J}}{J^2}$$

$$\mathbf{L} = \mathbf{J} - \mathbf{S}$$

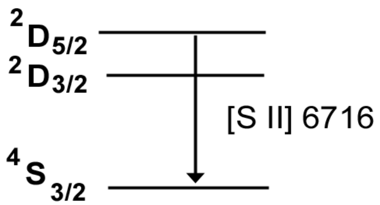
$$\mathbf{S}\cdot\mathbf{J} = \frac{1}{2}\left(J^2 + S^2 - L^2\right) = \frac{\hbar^2}{2}\left[j(j+1) - l(l+1) + s(s+1)\right]$$

$$\mathbf{L}\cdot\mathbf{J} = \frac{1}{2}\left(J^2 - S^2 + L^2\right) = \frac{\hbar^2}{2}\left[j(j+1) + l(l+1) - s(s+1)\right]$$

With $\mathrm{g}_S = 2$ we get

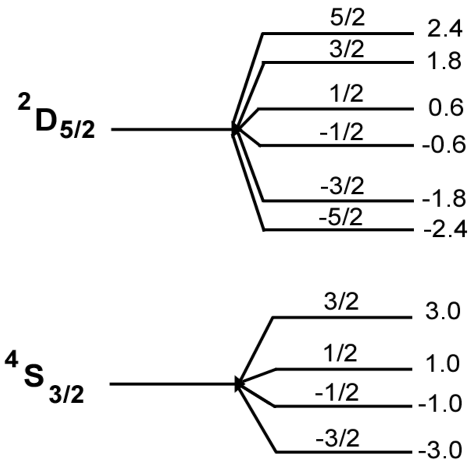
$$\mathrm{H}_1 = \mu_B B_\circ m_j \left[\frac{3j(j+1) - l(l+1) + s(s+1)}{2j(j+1)}\right] \sim \mu_B \mathrm{B}_\circ$$

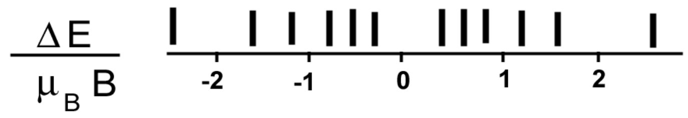
Energy Level Pattern, Energy Splitting in Velocity Units



$^2D_{5/2}$: S = 1/2, L = 2, J = 5/2; $g_J = 6/5$

$^4S_{3/2}$: S = 3/2, L = 0, J = 3/2; $g_J = 2$





+/- 2.4, 1.6, 1.2, 0.8, 0.6, 0.4

Magnetic Dipole $\Delta m = 0, +/- 1$

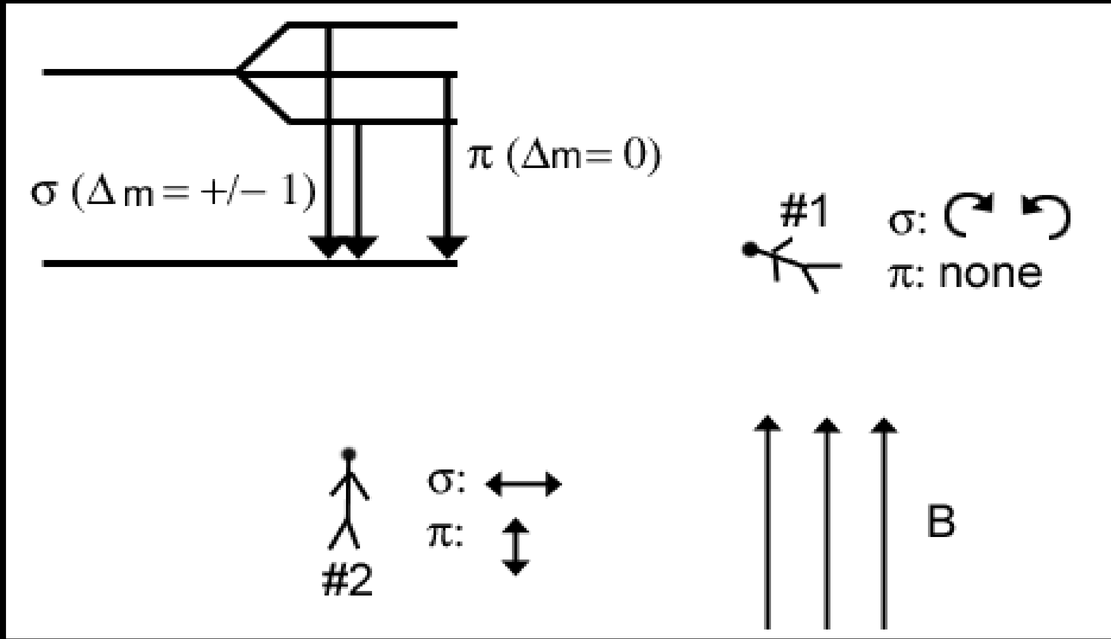
$$\frac{\Delta v}{c} \sim \frac{2\mu_B B}{h\nu}$$

$$\Delta v = 5.9 \times 10^{-4} \left(\frac{B}{\mu G}\right) \left(\frac{\lambda}{21\mathrm{cm}}\right) \mathrm{km\,s^{-1}}$$

$$\Delta v = 2.8 \left(\frac{B}{kG}\right) \left(\frac{\lambda}{1\mu\mathrm{m}}\right) \mathrm{km\,s^{-1}}$$

- Zeeman broadening often overwhelmed by Doppler
- Long wavelengths are better

Polarization



Strategies

- Subtract: LCP – RCP, look for signature (gives $B_{||}$)
- Compare broadening of magnetically sensitive lines to magnetically insensitive lines
- Resolve individual components and get B from the split

Zeeman Examples

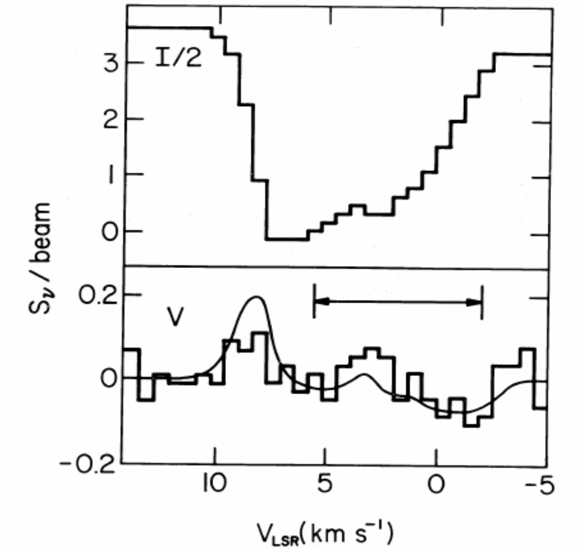
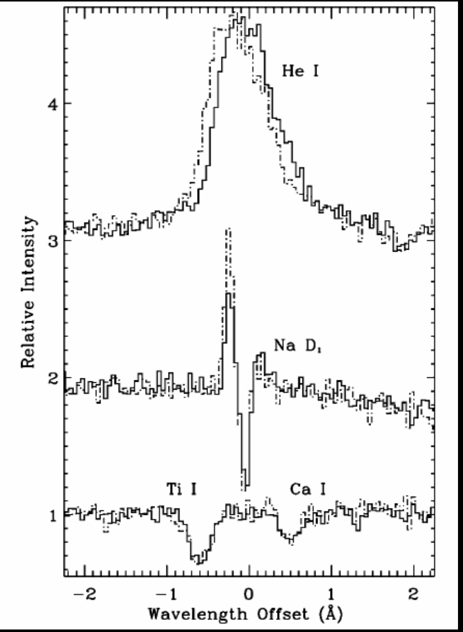


FIG. 8.—The same as Fig. 2 except for the position α[1950] = 05ʰ32ᵐ50ˢ0, δ[1950] = −50°23′06″12. The smooth line superposed upon the V spectrum represents a magnetic field of −174 μG, fitted over the channels denoted by the horizontal arrow.

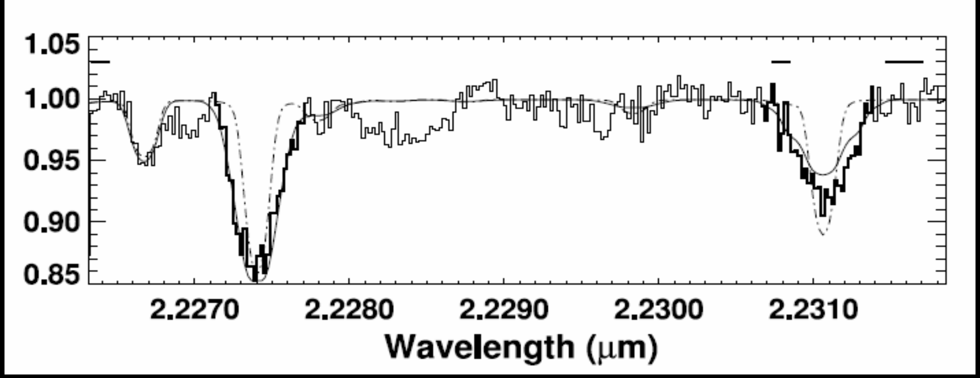
21 cm Circular Polarization in Orion A
$B_{||}$ = 174 μG +/- 20 μG (0.012 km/s)
(Troland, Heiles and Goss 1989 ApJ 337, 342)

Optical Ca II H&K circular polarization
+/- 30 G for Ae/Be stars with VLT
(Hubrig etal 2006 A&A 446, 1089)



BP Tau
He I 5876
Solid: LCP
Dashed: RCP
$B_{||}$ ~ 2.5 +/- 0.1 kG

Johns-Krull et al 1999, ApJ 510, L41

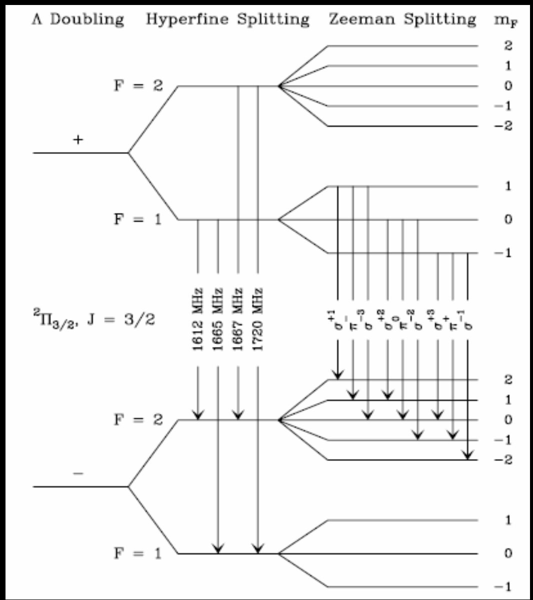


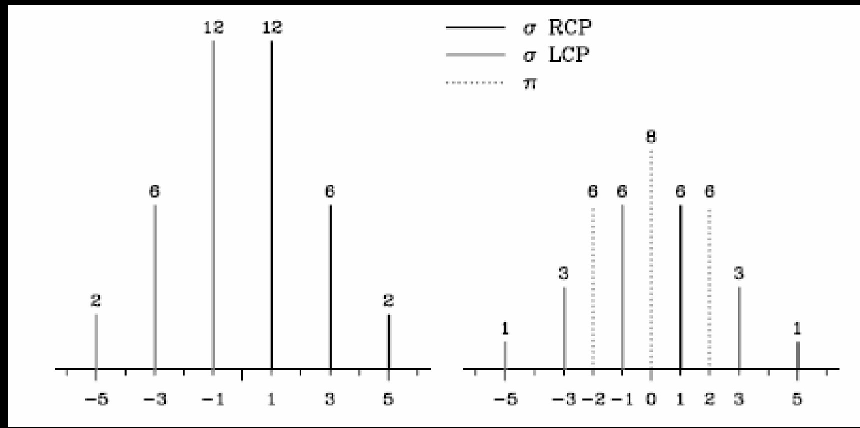
NIR Line Broadening on TTS
Solid: B = 2.5 kG; Dashed: B=0
Johns-Krull et al 2004, ApJ 617, 1204

Zeeman Examples: Masers

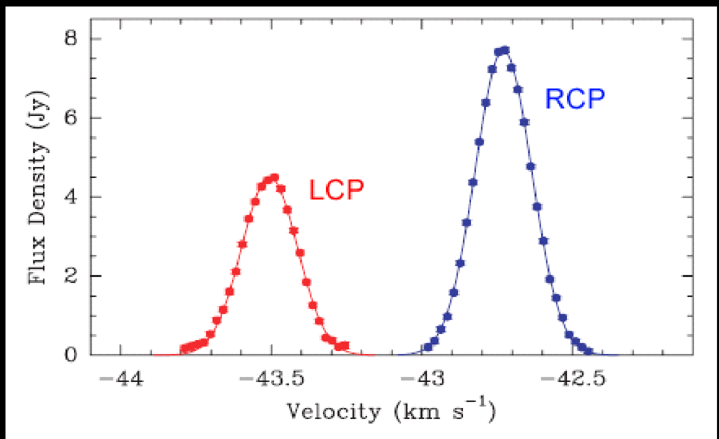
OH Masers in Massive Star Region W3
B ~ 5mG

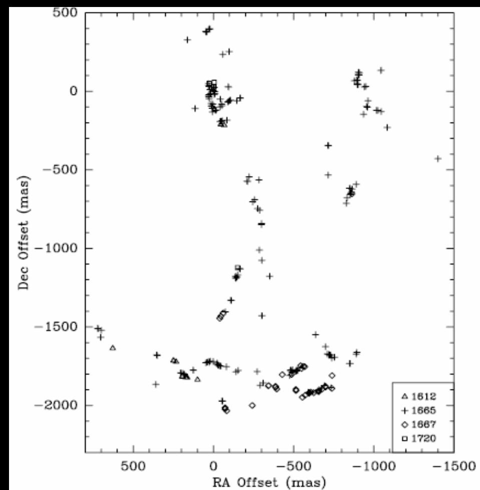
Fish et al 2006, ApJ 647, 418



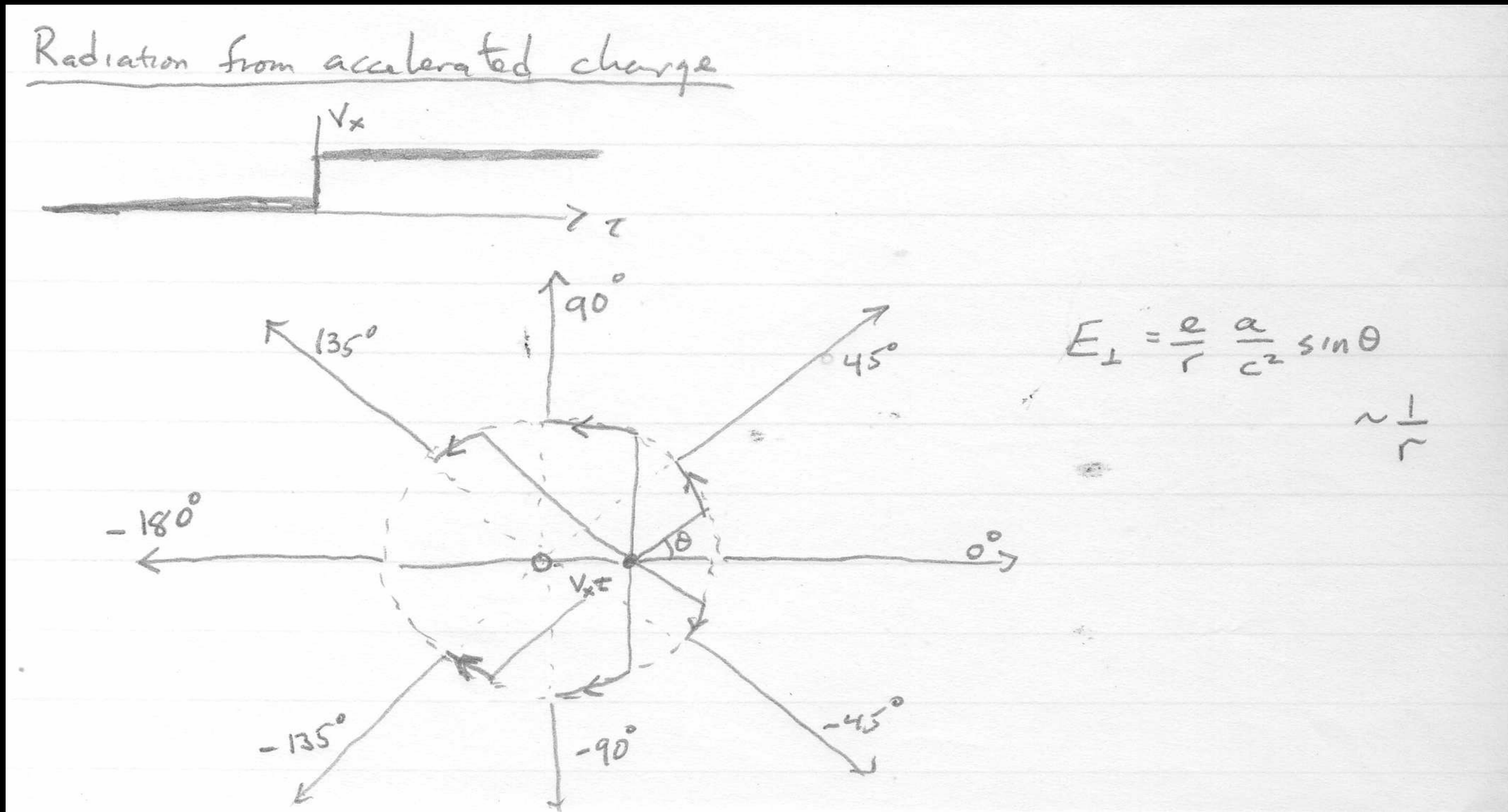


0.6 km/s
for B = 1mG

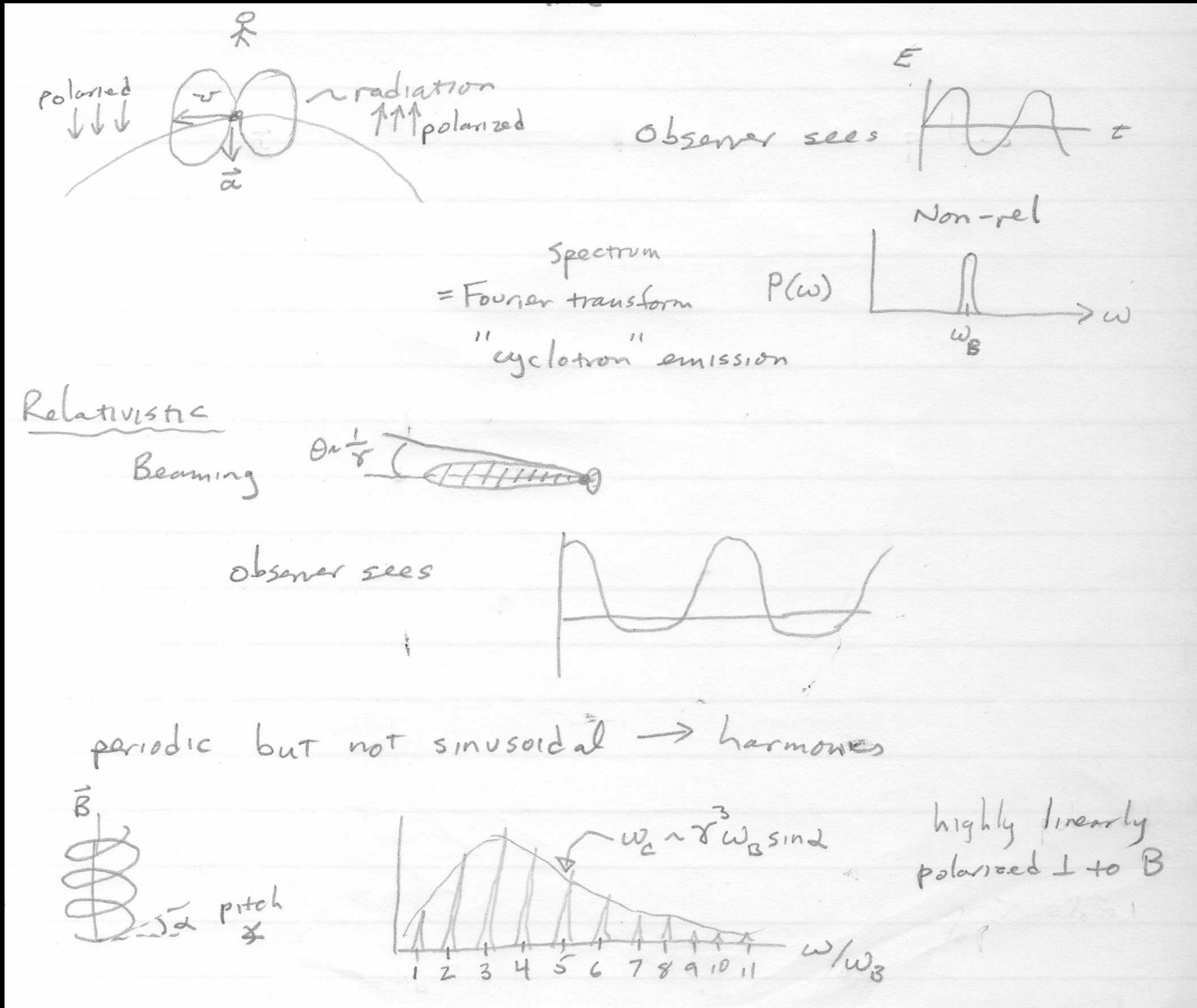




Physical Reason Why Accelerated Charges Radiate, Why the Radiation Pattern is sinθ and Why it is Polarized

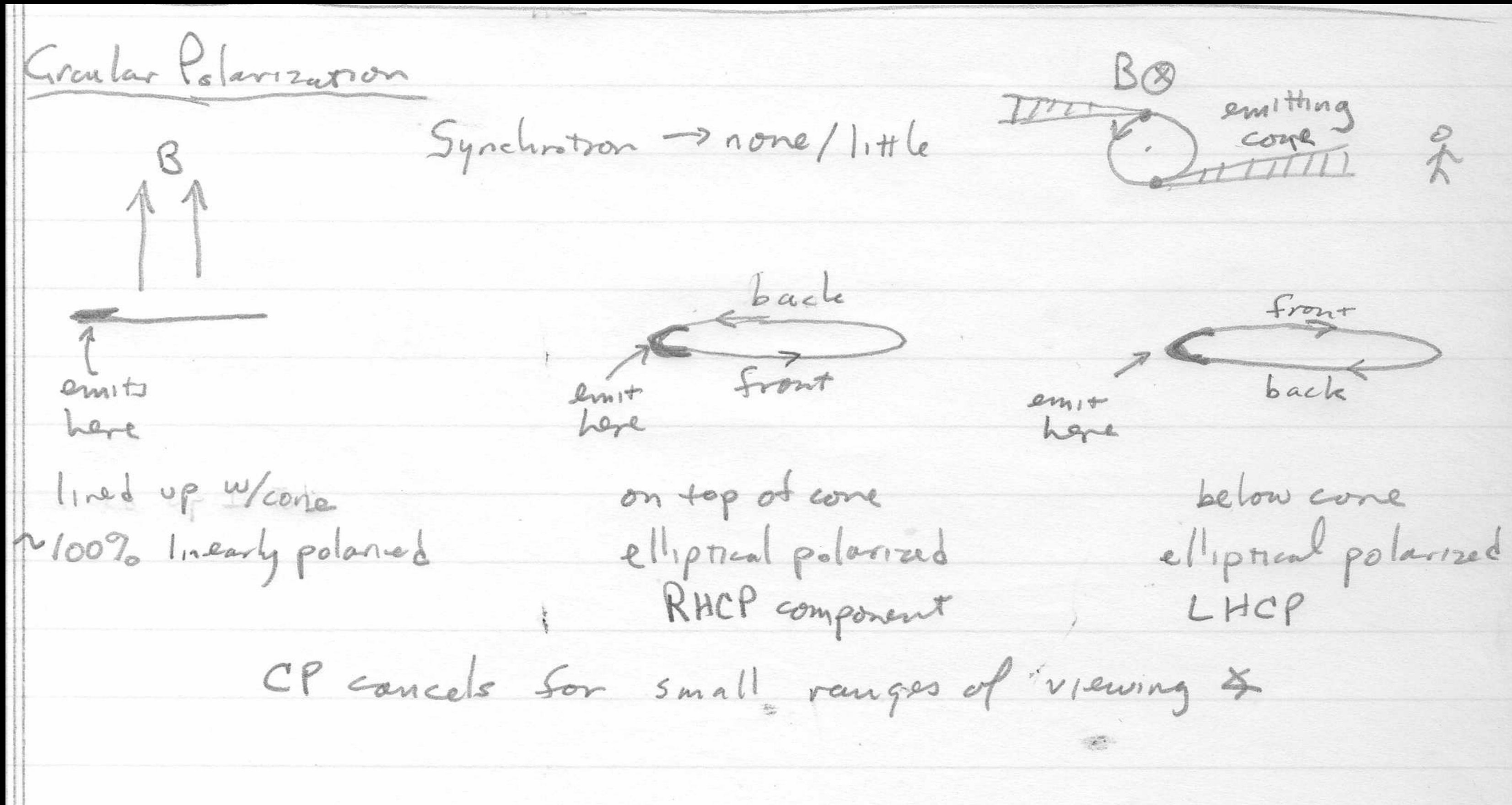


Cyclotron Spectra and Harmonics, Beaming



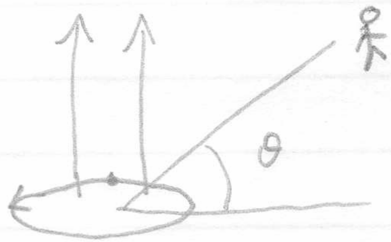
Power $P(\omega) = F(\omega,\gamma,\alpha)B^{(p+1)/2}$ $p-1=2s$ s=spectral index

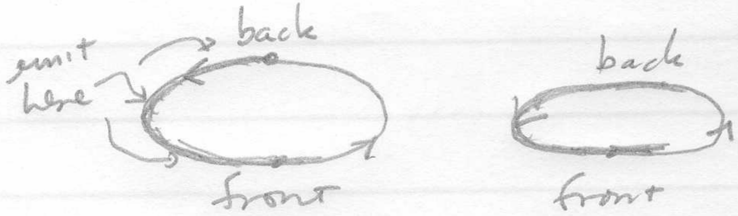
Linear and Circular Polarization of Synchrotron Emission



Circular Polarization of Gyrosynchrotron Emission

Gyrosynchrotron $\gamma \lesssim 3$ (i.e. not much beaming)





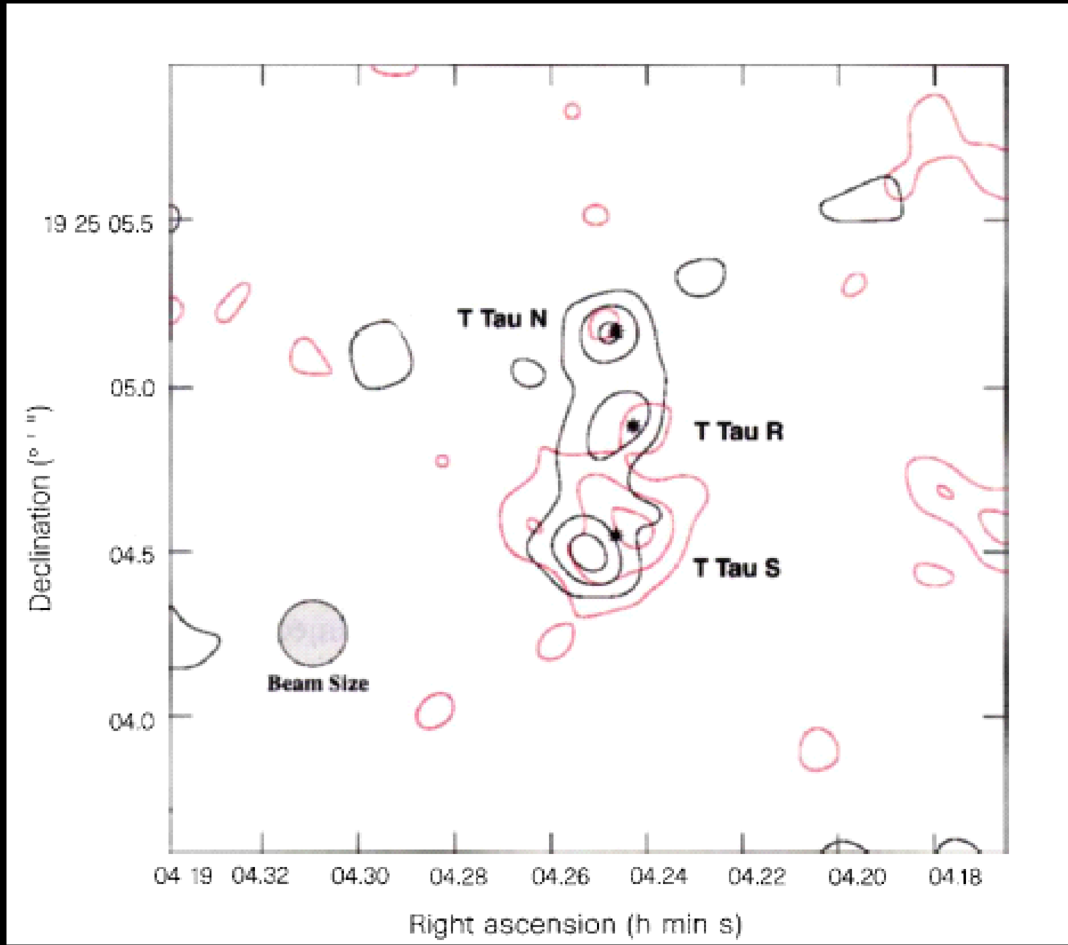
Both RHCP

$N(\epsilon) \sim \epsilon^{-p}$

$$\Rightarrow \Pi_c = \text{const}\, 10^{\frac{p}{28}}\, 10^{-\frac{\cos\theta}{14}} \left(\frac{\gamma\nu\, mc}{eB}\right)^{-0.78+0.55\cos\theta} \sim B^{0.78}$$

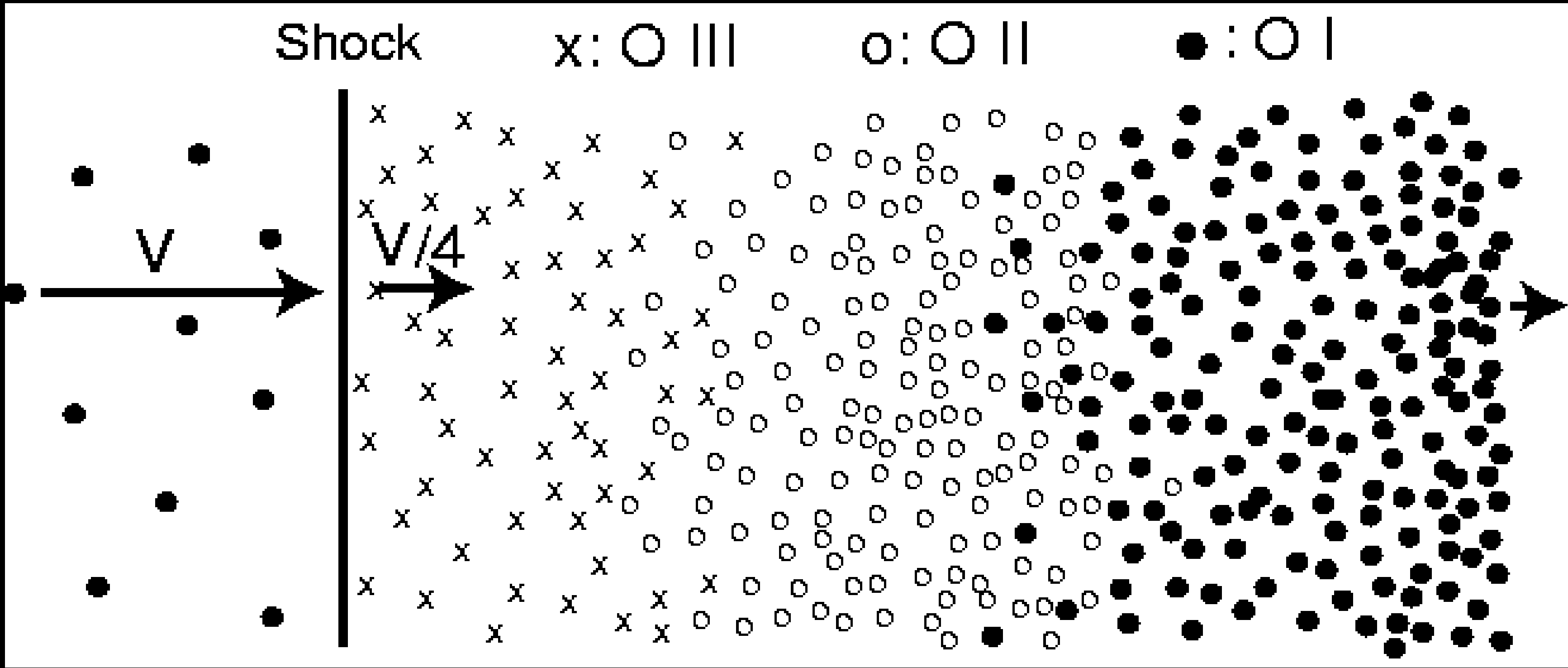
Guess $\gamma, \theta, p \rightarrow B$

Gyrosynchrotron Example

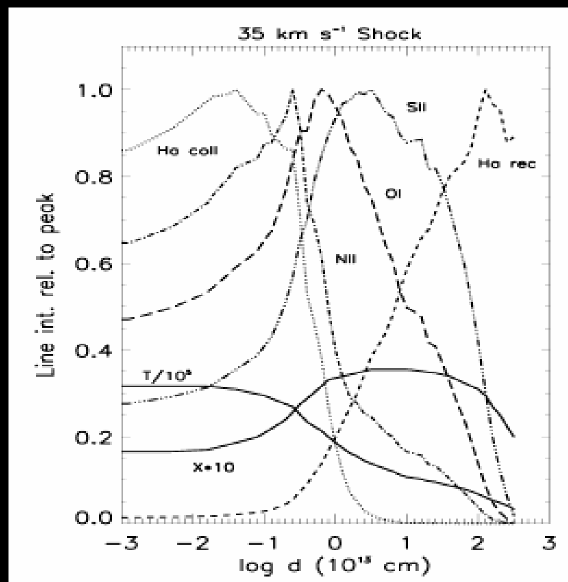


T Tau, 6 cm continuum
Red: RCP, Black: LCP
Offset from star +/- 10 AU
B ~ Gauss
Ray et al 1997, Nature 385, 415

I (c) Cooling Zones Behind A Radiative Shock



Layer of Collisionally Excited H



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

Example of Using Cooling Zone Observations to Measure Component of B Parallel to Shock Front

TABLE 7

EFFECT OF MAGNETIC FIELDS ON LINE RATIOS

Parameter	Large Field Model	Small Field Model
$B_{\parallel}$ (μG)[a]	1000	1
n_0 (cm^{-3})	1.0×10^5	1.08×10^4
V_S (km s^{-1})	50	30
[S II] λ6716/[S II] λ6731	1.11	1.11
[O I] λ6300/Hα	0.97	1.1
[S II] $\lambda\lambda$6723/Hα	2.4	2.7
[N I] $\lambda\lambda$5200/Hβ	2.2	2.5
[N II] λ6583/[O I] λ6300	0.036	0.053
N_e (cm^{-3})	390	390
$F_{(\mathrm{H}\beta)}$ (ergs cm^{-2} s^{-1})	4.4×10^{-4}	4.2×10^{-5}
$\langle C \rangle$[b]	3.0	19
$\langle I \rangle$[b]	0.013	0.019
$\langle N \rangle$ (cm^{-3})[b]	1.7×10^4	4.4×10^3

[a] Component of the preshock magnetic field that lies parallel to the surface of the shock.

[b] As defined in Tables 1–6.

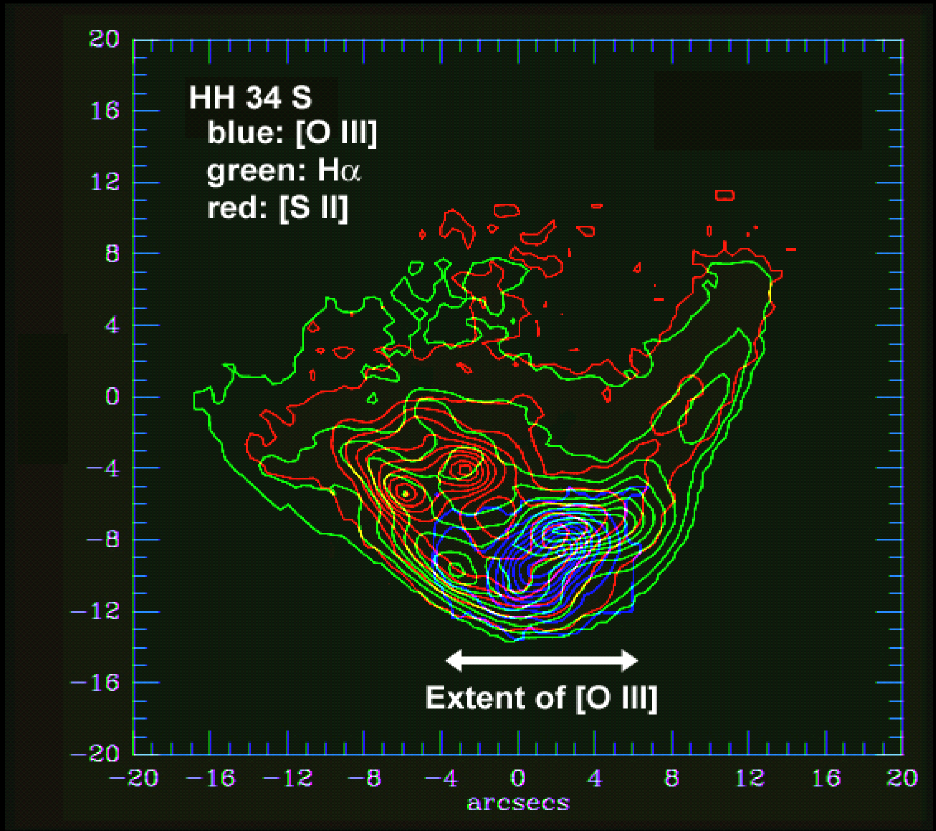
Line ratios nearly degenerate

High (B,V_S,n) ~ Low (B,V_S,n)

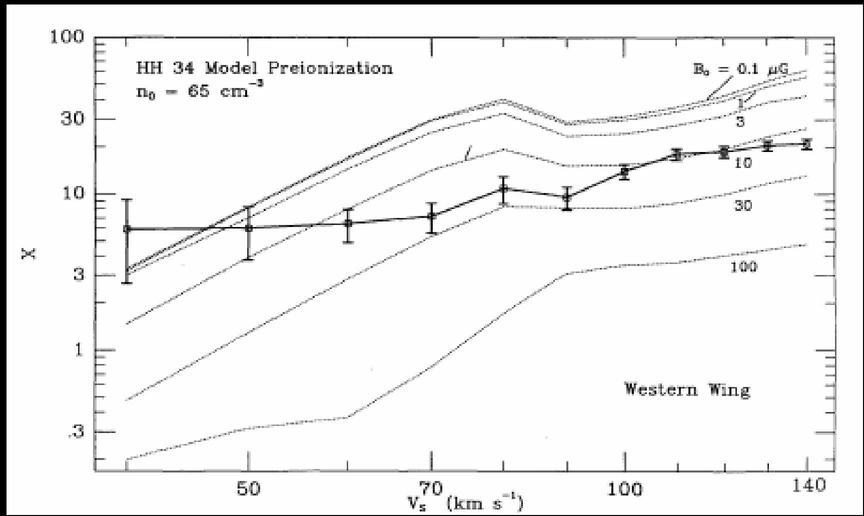
Fluxes break degeneracy

Hartigan et al 1994 ApJ 436 125

Example of Using Cooling Zone Observations to Measure B



Morse et al 1992, 1993



Compression (N_e/N_0) ~ 5 times lower than if B =0

- Use [O III] to get V_S
- Hα flux to get $n_{preshock}$
- Measure N_e

Gives $B_{preshock}$ ~ 15μG for $n_{preshock}$ ~ 65 cm^{-3}

So, B ~ 1G @ 10 AU, ~ 1mG in dense knots, ~ 20 μG in preshock gas

II. Implications of Pulsed Magnetic Flow

Hartigan, Frank, Varniere & Blackman 2007 ApJ

Goals:

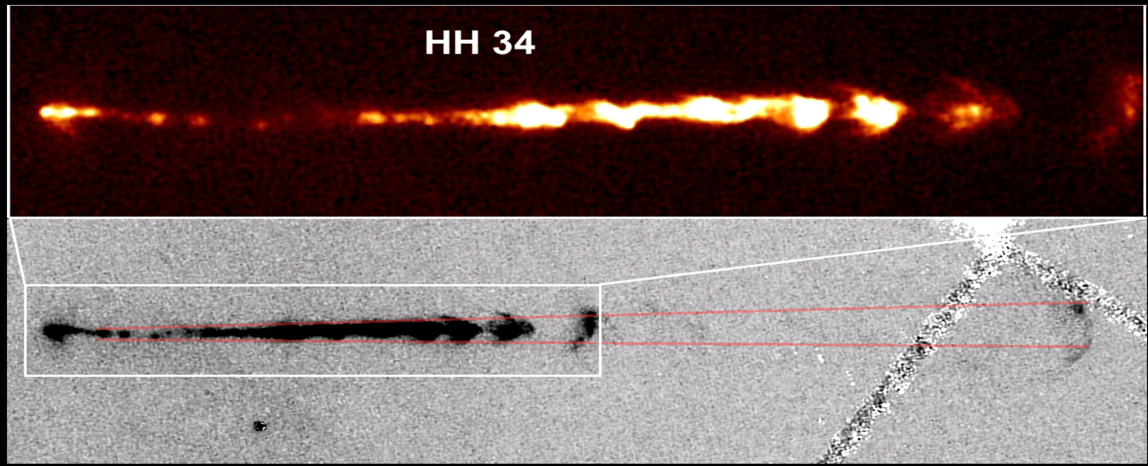
• Understand how velocity variable flows behave when fields are present

• What might we learn about fields closer to the star?

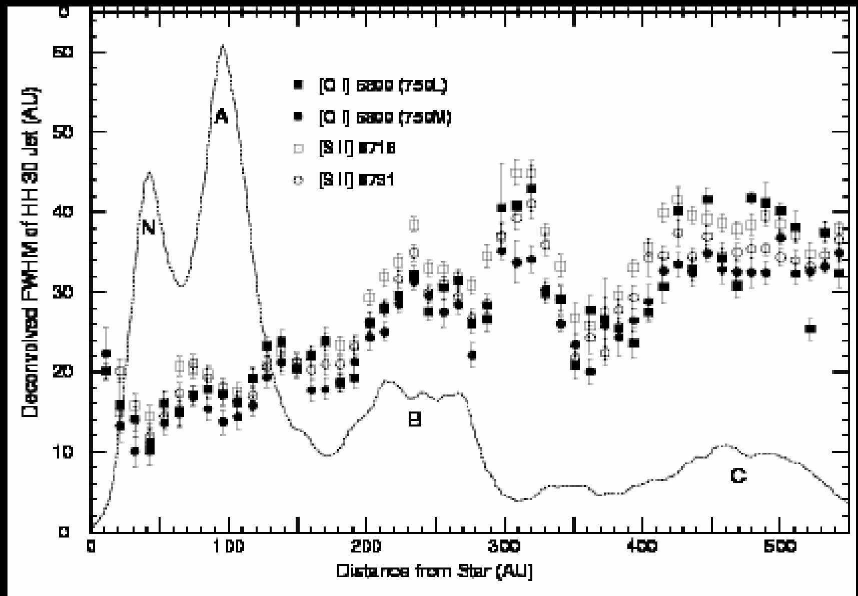
Note → All of this is for R >> R_A

- 2.5 D AstroBEAR simulation
- Random velocity pulses V = 200 + fA   f = -1 to 1; A=10% to 50%
- Conical magnetized flow, opening angle 5-degrees
- B-phi embedded in jet such that V_A = 35 km/s in first cell
- Jet/Ambient density ratio = 7.5
- Follow ~ 35 pulses, bow shock propagates off grid

Why conical?



The jet width increases linearly with distance ….

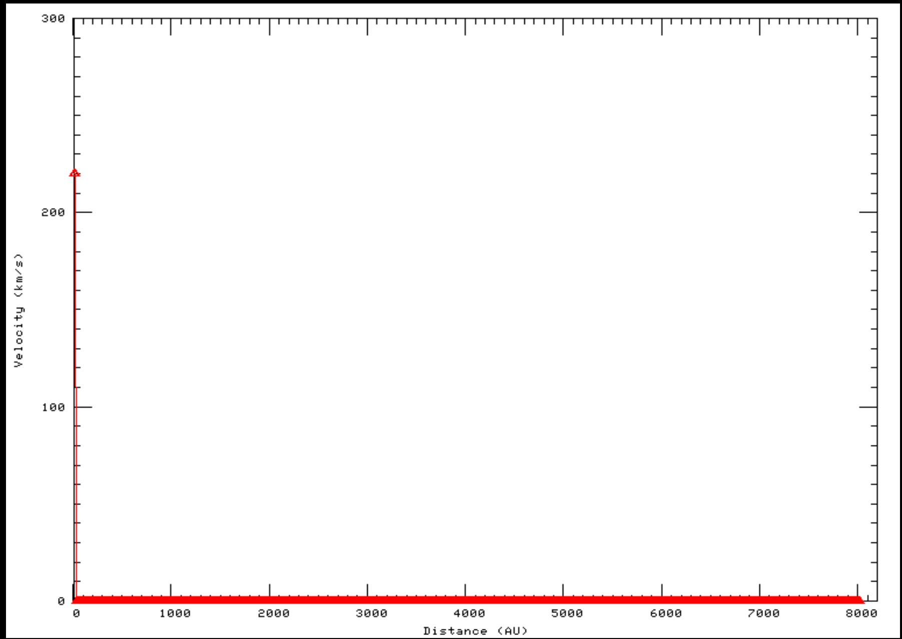


so $n \sim (r+r_0)^{-2}$

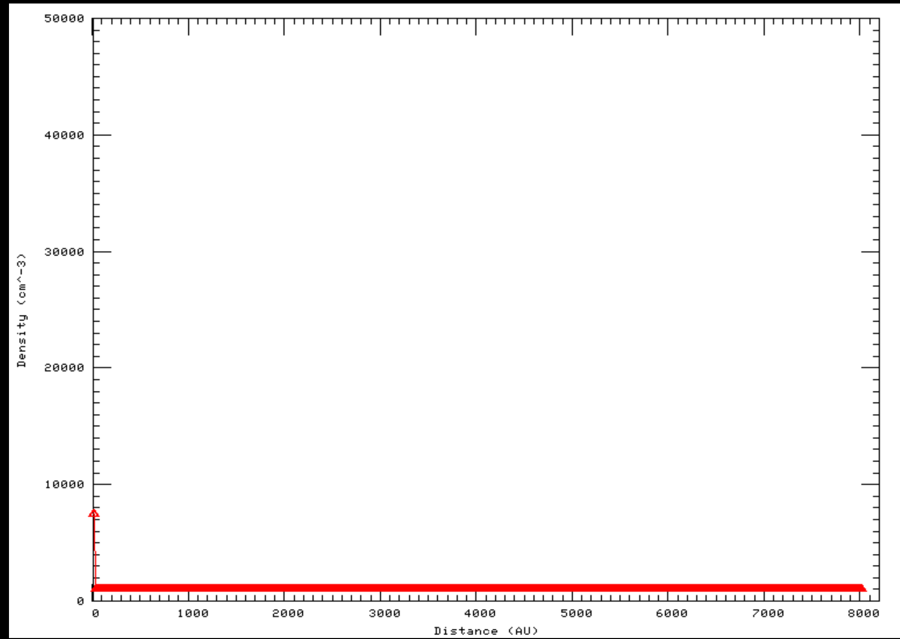
… but the edges of the jet do not project to a point

P. Hartigan (Rice), A. Frank, P. Varniere, E. Blackman (Rochester), 2007 ApJ

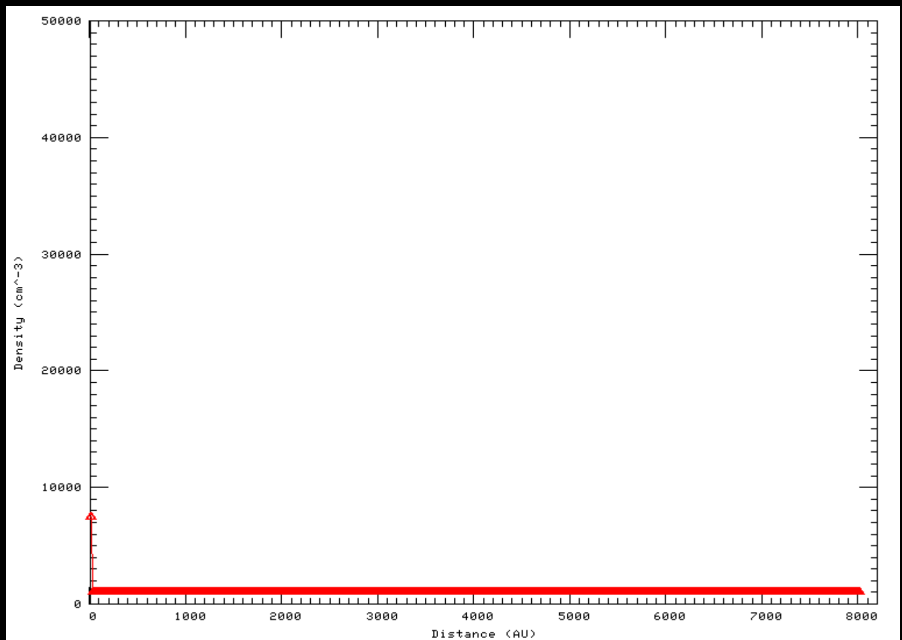
V



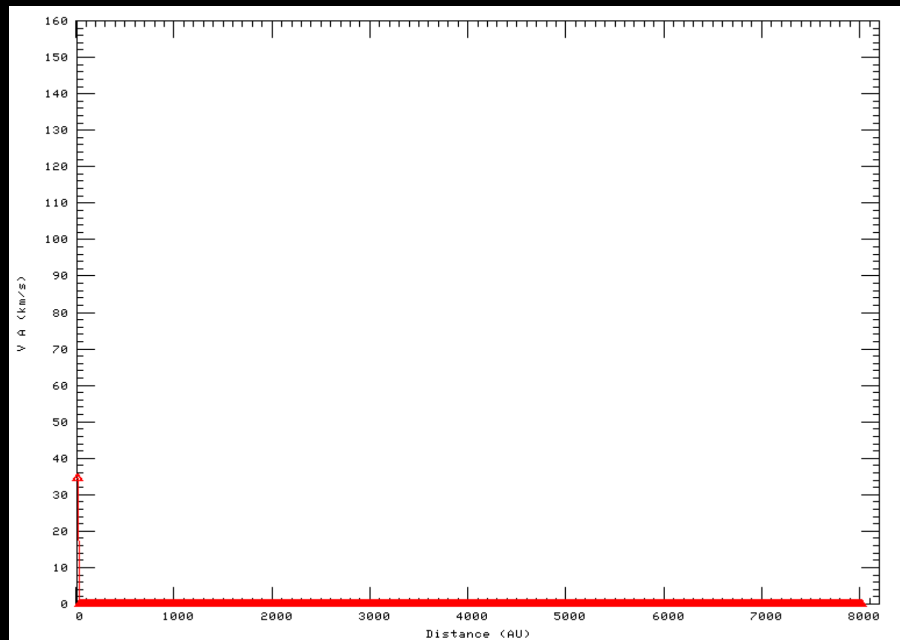
n



n

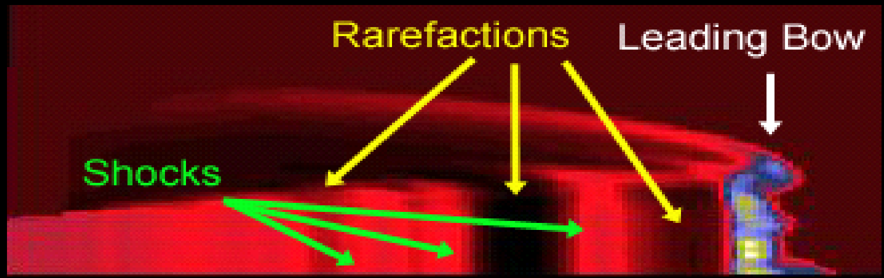


V_A



Distance from source

Distance from source



← Distance along axis of jet →

Table 1.
Average Jet Parameters

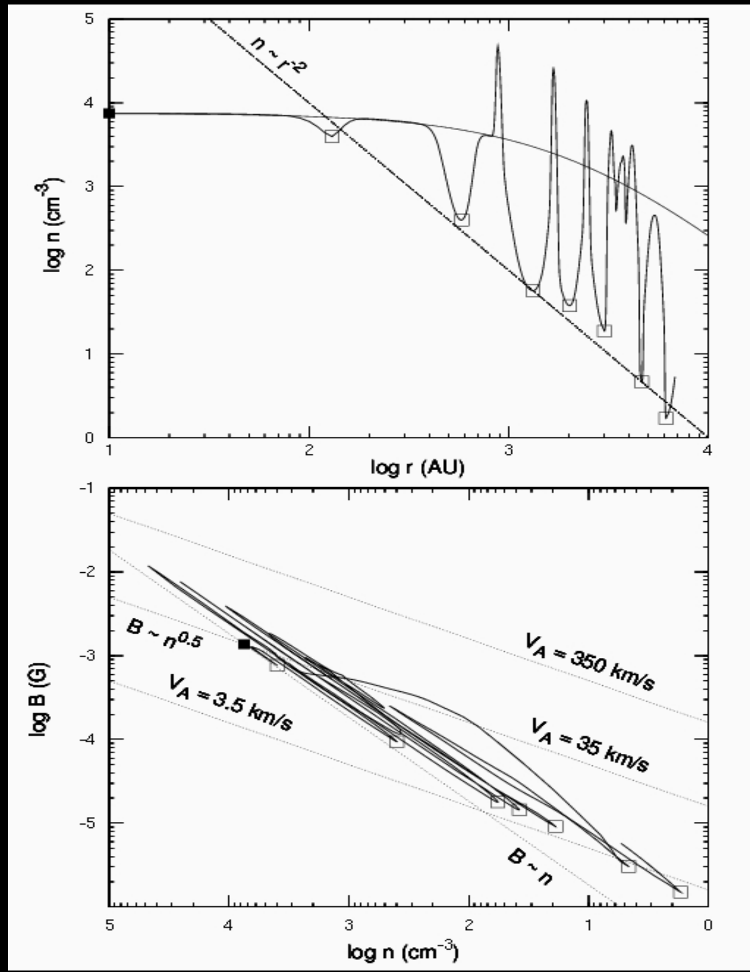
Distance From Star (AU)	Arcseconds[a]	n (cm^{-3})[b]	$B_{\perp}$	V_A (km s^{-1})[c]
10	0.02	2.5×10^{6}	82 mG	113
30	0.06	1.5×10^{6}	53 mG	94
100	0.2	4.5×10^{5}	19 mG	62
300	0.6	8.8×10^{4}	4.8 mG	35
10^{3}	2.2	10^{4}	0.75 mG	16
3×10^{3}	6.5	1.2×10^{3}[d]	124 μG[d]	7.8
10^{4}	22	110[d]	16μG[d]	3.3
3×10^{4}	65	12[d]	2.4μG[d]	1.5

[a]Spatial offset from the star at the distance of the Orion star forming region (460 pc).

[b]Densities for a conical flow with a half opening angle of 5 degrees and a base width of 10 AU, taking the density to be 10^{4} cm^{-3} at 1000 AU.

[c]The Alfven speed V_A determined from the total density n.

[d]Values refer to an average density; densities at large distances are highly influenced by shocks and rarefaction waves, see text.

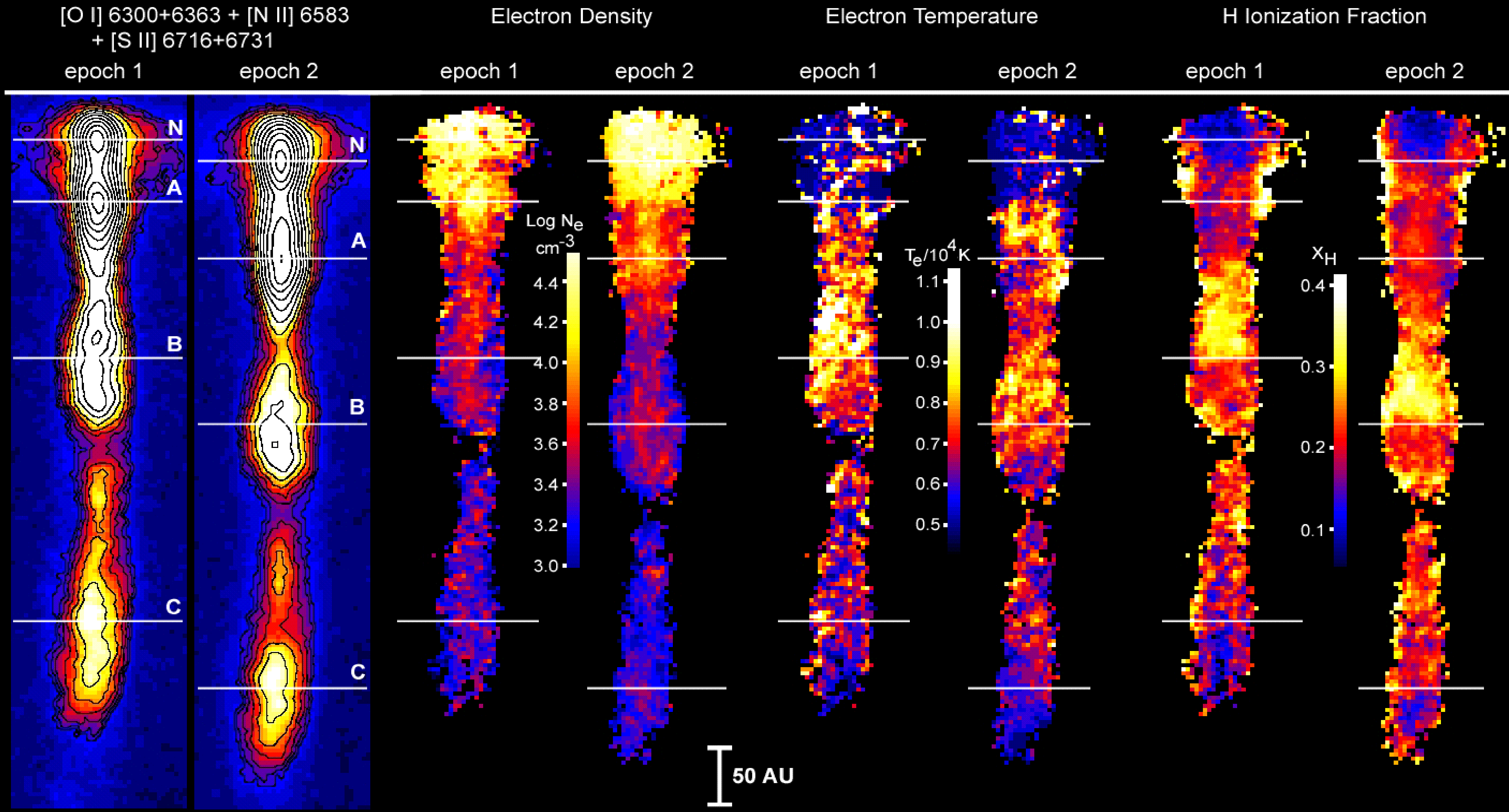


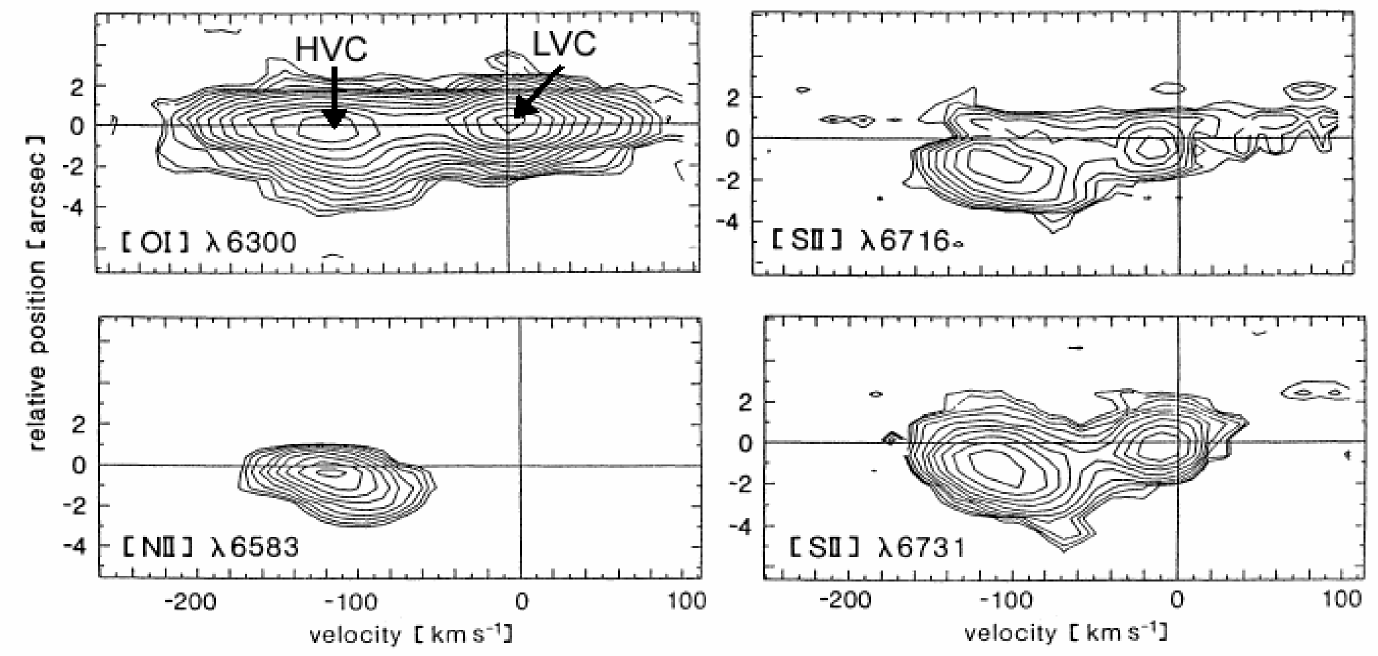
- B field concentrates into dense blobs, Rarefactions decouple
- Preshock B (in rarefactions) drops with distance 30 km/s perturbations make shocks in jets. B inhibits compression in blobs
- Close to the source B is higher – magnetic zone?

Simulation began with V_A = 35 km/s and V_J = 200 +/- 100 km/s

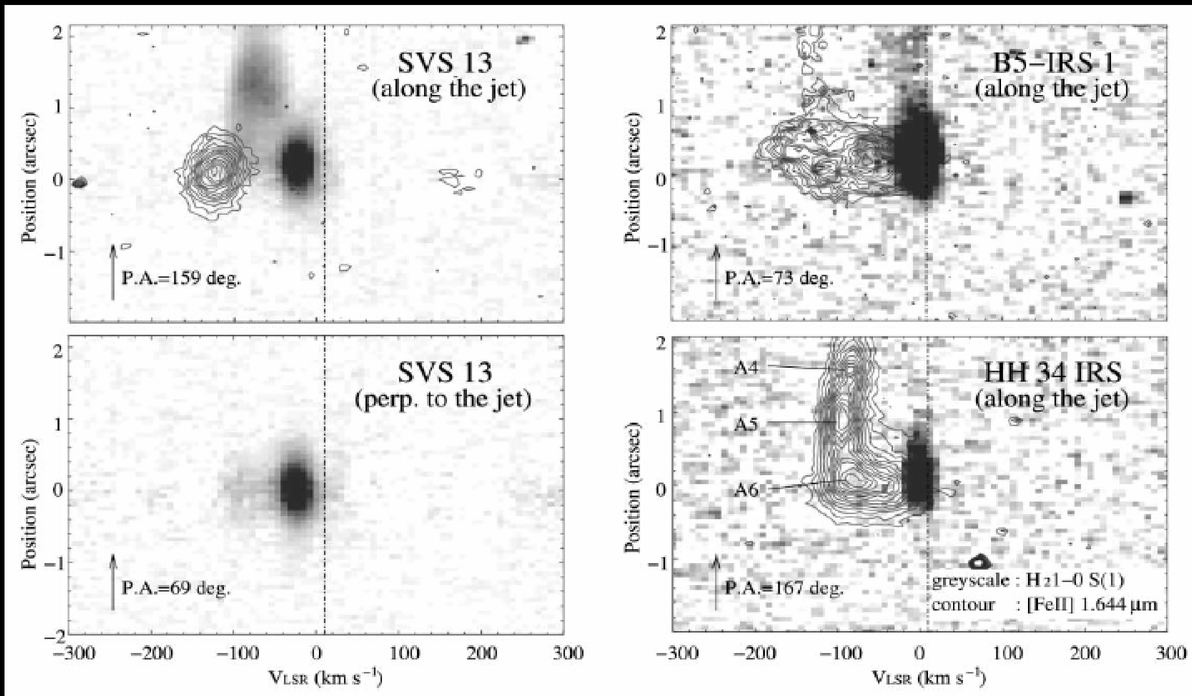
Will have trouble if V_A gets too high because then velocity perturbations give (longitudinal) magnetic waves rather than shocks

III. Information about Jet Launching Radii





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

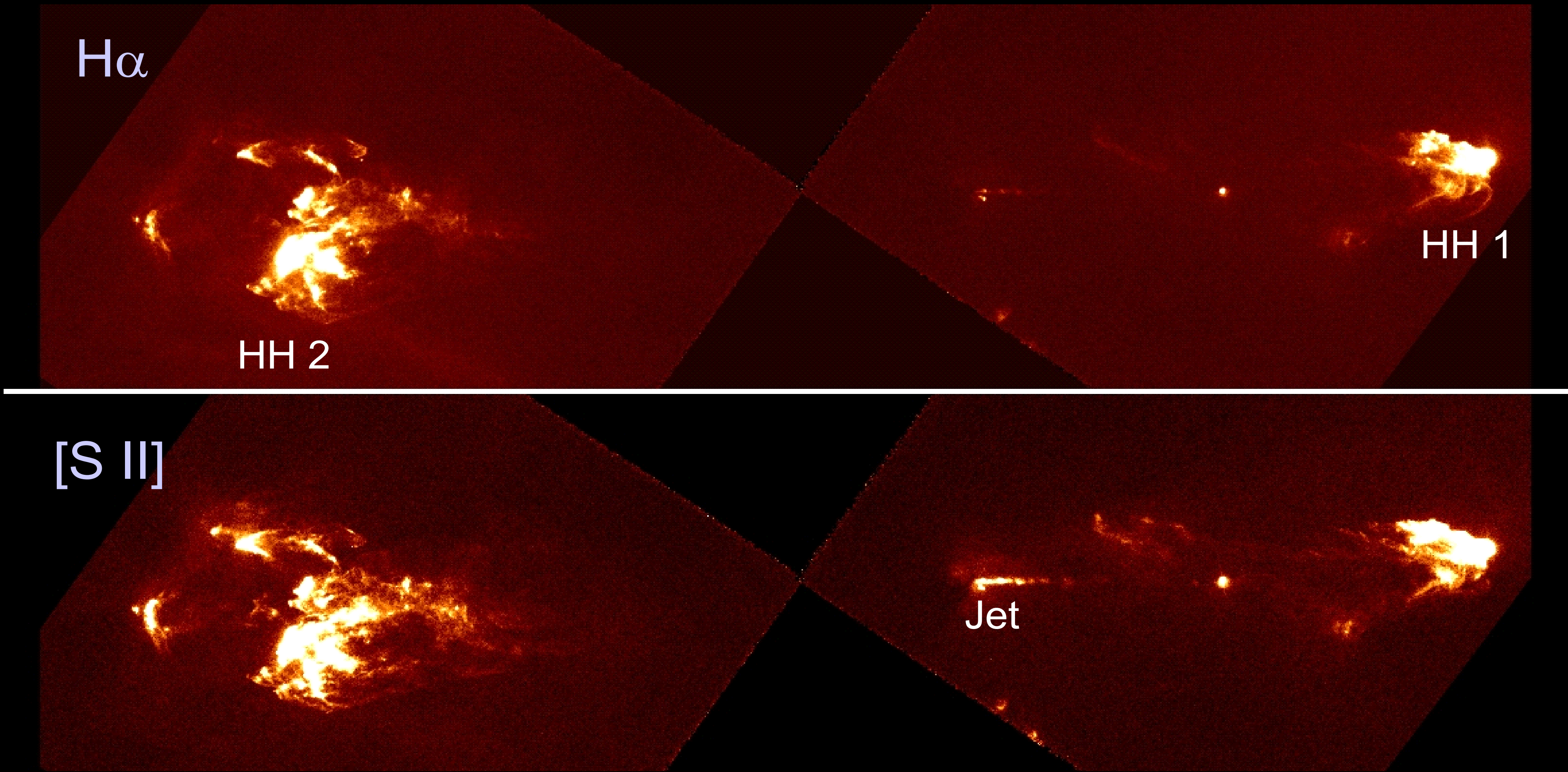


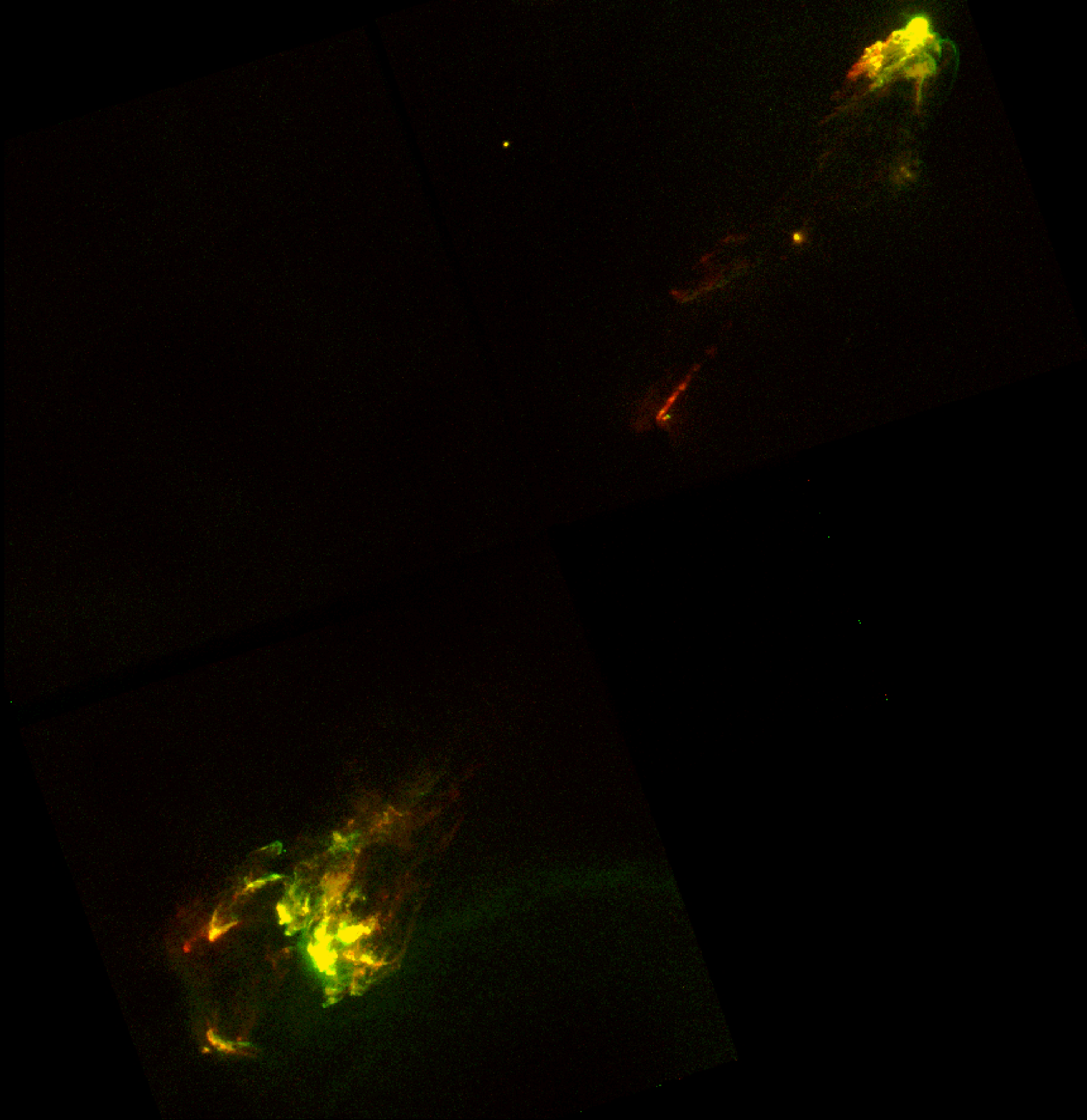
Contours: [Fe II]
Greyscale: H_2

Takami et al 2006 ApJ 641 357

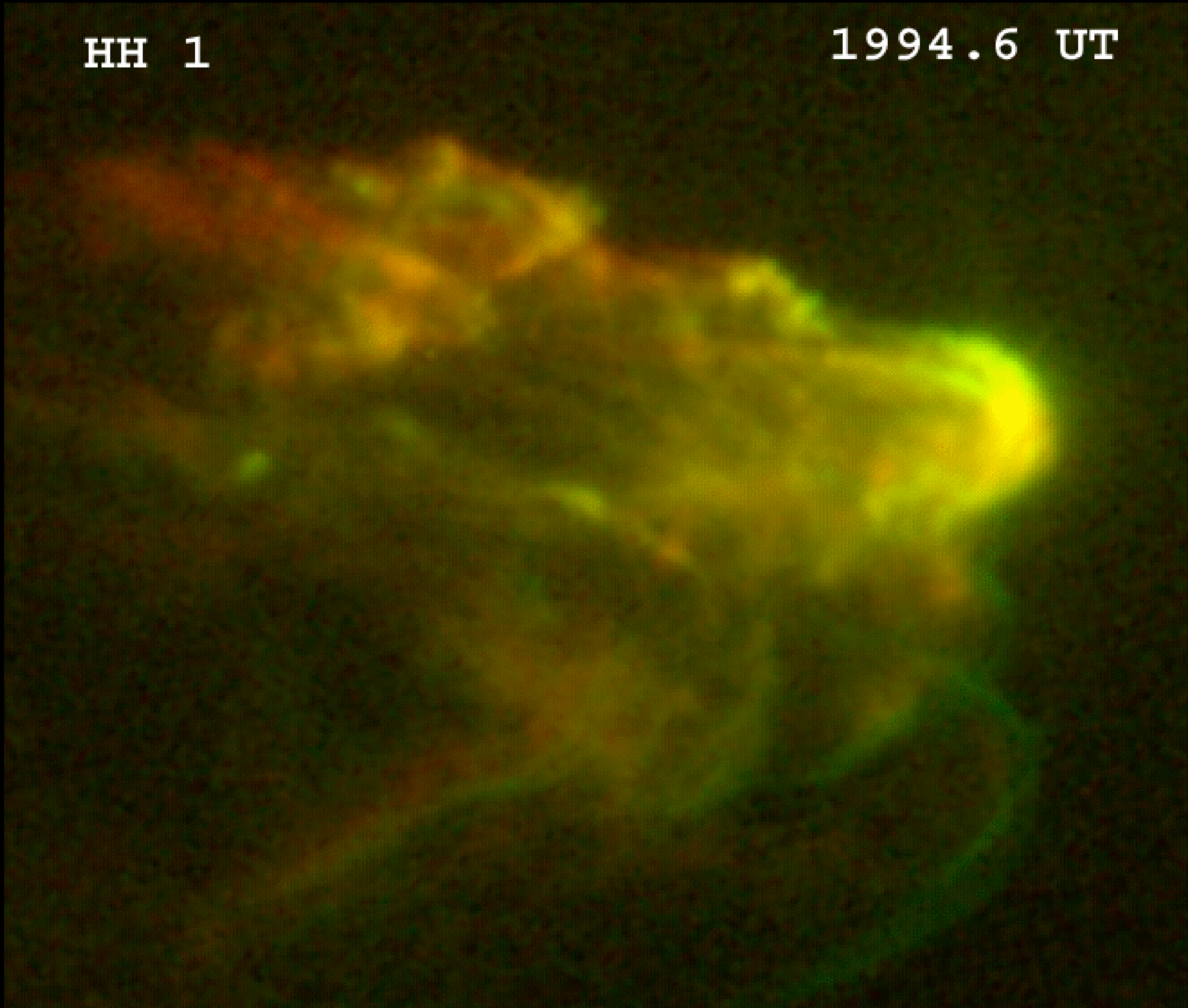
Finish with some fun stuff

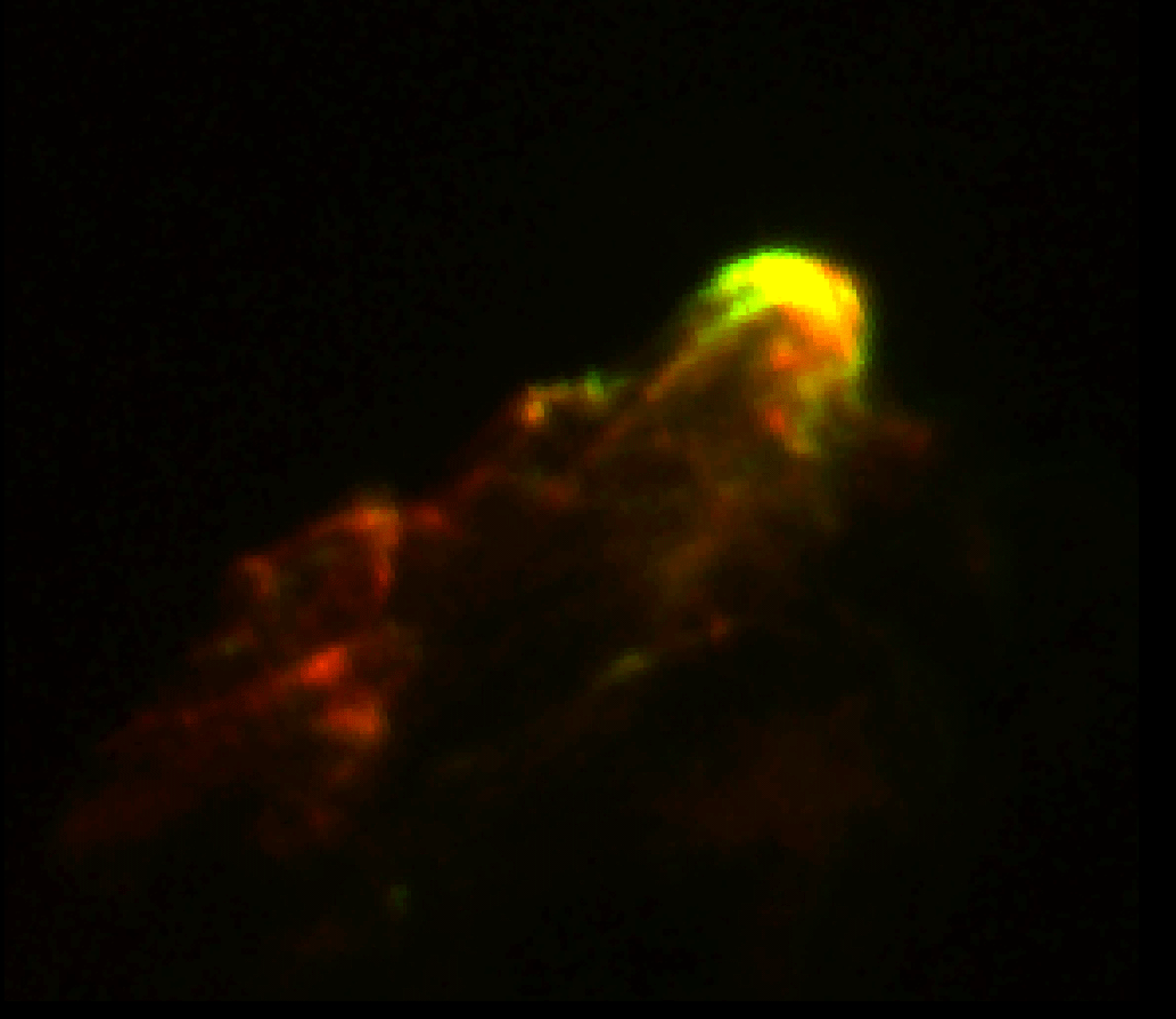
3rd Epoch of HST movies for HH 1 and HH 2

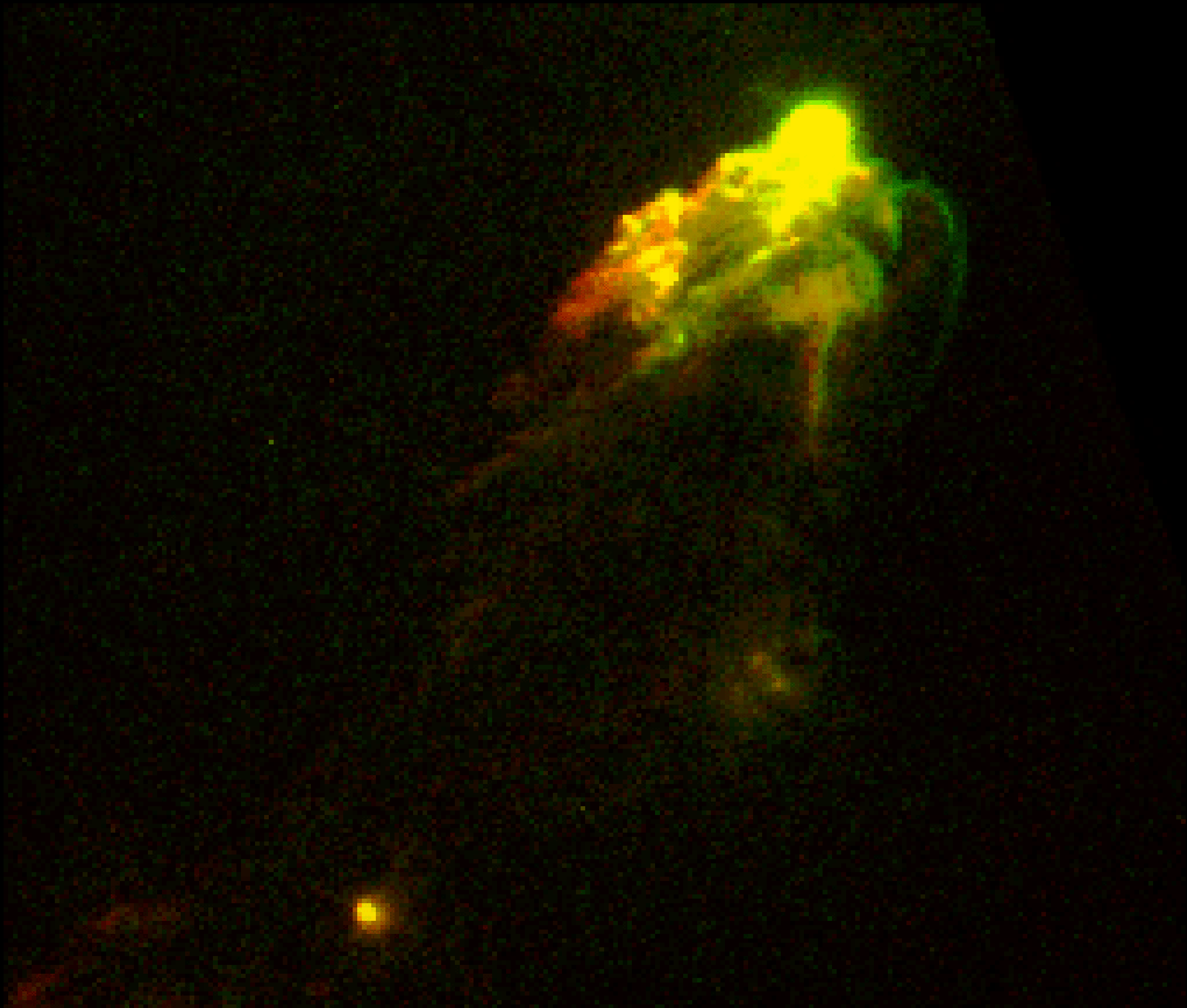


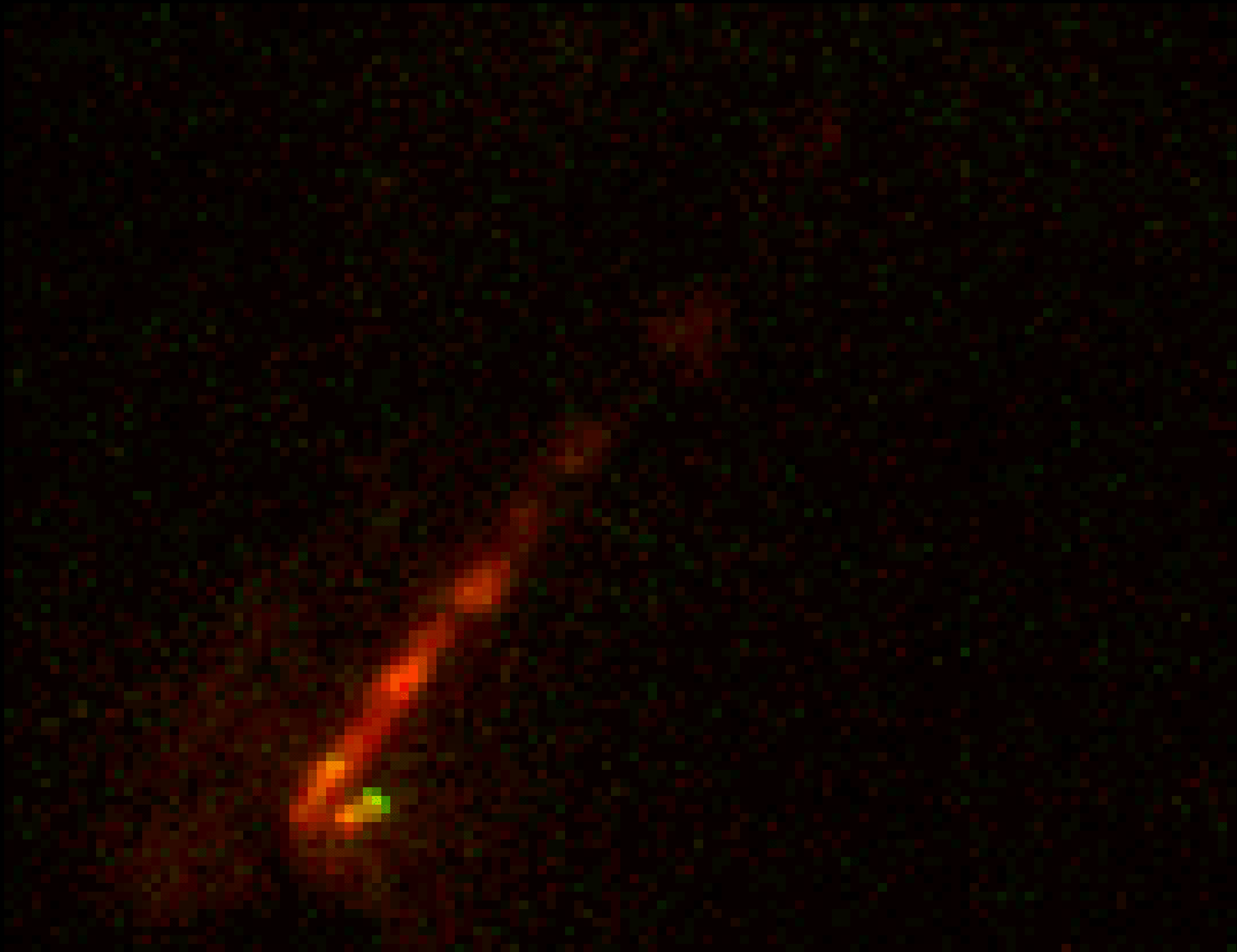


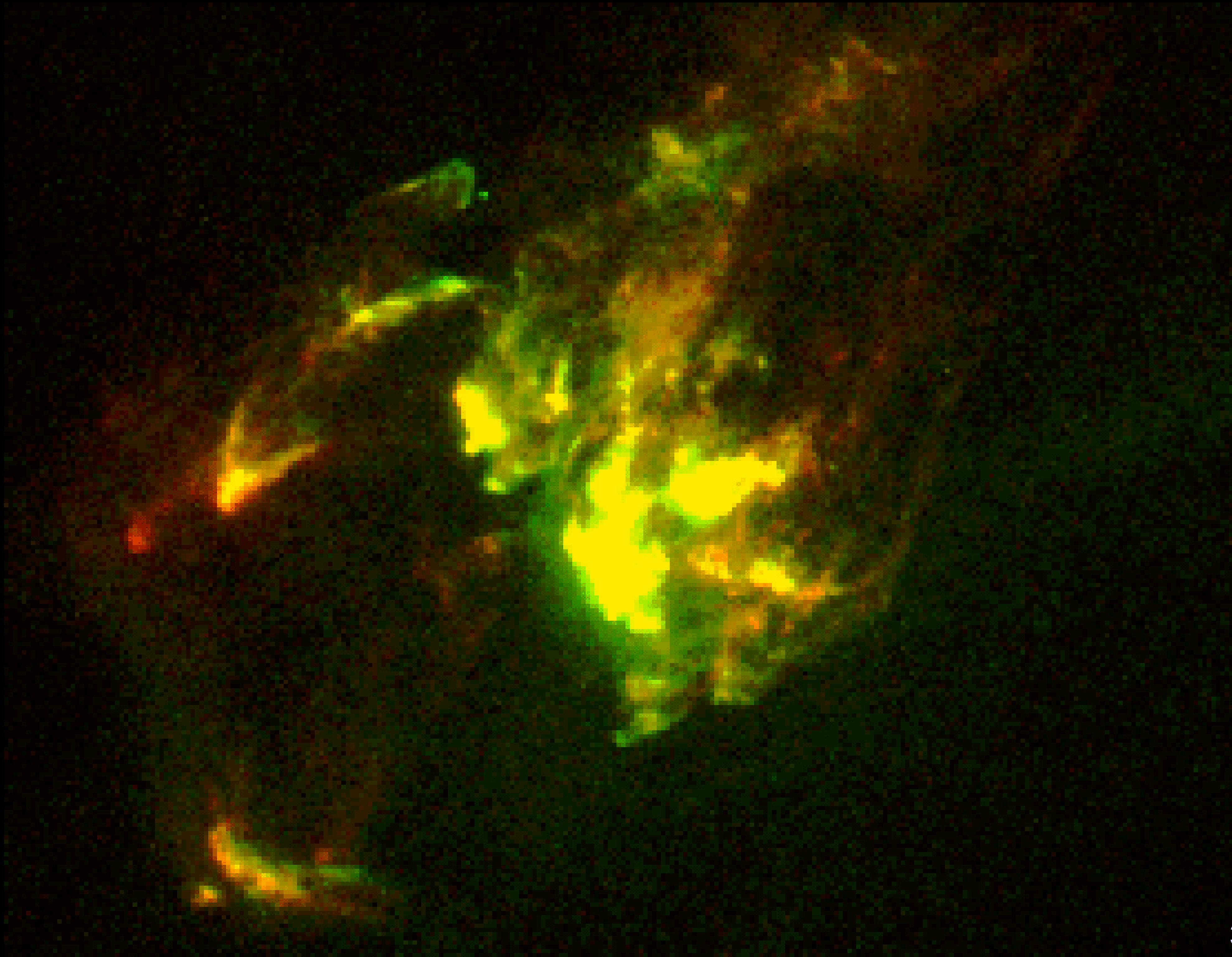
Red: [S II]
Green: Hα
Yellow: Both

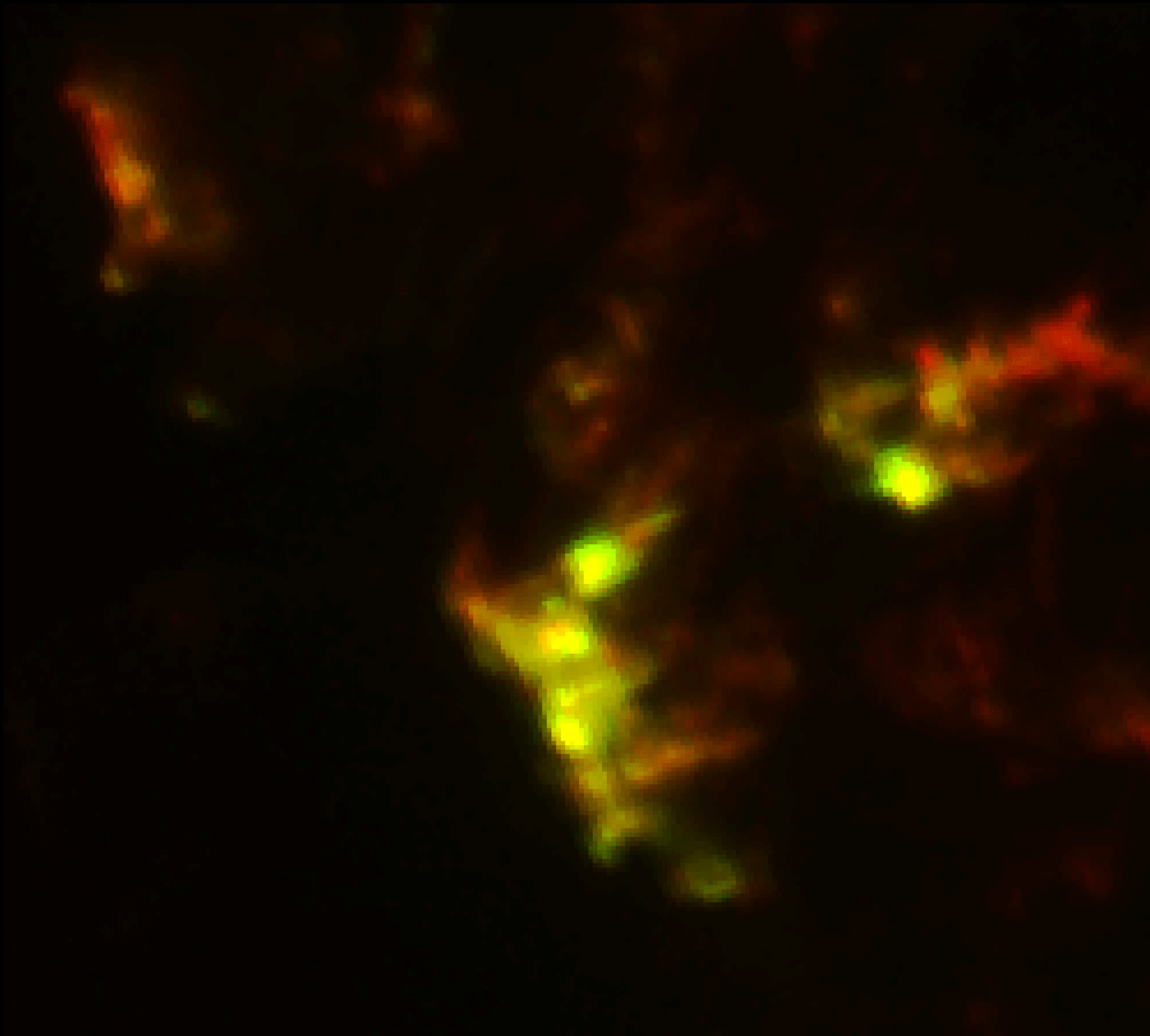

HH 1
1994.6 UT









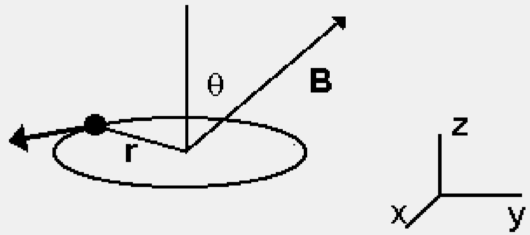


SUMMARY

- B fields are difficult to measure in jets. Several techniques, all have limitations.
- > 1000 AU B ~ 20 μG in rarefactions, ~ 1 mG in blobs
- B higher closer in, ~ 100 mG (?) aroud 10 AU
- Best scenario: V_A(phi) < ~ 5 V(jet)
- LVC/HVC suggest two launching regions separated by a 'dead' zone where disk wind is not occurring.
- Disk Wind Modelers: Please let observers know what magnetic signal speed you predict at large distances.

Classical Current Loop

$$\vec{\mu} = \frac{IA}{c}\hat{\mathbf{z}} \qquad I = \frac{ev}{2\pi r} \qquad A = \pi r^2$$



$$\begin{aligned} \mathbf{r} &= r\left[\cos\phi\,\hat{\mathbf{x}} + \sin\phi\,\hat{\mathbf{y}}\right] \\ \mathbf{v} &= v\left[-\sin\phi\,\hat{\mathbf{x}} + \cos\phi\,\hat{\mathbf{y}}\right] \\ \mathbf{B} &= B_\circ\left[\cos\phi\,\hat{\mathbf{z}} + \sin\phi\,\hat{\mathbf{y}}\right] \end{aligned}$$

So $\vec{\mu} = \frac{evr}{2c}\hat{\mathbf{z}} = \frac{e\mathbf{L}}{2mc}$

$$\vec{\tau} = \mathbf{r} \times \mathbf{F} = \mathbf{r} \times \frac{e\mathbf{v}\times\mathbf{B}}{c} \qquad \langle\vec{\tau}\rangle = -\mu B_\circ \sin\theta\,\hat{\mathbf{x}}$$

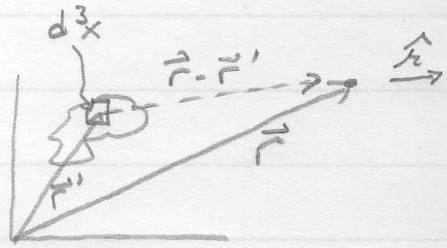
$$U = -\int_{\pi/2}^{\theta} \langle\vec{\tau}\rangle\, d\theta = -\mu B_\circ \cos\theta = -\vec{\mu}\cdot\mathbf{B}$$

Magnetic Potential Energy: Classical Current Loop

Retarded Potentials

Synchrotron Emission

Poisson eqn
$$\nabla^2 V - \frac{1}{c^2}\frac{\partial^2 V}{\partial t^2} = -4\pi\rho$$
$$\nabla^2 A - \frac{1}{c^2}\frac{\partial^2 A}{\partial t^2} = -\frac{4\pi J}{c}$$



Static case: $V(r) = \int \frac{\rho(\vec{r}\,')}{|\vec{r}-\vec{r}\,'|}\, d^3x$, $\vec{A}(r) = \int \frac{\vec{J}(\vec{r}\,')\, d^3x}{|\vec{r}-\vec{r}\,'|}$

General case: $V(r) = \int \frac{\rho(\vec{r}\,', t')\, d^3x}{|\vec{r}-\vec{r}\,'|}$, $\vec{A}(\vec{r}) = \int \frac{\vec{J}(\vec{r}\,', t')\, d^3x}{|\vec{r}-\vec{r}\,'|}$

$t' = t - \frac{|\vec{r}-\vec{r}\,'|}{c}$ = retarded time

→ must use Poisson eqn to show this

→ e.g. $\vec{E}(r,t) \neq \int \frac{\rho(r',t')}{|\vec{r}-\vec{r}\,'|^2}\,\hat{r}\, d^3x$! (Jefimenko eqn)

$$\vec{E}(\vec{r},t) = \int \left[\frac{\rho(r',t')}{|\vec{r}-\vec{r}\,'|^2} + \frac{\dot{\rho}(r',t')}{c|\vec{r}-\vec{r}\,'|} - \frac{\dot{\vec{J}}(\vec{r}\,',t')}{c^2|\vec{r}-\vec{r}\,'|} \right] d^3x\, \hat{r}$$

Larmor's Formula; Gyroradius and Cyclotron frequency

Poynting vector $S = \frac{c}{4\pi} E_\perp^2$

Power $P = \int_{4\pi} S r^2 \, d\Omega = \frac{e^2 a^2}{2c^3} \int_0^\pi \sin^3\theta \, d\theta = \frac{2}{3} \frac{e^2 a^2}{c^3}$

Larmor's formula

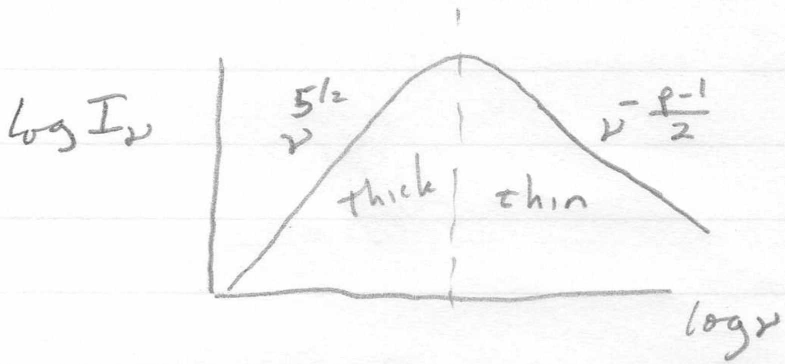
$\vec{B} \otimes$ $\quad e \frac{\vec{v}}{c} \times \vec{B} = \frac{m v^2}{r}$ $\quad r$ = gyroradius

$\omega_B = \frac{eB}{\gamma m c}$ cyclotron frequency

Synchrotron Power Law Spectrum

Power law, $N(\epsilon)\,d\epsilon \sim \epsilon^{-p}\,d\epsilon$ $\quad$ ϵ = energy of $\bar{e}$

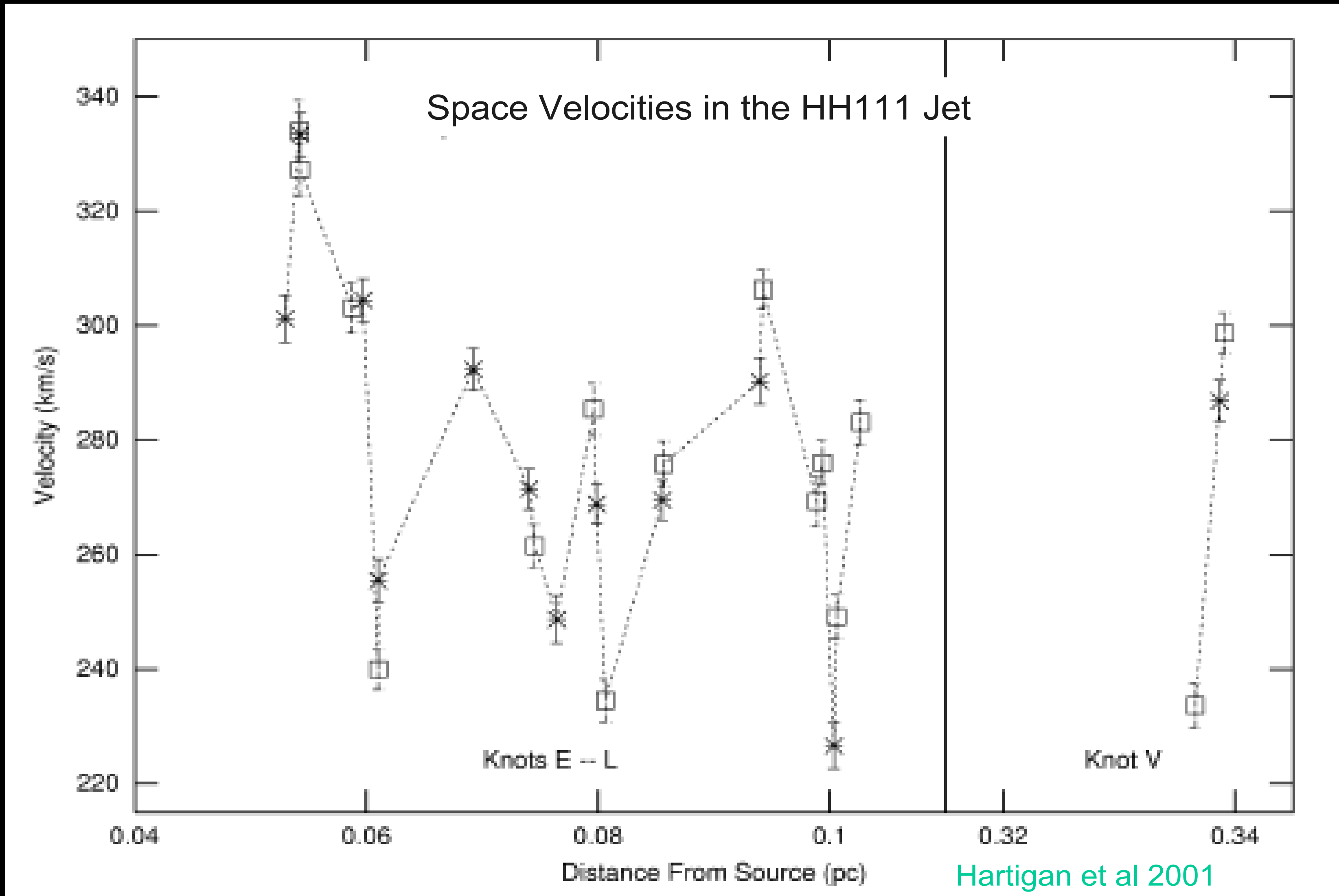
→ emitted power $P(\omega) \sim \omega^{-\frac{(p-1)}{2}} = \omega^{-s}$ $\quad$ s = spectral index



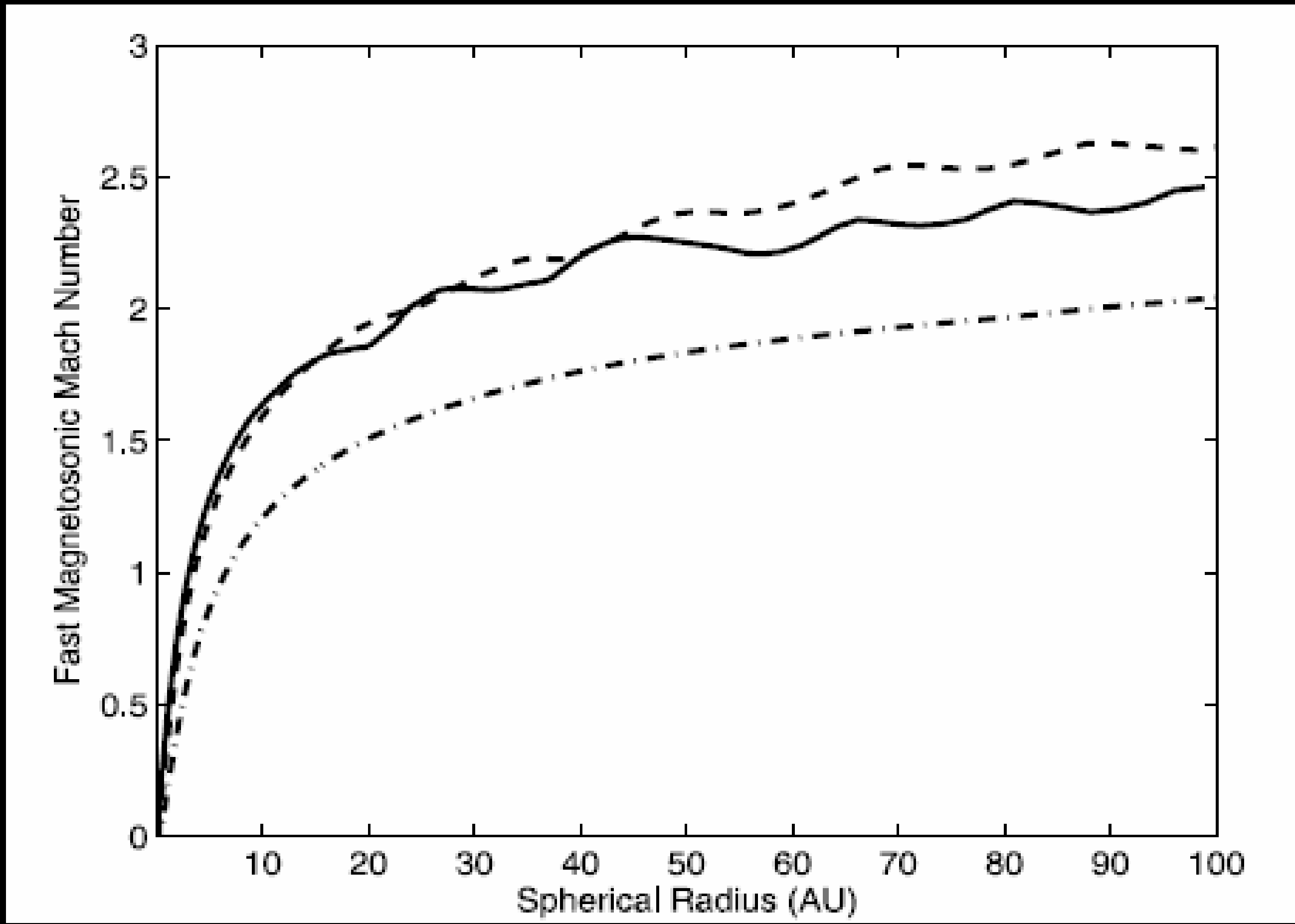
Polarization percentage for power law $= \dfrac{p+1}{p+\frac{7}{3}}$

$$P(\omega) = \text{const}\; B\; \underbrace{F(\omega,\gamma,\alpha)}_{\text{function}} \sim B^{\frac{p+1}{2}} \text{ for power law}$$

Errors in HST Proper Motions Small Compared to Differential Motions
…and differential motions agree with shock models



So, V_A <~ 30 km/s, $n_{preshock}$ ~ 100 cm^{-3}, So $B_{preshock}$ < 140 μG
Want tracers sensitive in 10μG – 10 mG regime



Anderson et al 2005, ApJ 630, 945

Solid: 25% of mass
Dashed: 50% of mass
Dot-dashed: 75% of mass

Terminal Magnetic Mach number ~ 2
X-wind terminal number ~ 5 – 6