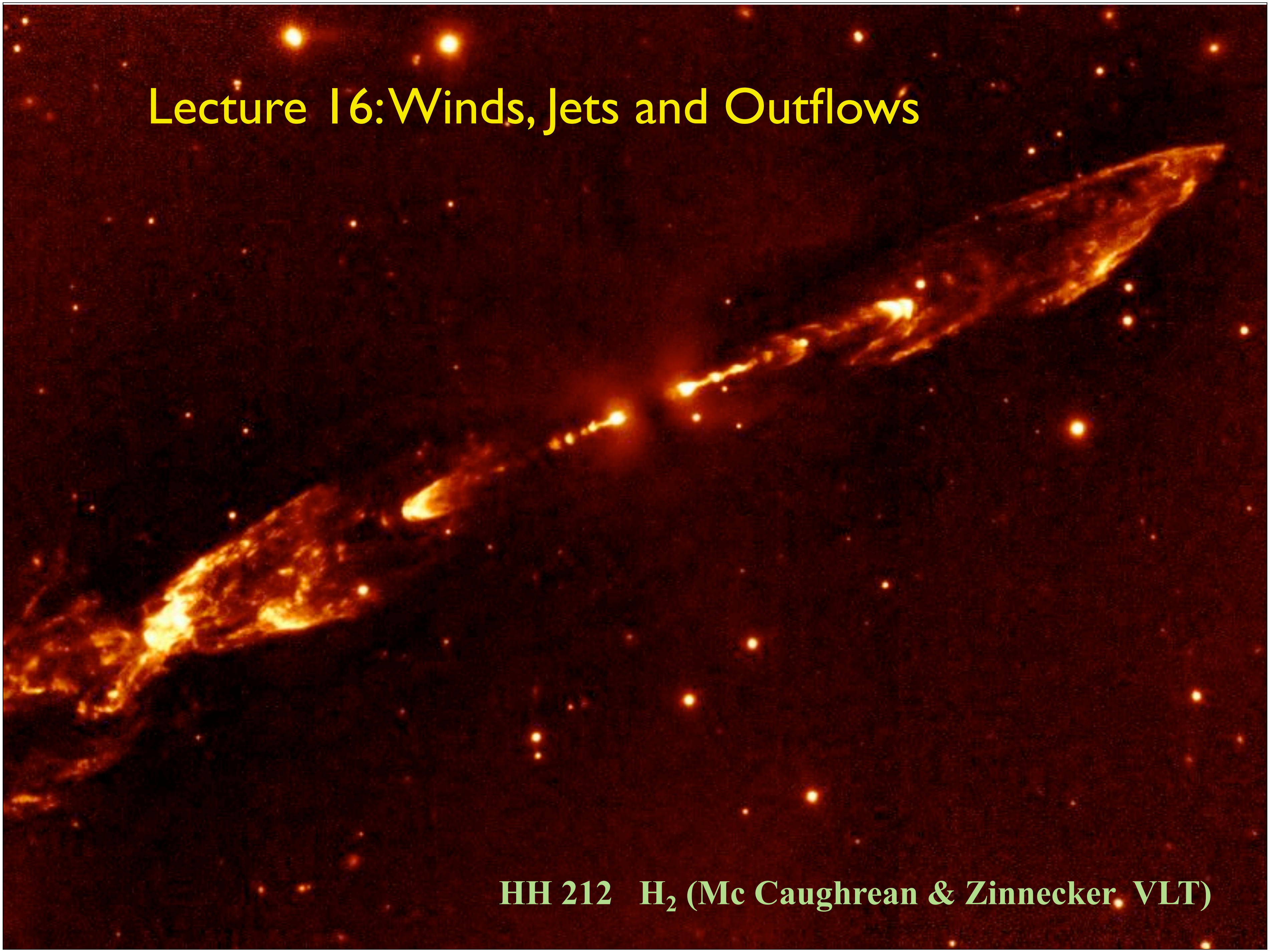
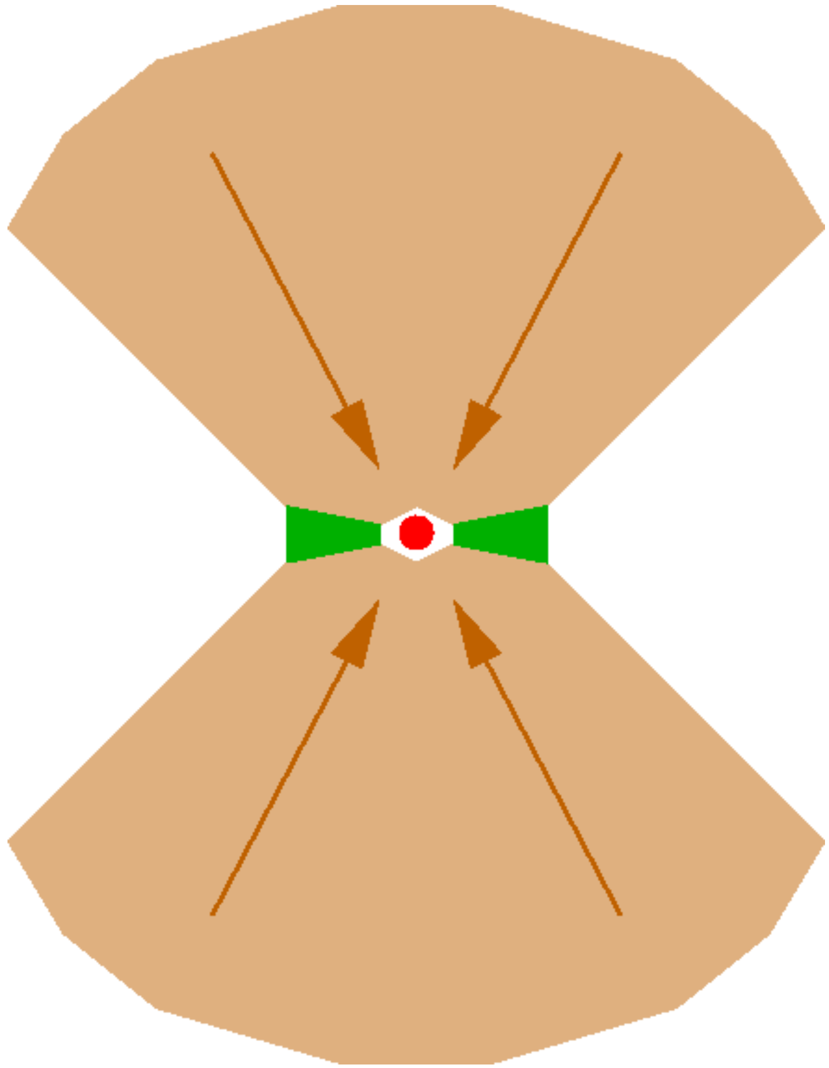
Lecture 16: Winds, Jets and Outflows



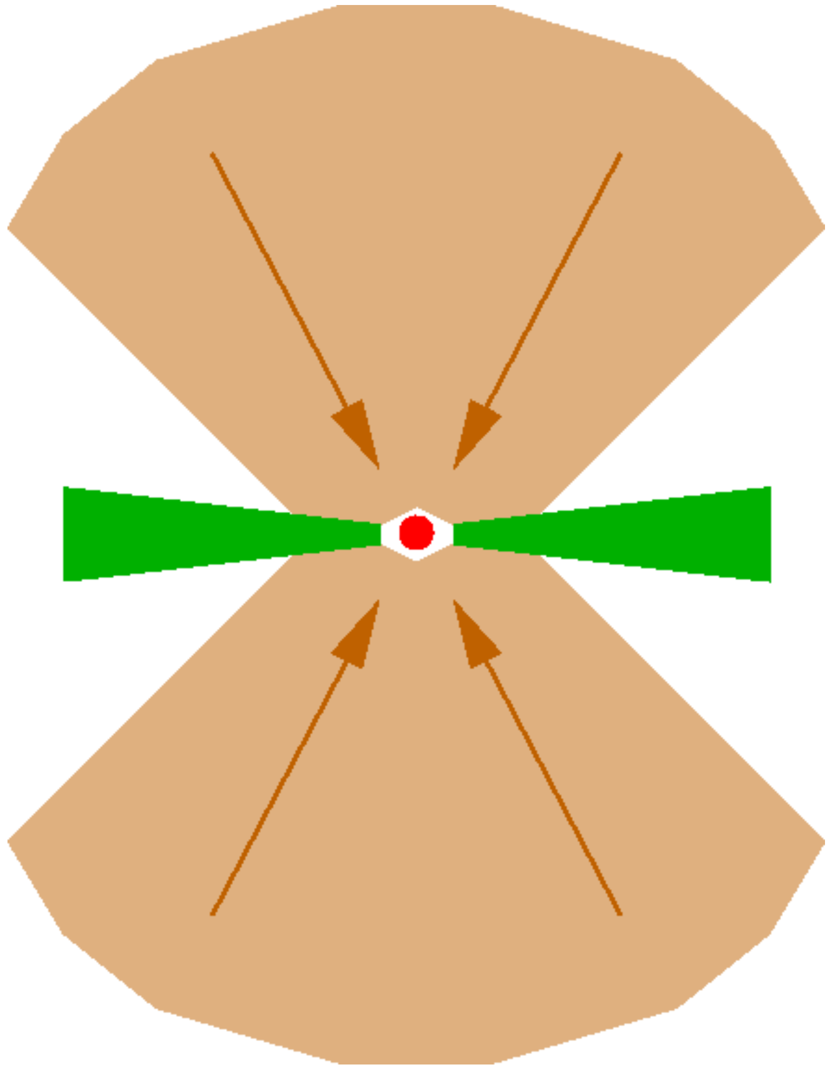
HH 212 H_2 (Mc Caughrean & Zinnecker, VLT)

Losing Material from the Outer Disk Through Photoevaporation

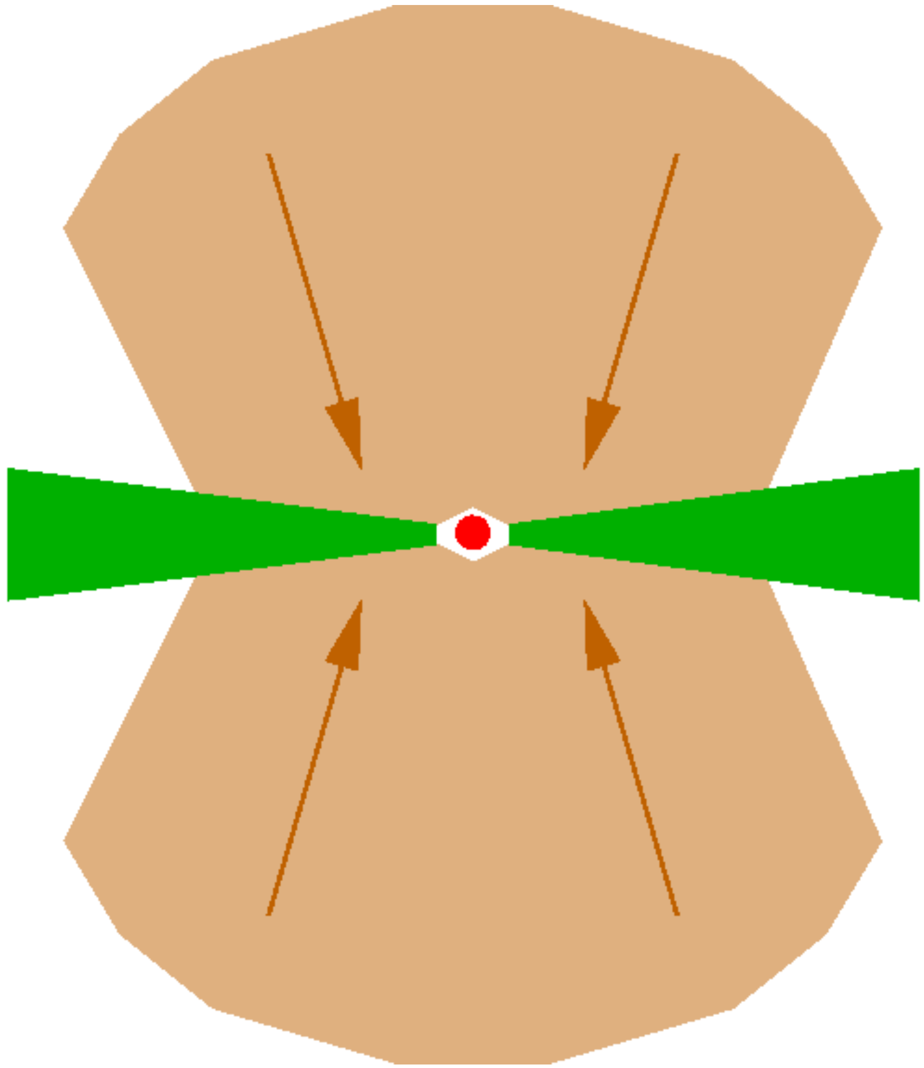
Formation & viscous spreading of disk



Formation & viscous spreading of disk

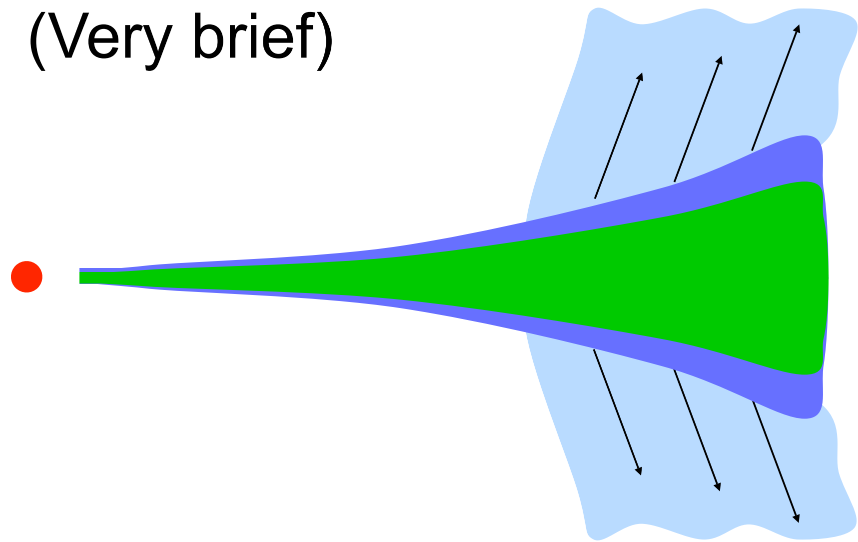


Formation & viscous spreading of disk



Photoevaporation of disks

(Very brief)



Ionization of disk surface creates surface layer of hot gas. If this temperature exceeds escape velocity, then surface layer evaporates.

$$v_{\mathrm{esc}} \approx \left(\frac{GM}{r}\right)^{1/2}$$

Evaporation proceeds for radii beyond:

$$r \geq \frac{GM}{c_{\mathrm{SHII}}^2} \equiv r_{\mathrm{gr}}$$

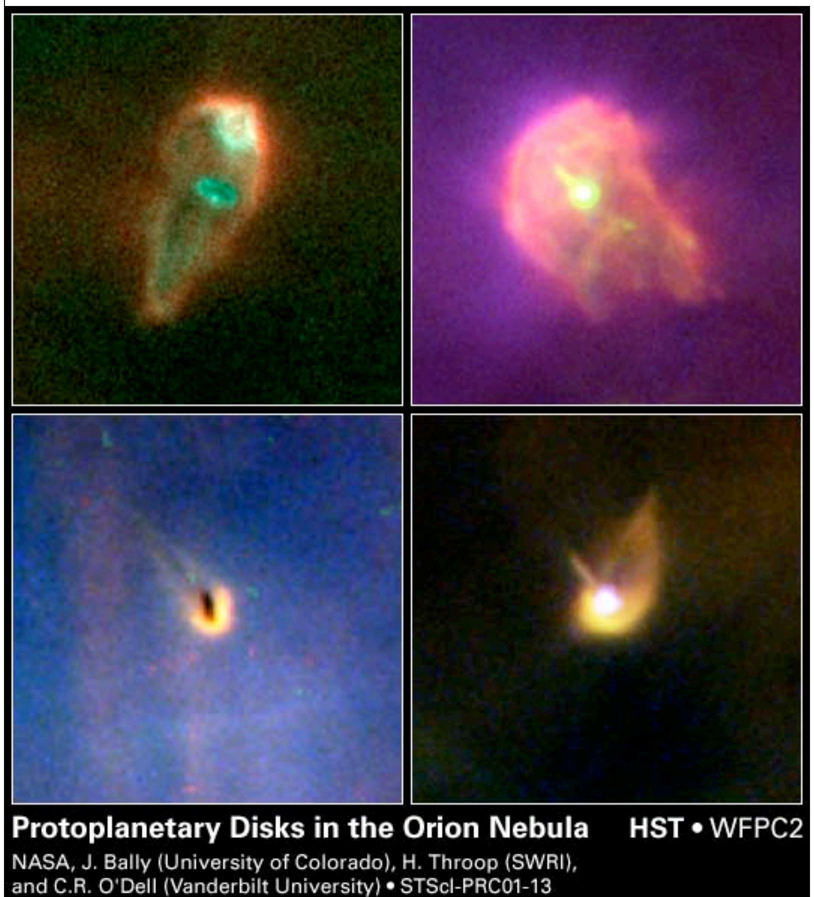
The Edge of The Solar System: Evaporation of Disks by UV Radiation

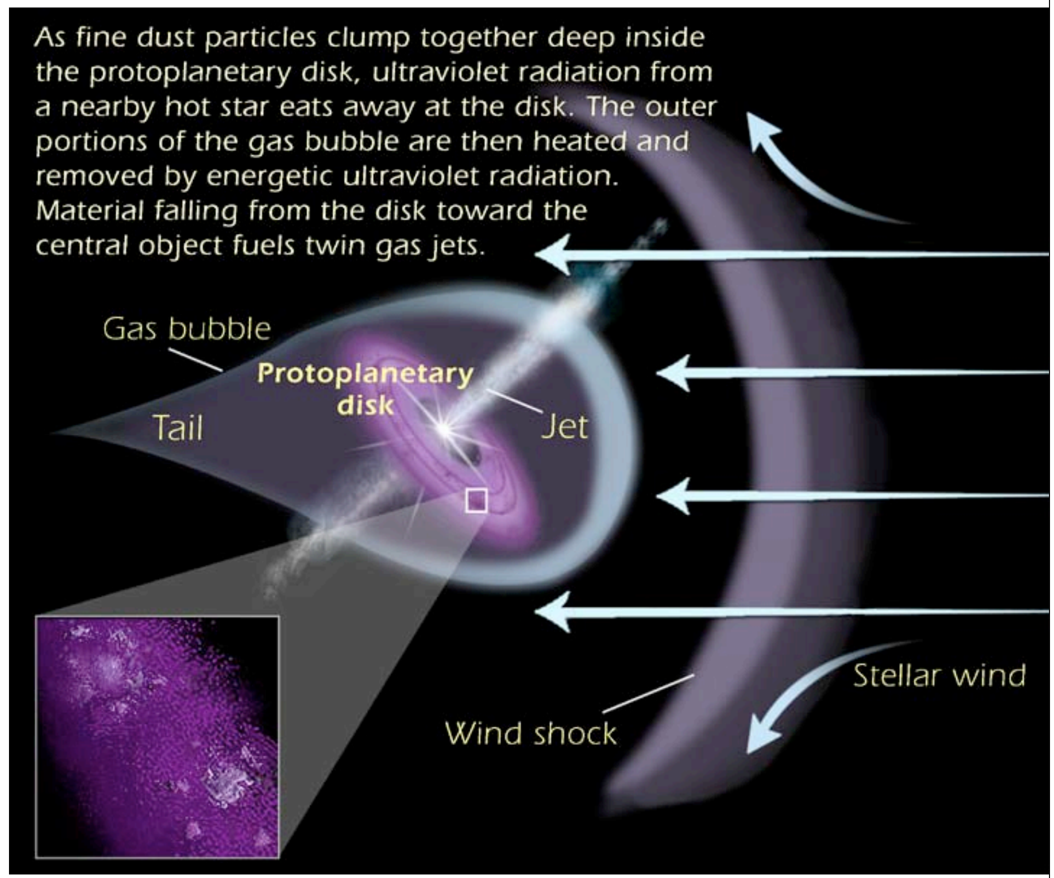
Center of Orion Nebula

Hot O and B-type stars produce powerful UV radiation field.

Young disk bathed in UV light.

Why is there an Edge to the Solar System: Evaporation of Disks by UV Radiation





Losing Material from the Inner Disk through Accretion and Outflow

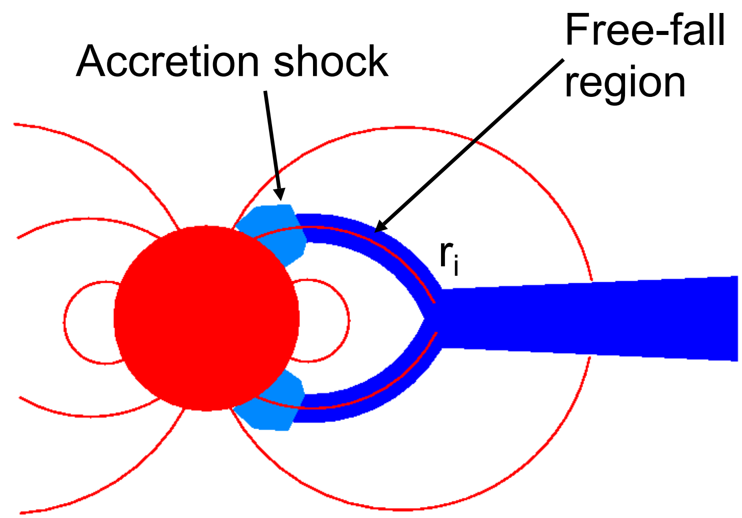
Magnetospheric accretion

Free-fall and accretion shock

From r_A down to star: matter is in supersonic free-fall.

Near the star the matter gets to a halt in a stand-off shock.

Shock velocity:

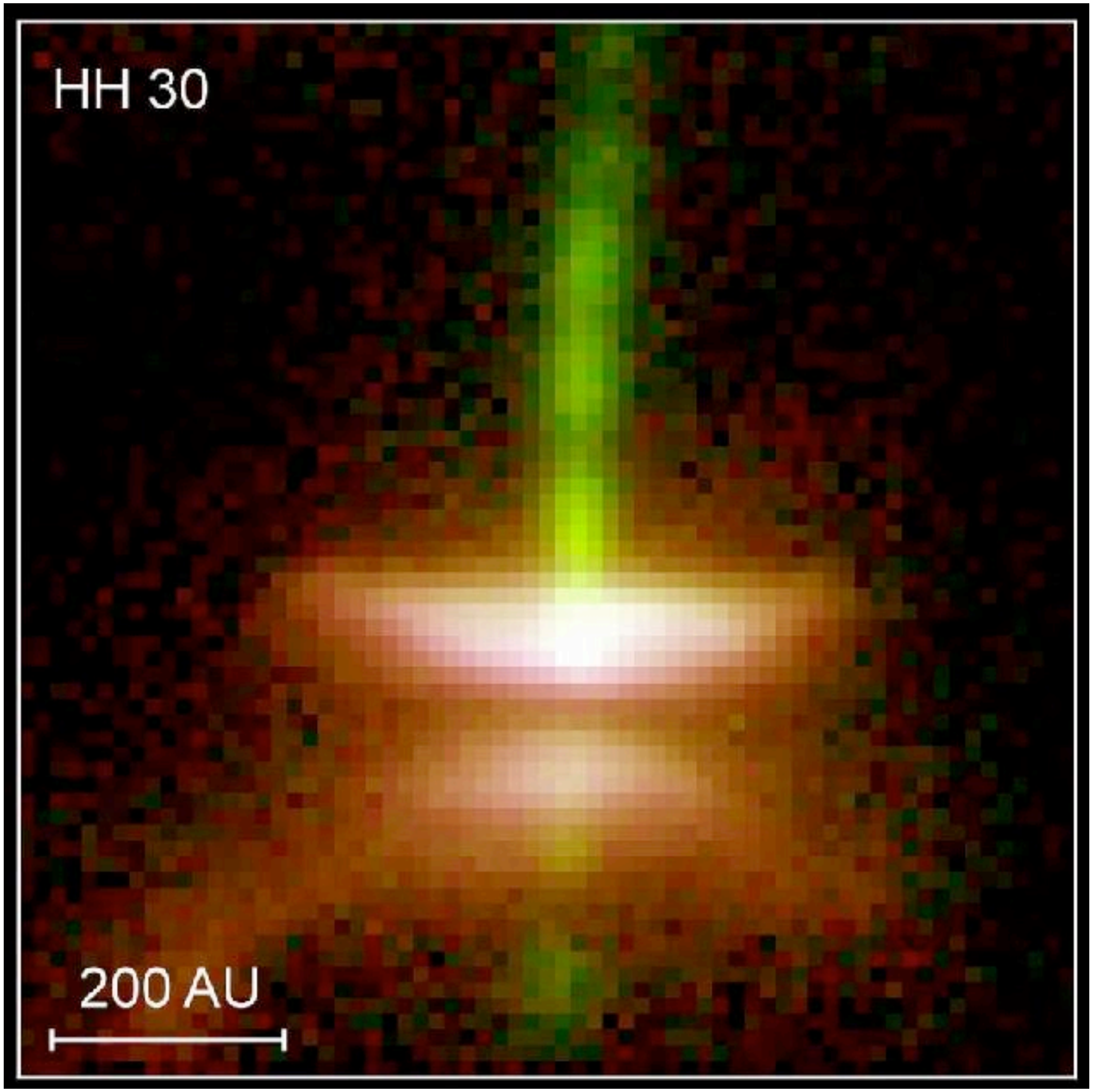


$$v_s = \sqrt{\frac{2GM}{r_*}}\sqrt{1-\frac{r_*}{r_i}}$$

Dissipated energy (=accretion luminosity from shock):

$$L_{\mathrm{accr}} = \left(1-\frac{r_*}{r_i}\right)\frac{G\dot{M}M}{r_*}$$

Bipolar outflows

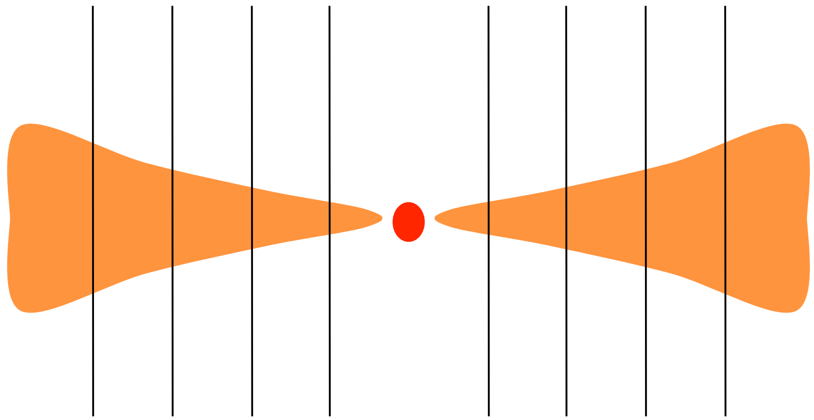


Hubble Space Telescope image

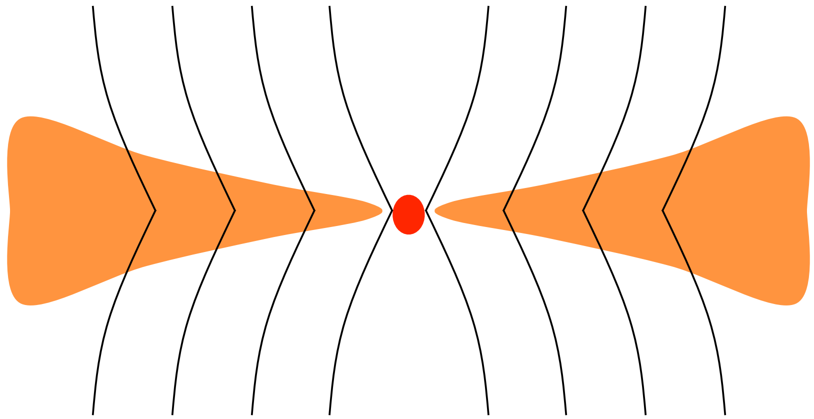
Jets originate from inner regions of protoplanetary disks

Magnetically threaded disks

Suppose disk is treaded by magnetic field:



Inward motion of gas in disk drags field inward:

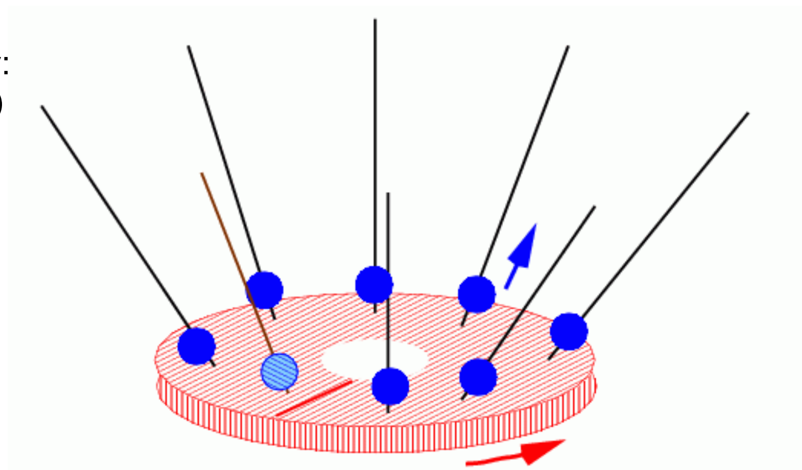


B-field aquires
angle with disk

Disk winds

Slingshot effect. Blandford & Payne (1982)

(courtesy: C. Fendt)



Use *cylindrical* coordinates r,z

Gravitational potential:

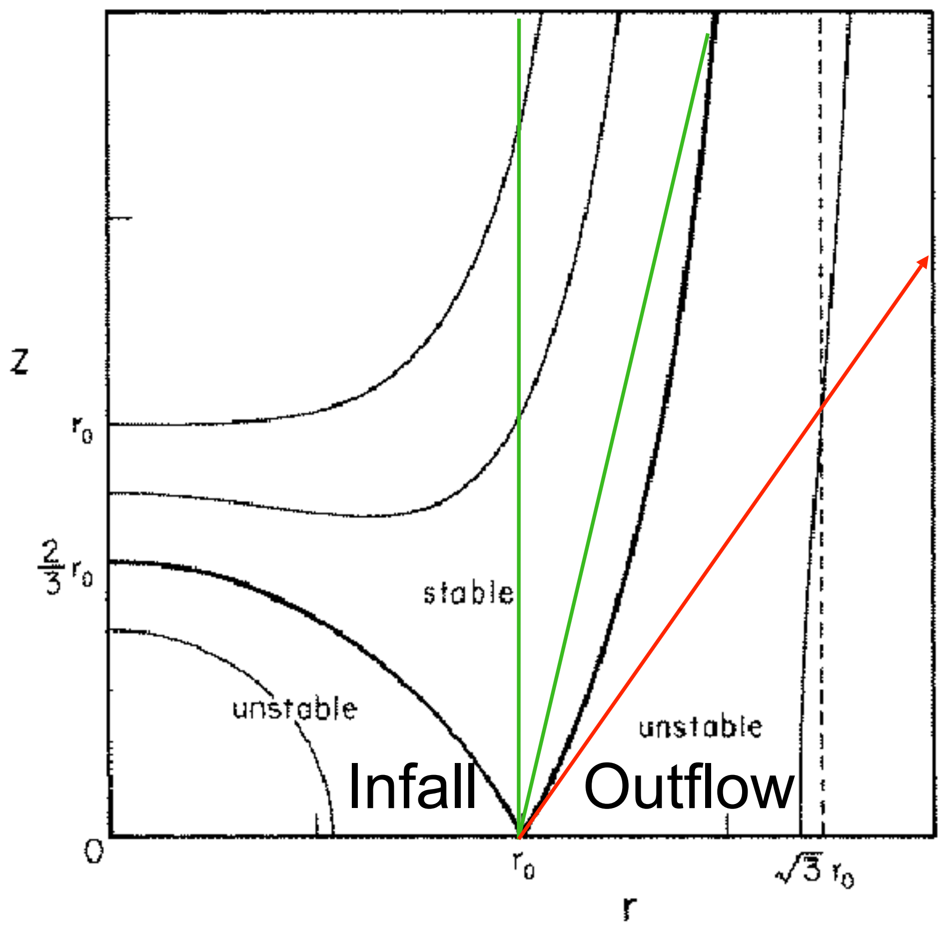
$$\Phi = -\frac{GM}{\sqrt{r^2 + z^2}}$$

Effective gravitational potential along field line (incl. sling-shot effect):

$$\Phi = -\frac{GM}{r_0}\left[\frac{1}{2}\left(\frac{r}{r_0}\right)^2 + \frac{r_0}{\sqrt{r^2+z^2}}\right]$$

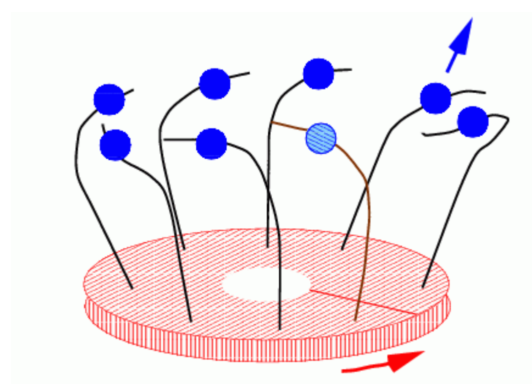
Disk winds

Blandford & Payne (1982)



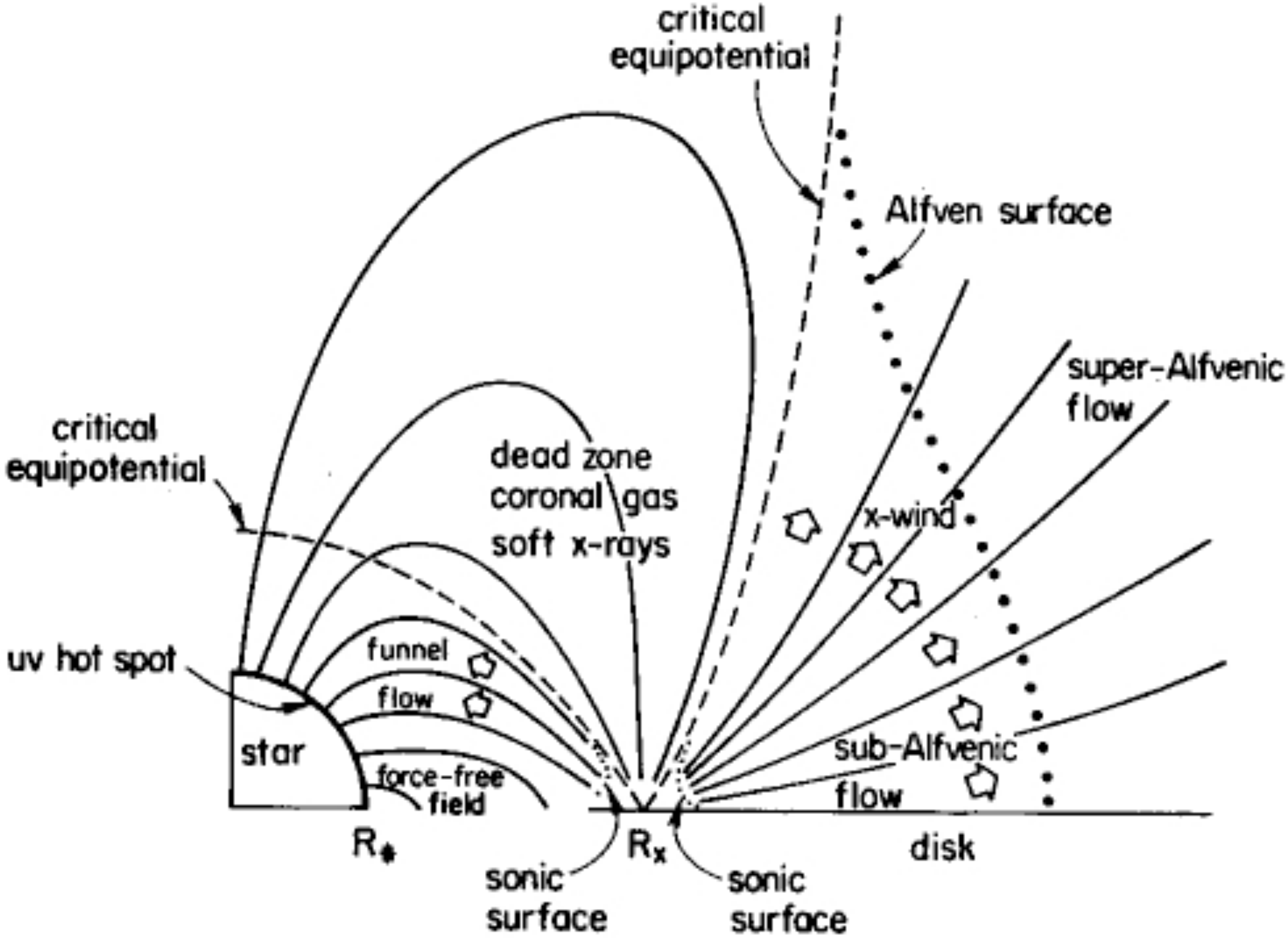
$$\Phi = -\frac{GM}{r_0}\left[\frac{1}{2}\left(\frac{r}{r_0}\right)^2 + \frac{r_0}{\sqrt{r^2 + z^2}}\right]$$

Critical angle: 60 degrees with disk plane. Beyond that: outflow of matter.



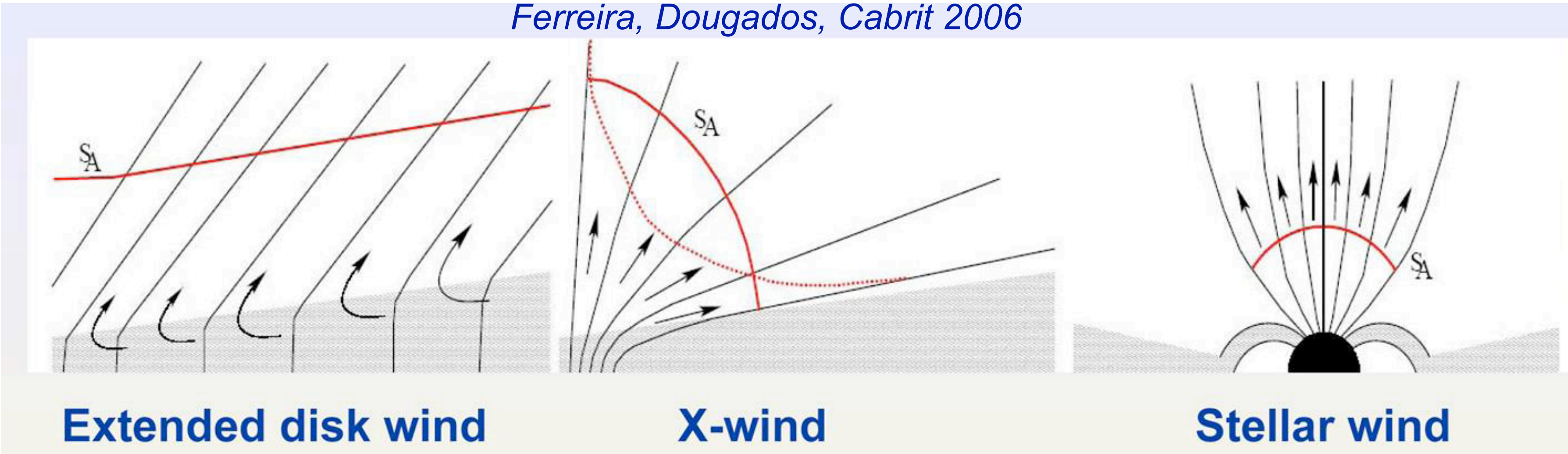
Gas will bend field lines

Disk + star: X-wind model of Frank Shu



Shu 1994

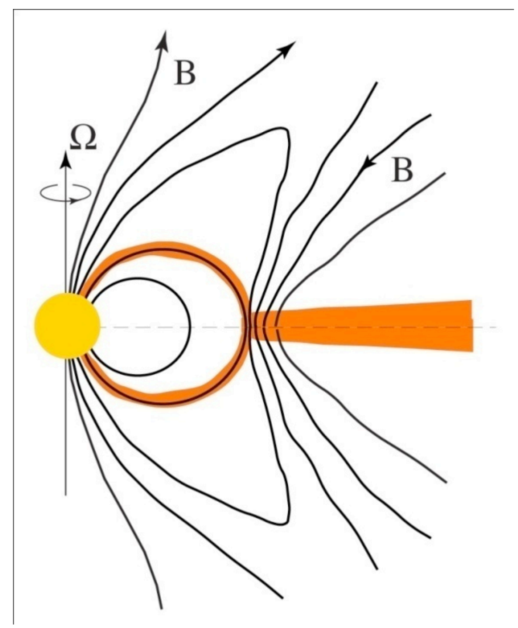
Different kinds of Winds



Blandford & Payne 1982
Konigl & Pudritz 2000

Shu et al. 1994

Matt & Pudritz 2005,…

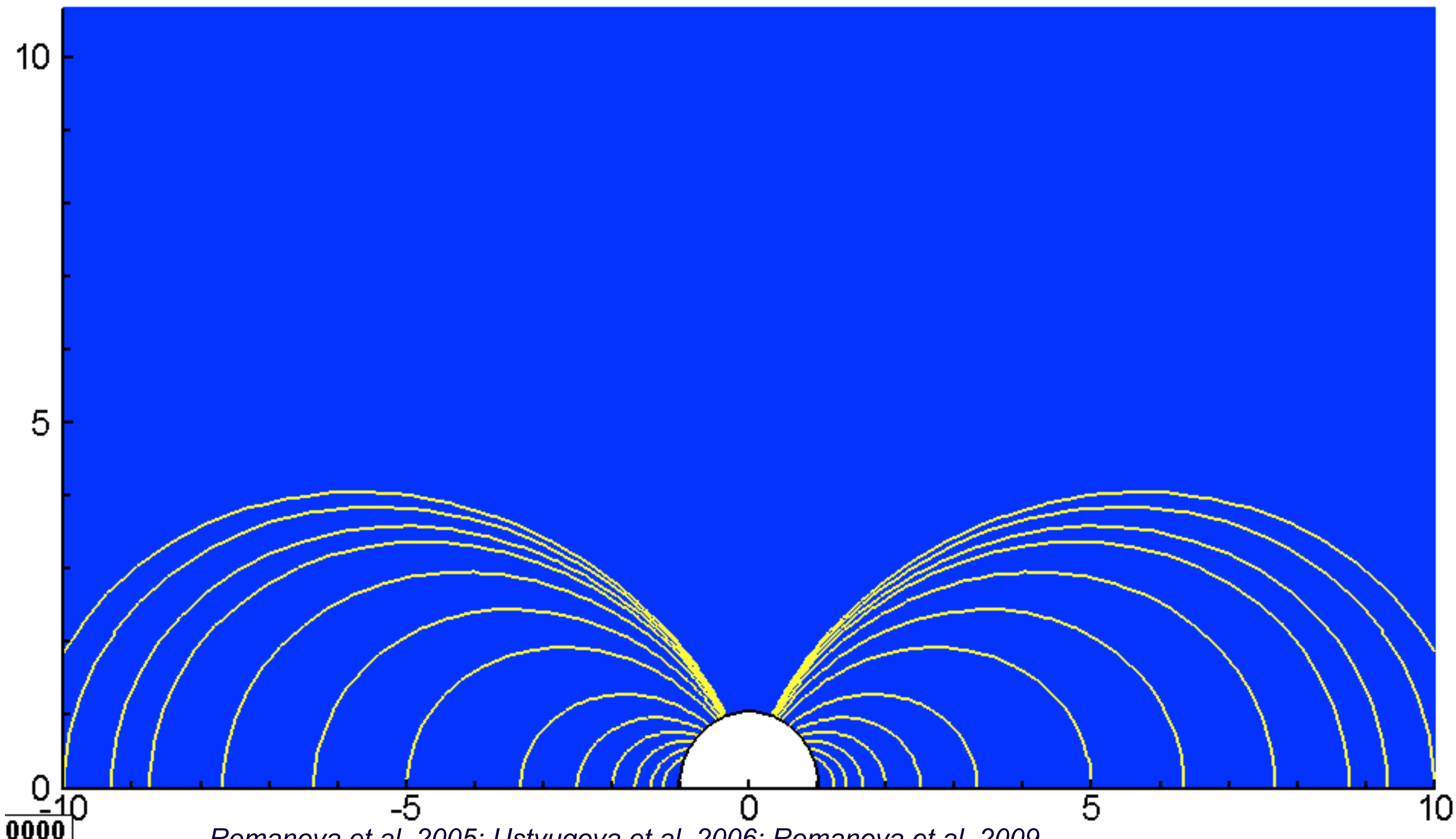


Configuration favorable for outflows

Pirated from talk by
Marina Romanova

Bunching, $\alpha_v > \alpha_d$

Magnetocentrifugal Winds



Romanova et al. 2005; Ustyugova et al. 2006; Romanova et al. 2009

Jets or Winds?

Wind Blown Cavities

Bipolar Outflows driven by Wind

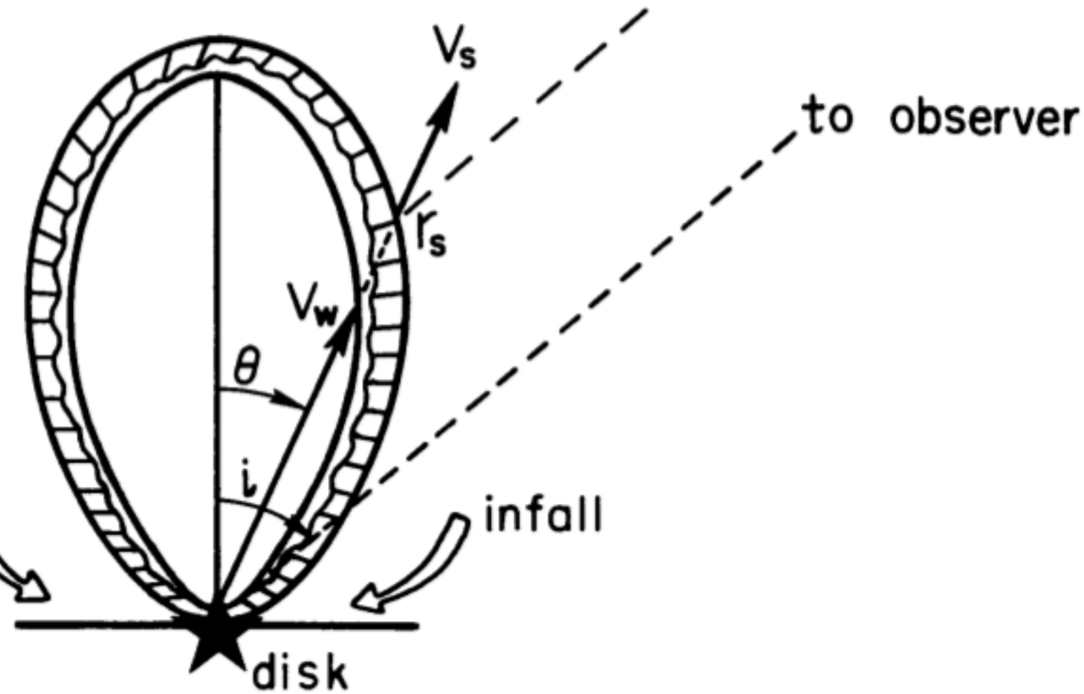


FIG. 1.—Geometry for shell of molecular gas, moving at speed $v_s(\theta)$ at position $r_s(\theta)$, as swept up by a protostellar wind moving at speed $v_w(\theta)$ into a molecular cloud core with the density profile given by eq. (1). The observer views the system at an inclination angle i with respect to the rotation axis of the protostellar disk, and residual infall of cloud material onto the disk occurs in those directions near the equatorial plane not affected by the outflow.

Shu et al. 1991

Wind Blown Bubble

Equations for core:

$$\rho(r,\theta) = \frac{c_s^2}{2\pi G r^2} Q(\mu) \tag{1}$$

e

$$\int_0^1 Q(\mu) d\mu = 1 \tag{2}$$

$$\dot{M} \approx \frac{c_s^3}{G},\ \dot{M}_w = f\dot{M} \tag{3}$$

Equations for wind:

$$P(r,\theta) = \frac{\dot{M}_w v_w}{4\pi} P(\mu) \tag{4}$$

ere

$$\int_0^1 P(\mu) d\mu = 1 \tag{5}$$

Wind Blown Bubble

Assuming momentum conservation but not energy conservation (snowplot), the mass per steradian, M_{sr}, grows

$$\frac{dM_{sr}}{dt} = \frac{c_s^2}{2\pi G} Q(\mu) v_s \tag{6}$$

And the momentum grows by:

$$\frac{d}{dt}(M_{sr} v_s) = \frac{\dot{M}_w v_w}{4\pi} P(\mu) \tag{7}$$

Now we balance momentum change per steradian due to wind with ram pressure per steradian

$$v_s \frac{dM_{sr}}{dt} = \frac{c_s^2}{2\pi G} Q(\mu) v_s^2 = \frac{\dot{M}_w v_w}{4\pi} P(\mu) \tag{8}$$

Wind Blown Bubble

implying

$$v_s = \left(\frac{\dot{M}_w}{2\dot{M}}\right)^{1/2} (c_s v_w)^{1/2} \beta(\mu), \; where \; \beta(\mu) = \left(\frac{P(\mu)}{Q(\mu)}\right)^{1/2} \tag{9}$$

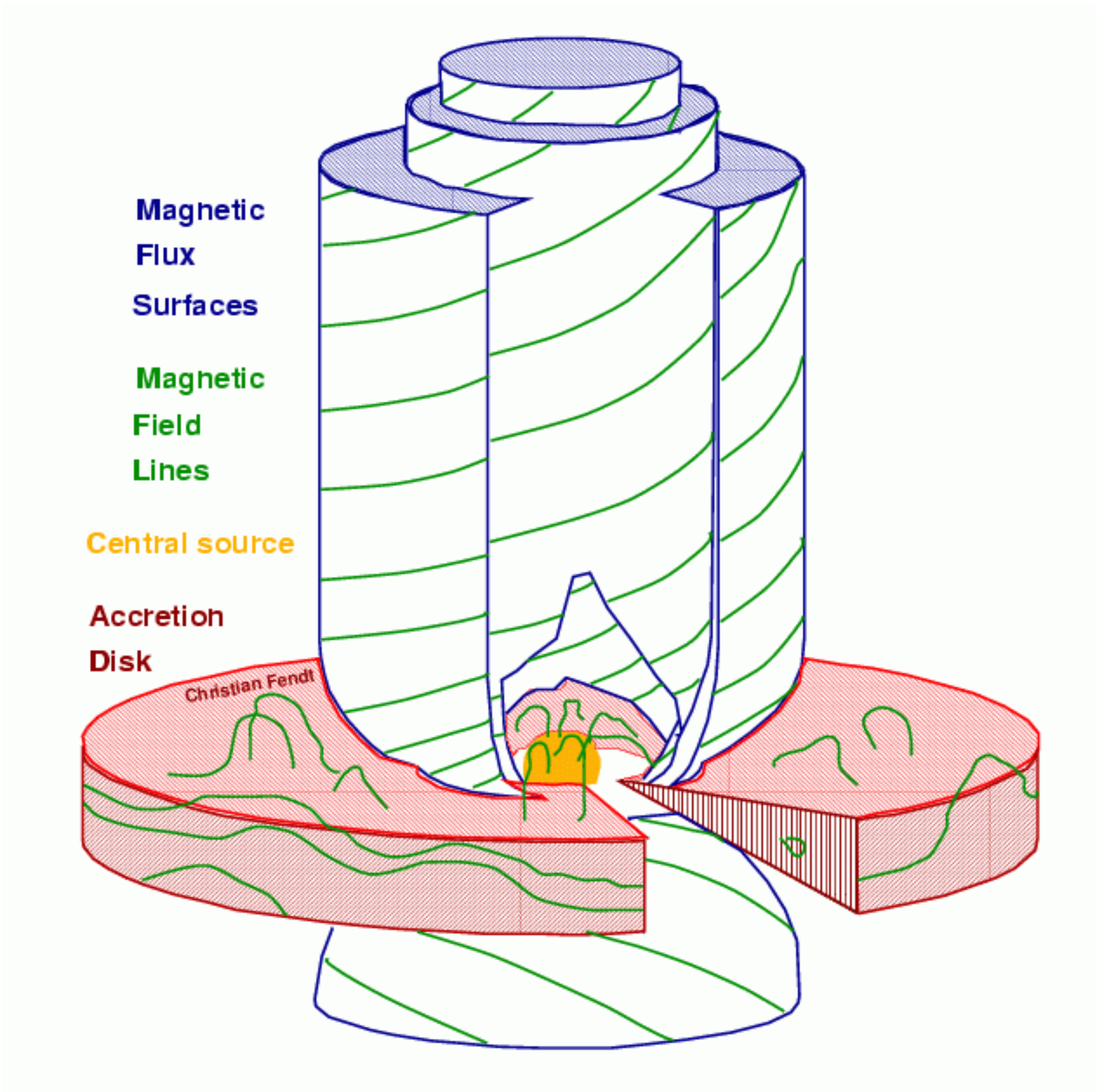
$$r_s = (f/2)^{1/2} (c_s v_w)^{1/2} t \beta(\mu) \tag{10}$$

This gives a "Hubble" law for outflows:

$$v_s = \frac{r_s}{t} \tag{11}$$

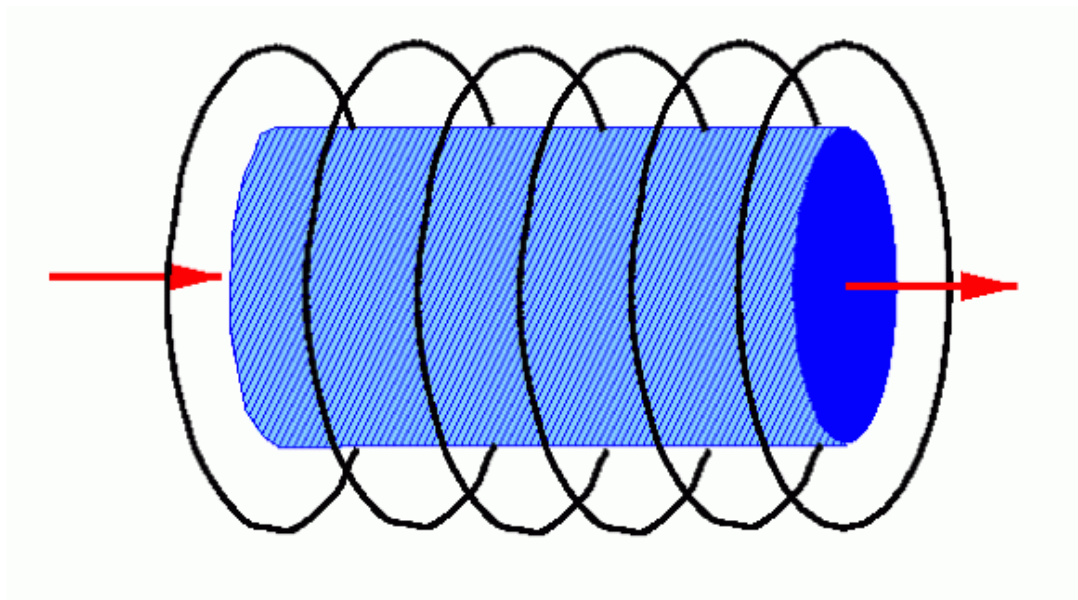
Creating Jets

Creating Jets: Magnetic field winding - confinement



C. Fendt

Magnetic field winding - confinement



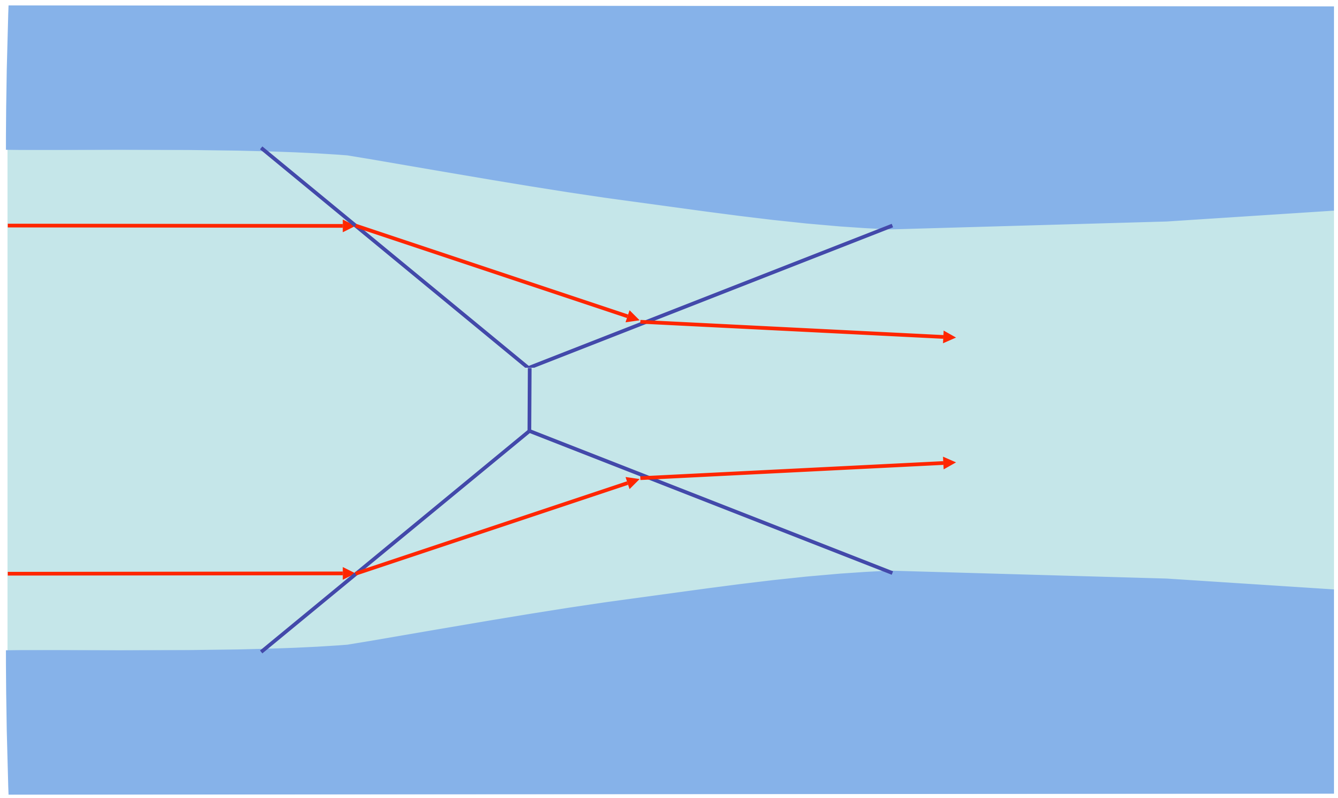
(courtesy:
C. Fendt)

$$\vec{j} = \frac{c}{4\pi} \nabla \times \vec{B}$$

$$\vec{f} = \frac{1}{c} \vec{j} \times \vec{B}$$

Right-hand rule:
force points
inwards

Hydrodynamic confinement in jet:

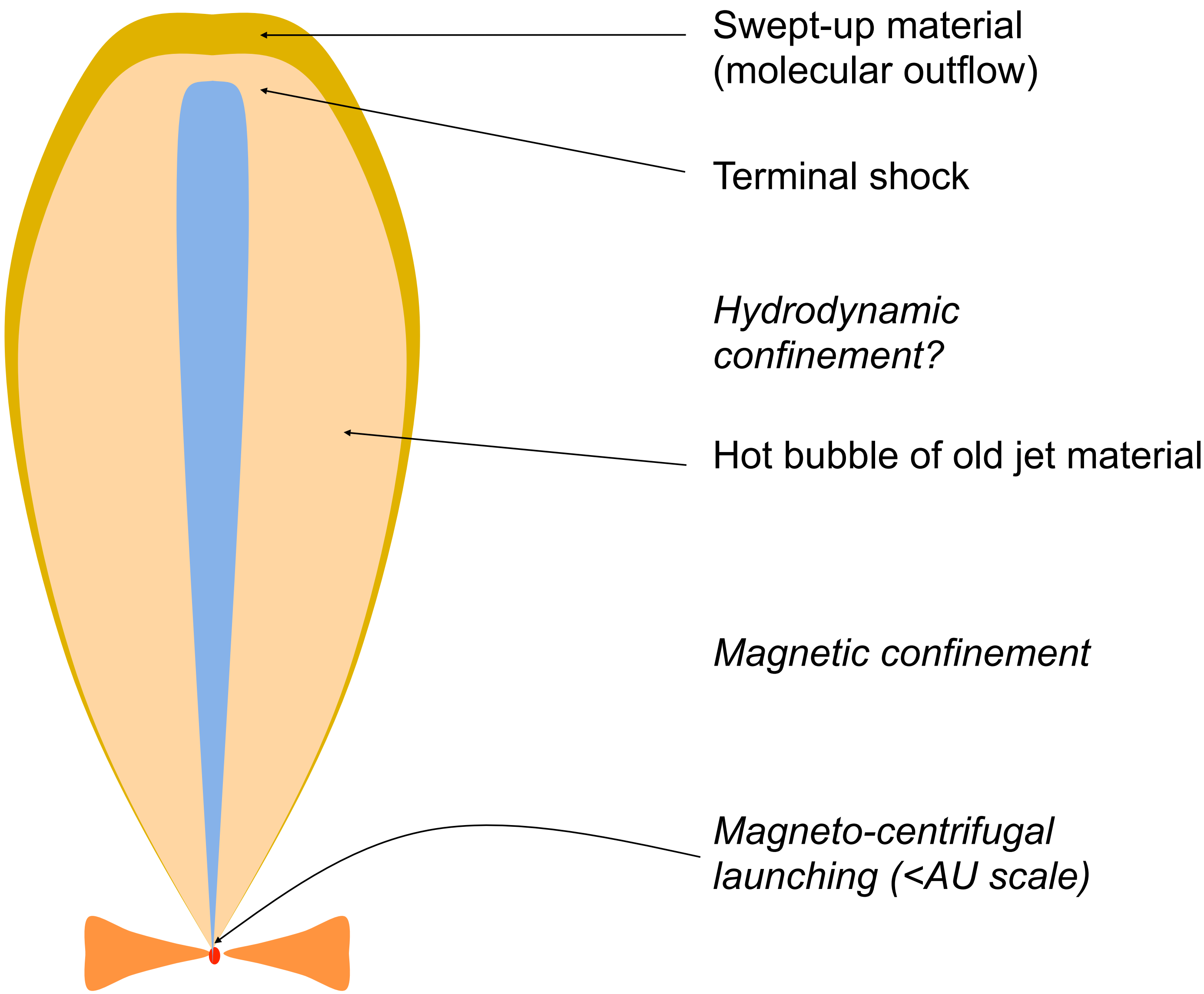


Shock only reduces the velocity component perpendicular to shock front. Therefore obliquely shocked gas is deflected toward the shock plane.

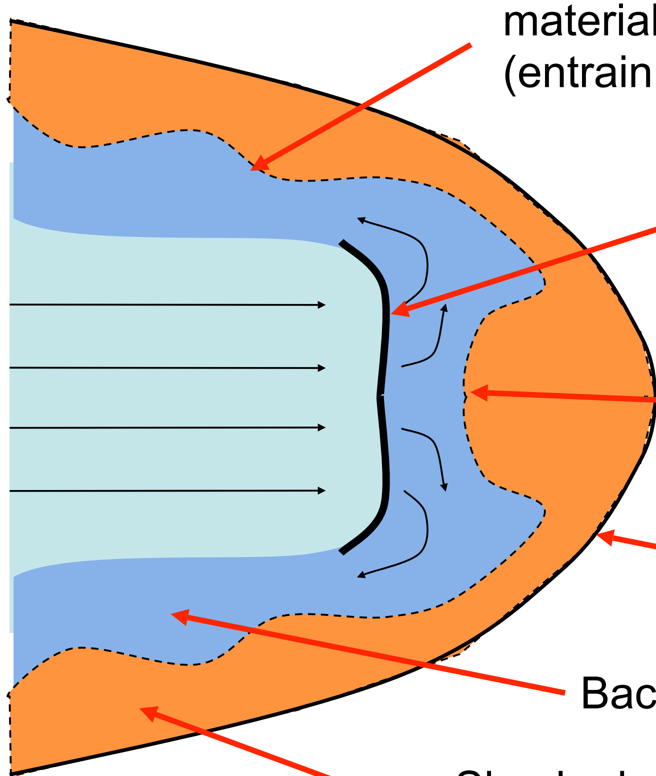
Hydrodynamic confinement in jet:

Dryden Flight Research Center EC93-03092-7 Photographed 1994
SR-71 Ship #1

Bipolar outflows driven by Jets



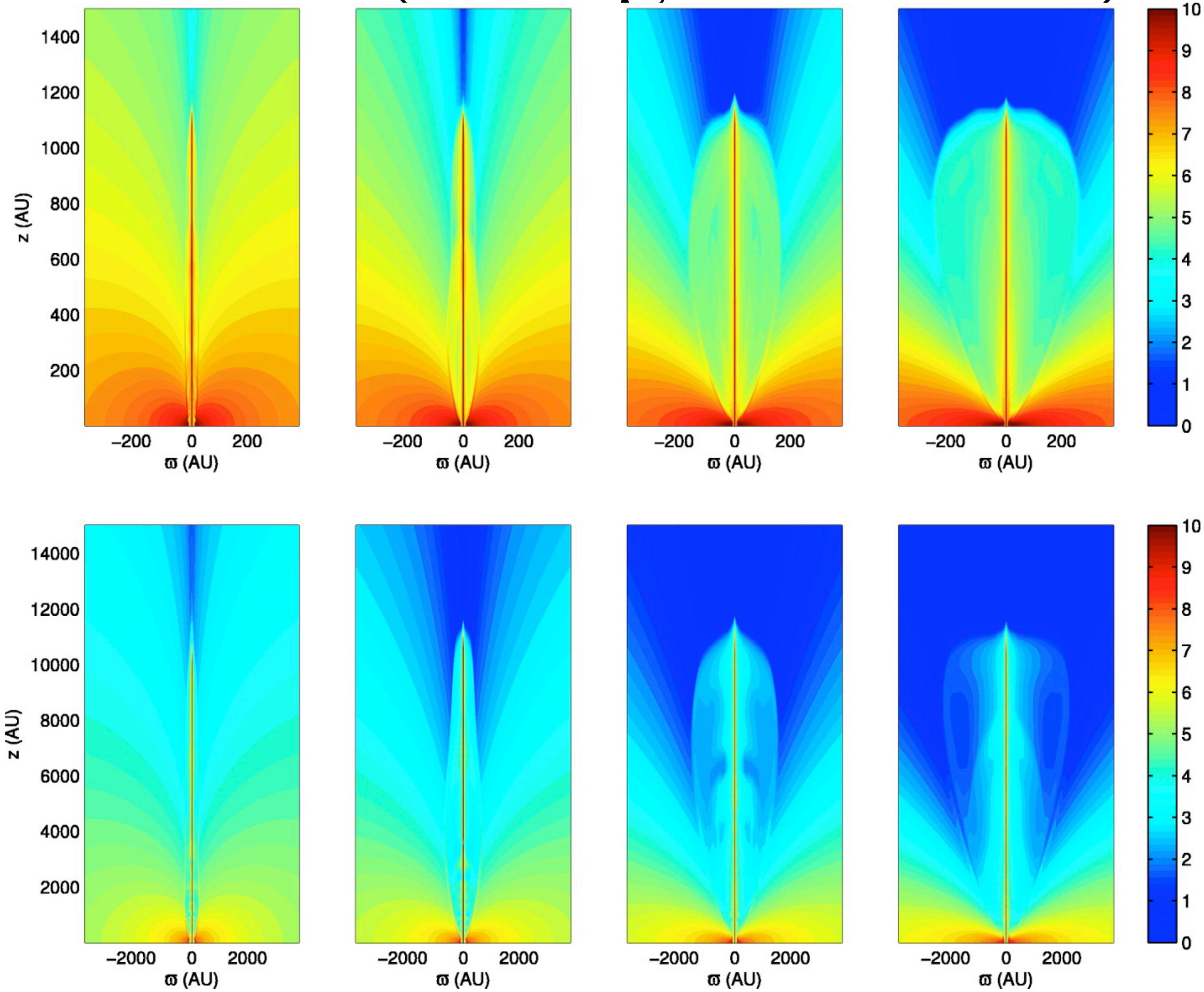
Head of the jet:



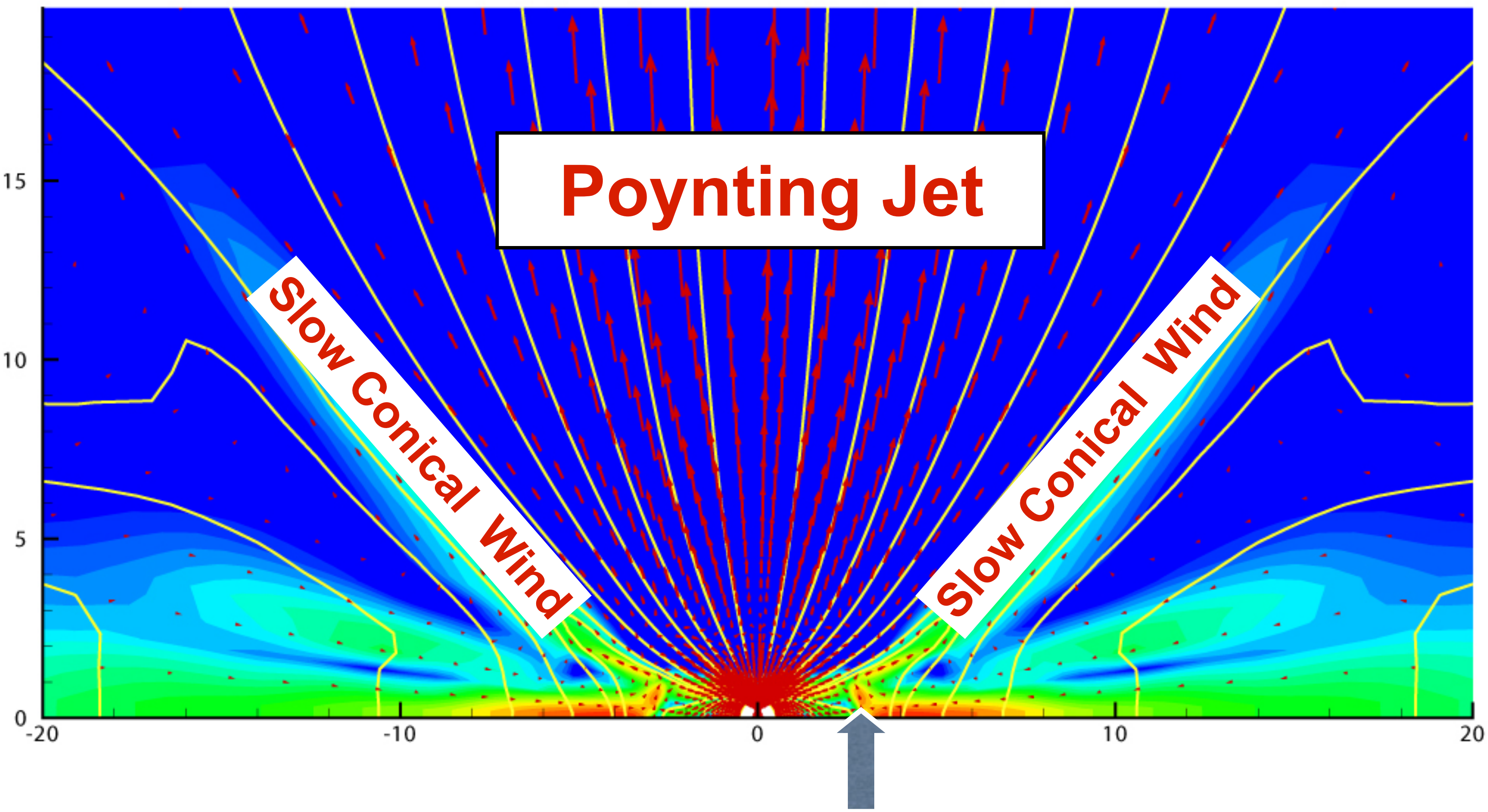
Jet flow much faster than propagation of bow shock.
Jet material much more tenuous than external medium

Most Likely a Combination of Both

A Unified Models of Jets and Winds (Shang et al 2006)



Rapidly-rotating stars: Propeller regime

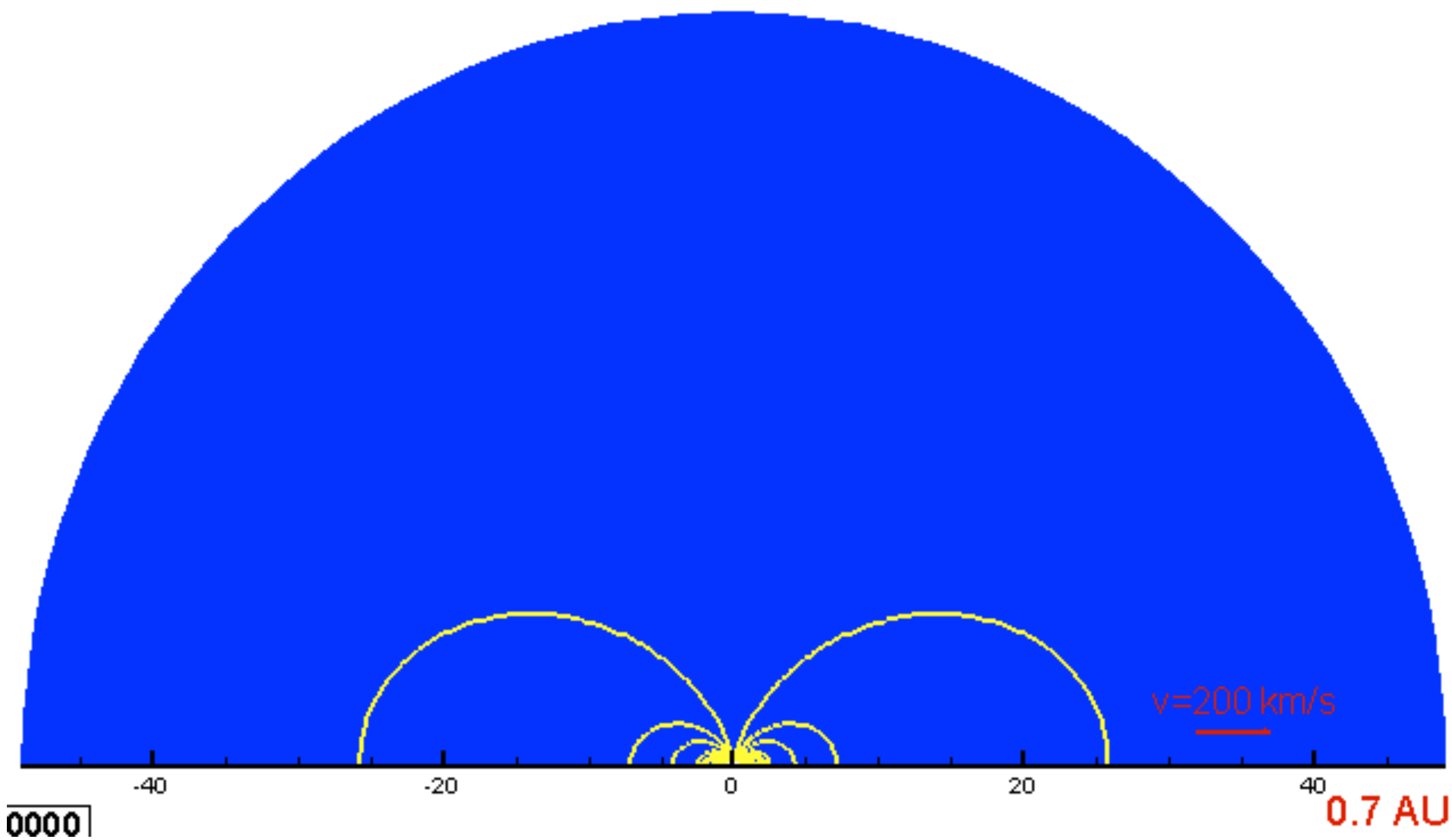


- Two-component outflow forms
- Conical winds carry most of matter outwards
- Poynting jet carries energy and ang. momentum

Romanova et al. 2005; Ustyugova et al. 2006; Romanova et al. 2009

The Propeller Regime

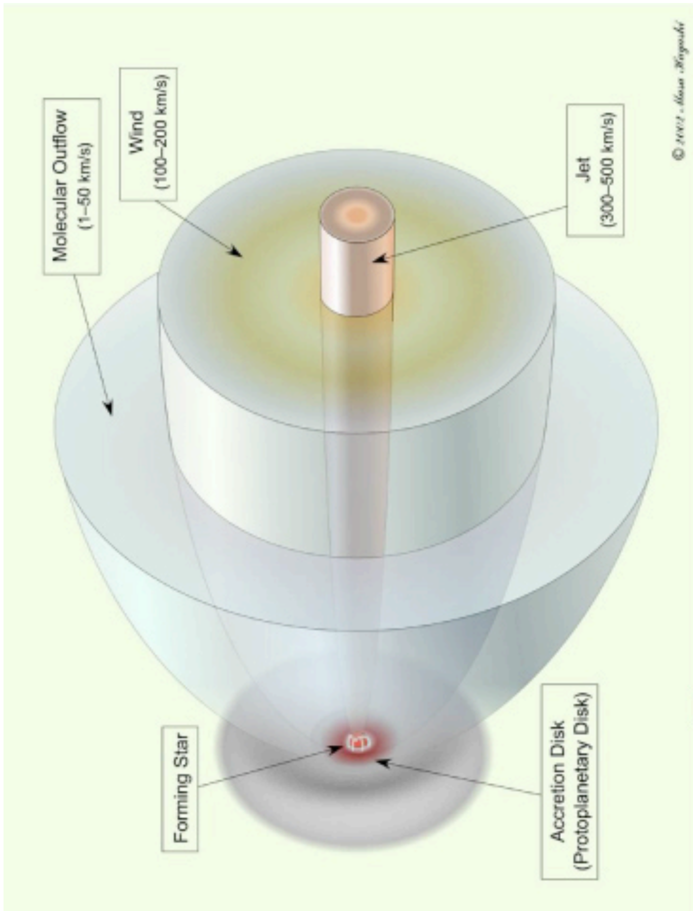
Disk radius > Corotation Axis:
Magnetic field rotating faster than disk

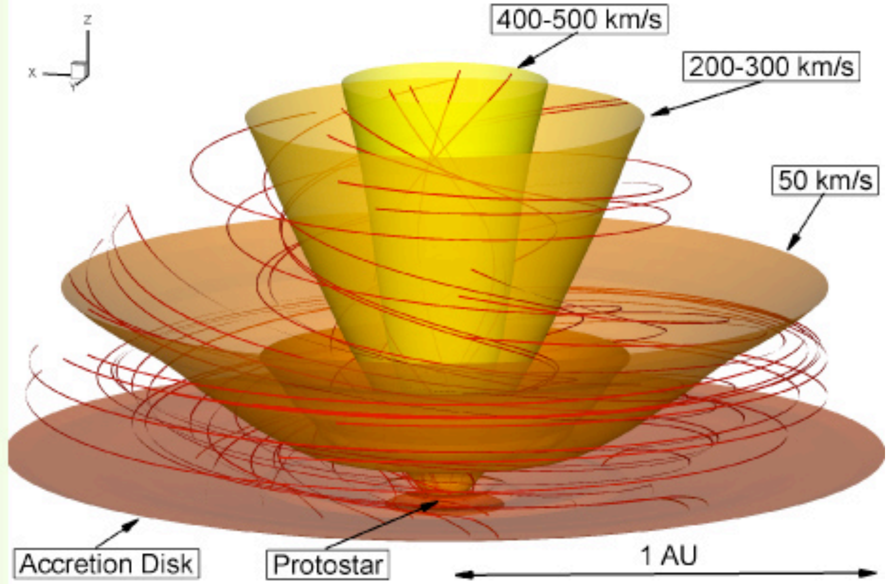


Ustyugova et al. 2006

Outflows at the Propeller Stage:

Conical Winds + Axial Jet

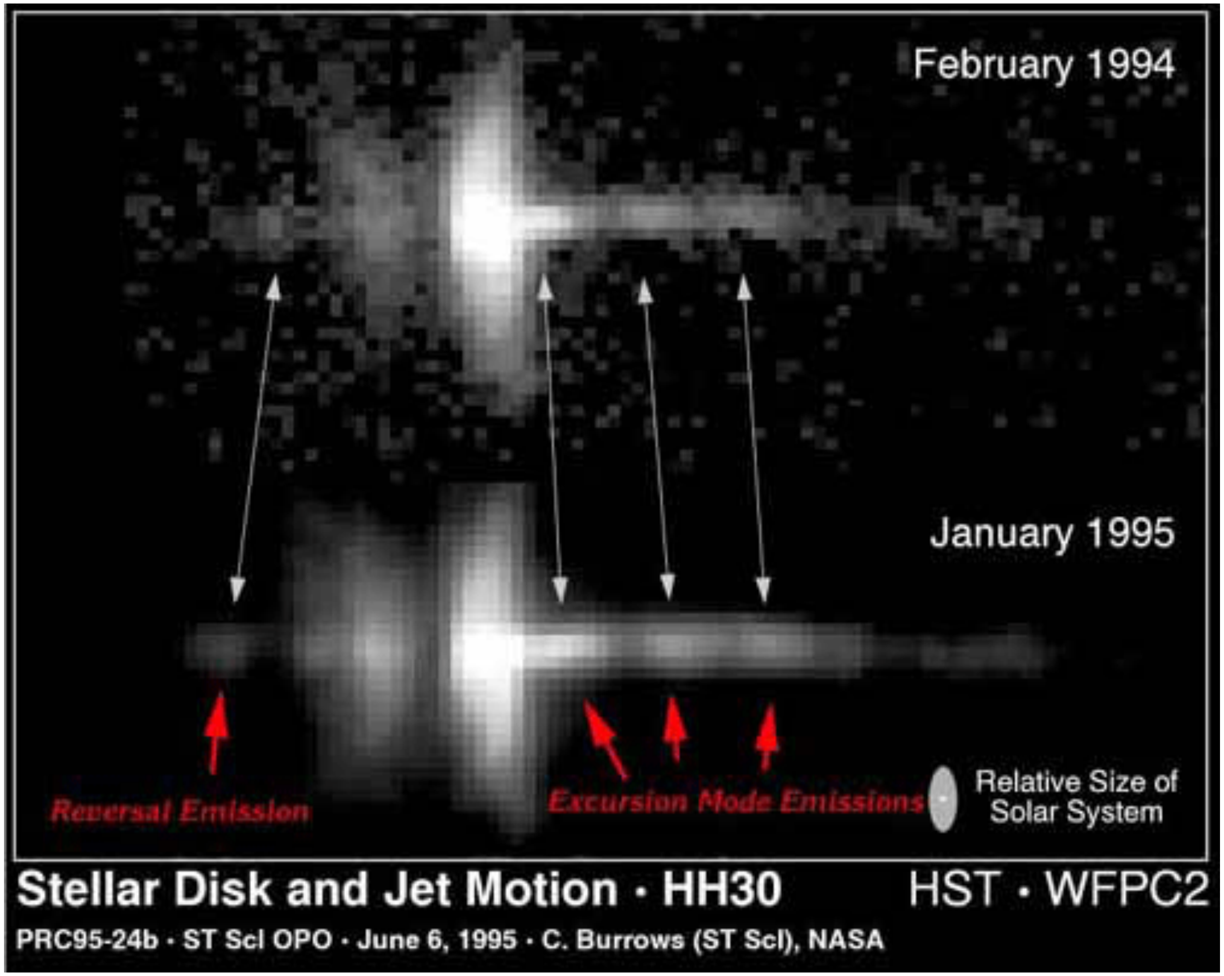




A star spins-down due to axial magnetic jet

Pirated from talk by Marina Romanova

Observed knot movement



Observations of Jets and Winds

Herbig-Haro Objects

Discovered independently by George Herbig and Guillermo Haro in 1950s

Small knots of nebulosity in dark clouds

Displayed lines of hydrogen and forbidden lines of [OI], [NII] and [SII].

Now known to be shock ionized nebulae.

More than 400 Herbig Haro (HH) objects are known.

Only trace a small fraction of the outflowing gas

Forbidden Lines, Atomic Hydrogen Lines and Molecular Hydrogen Lines

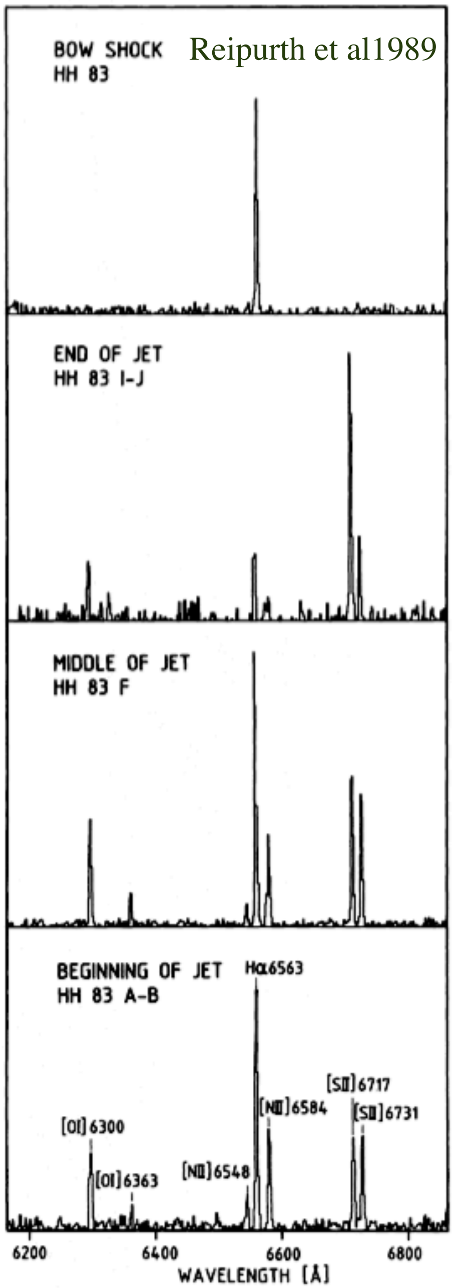
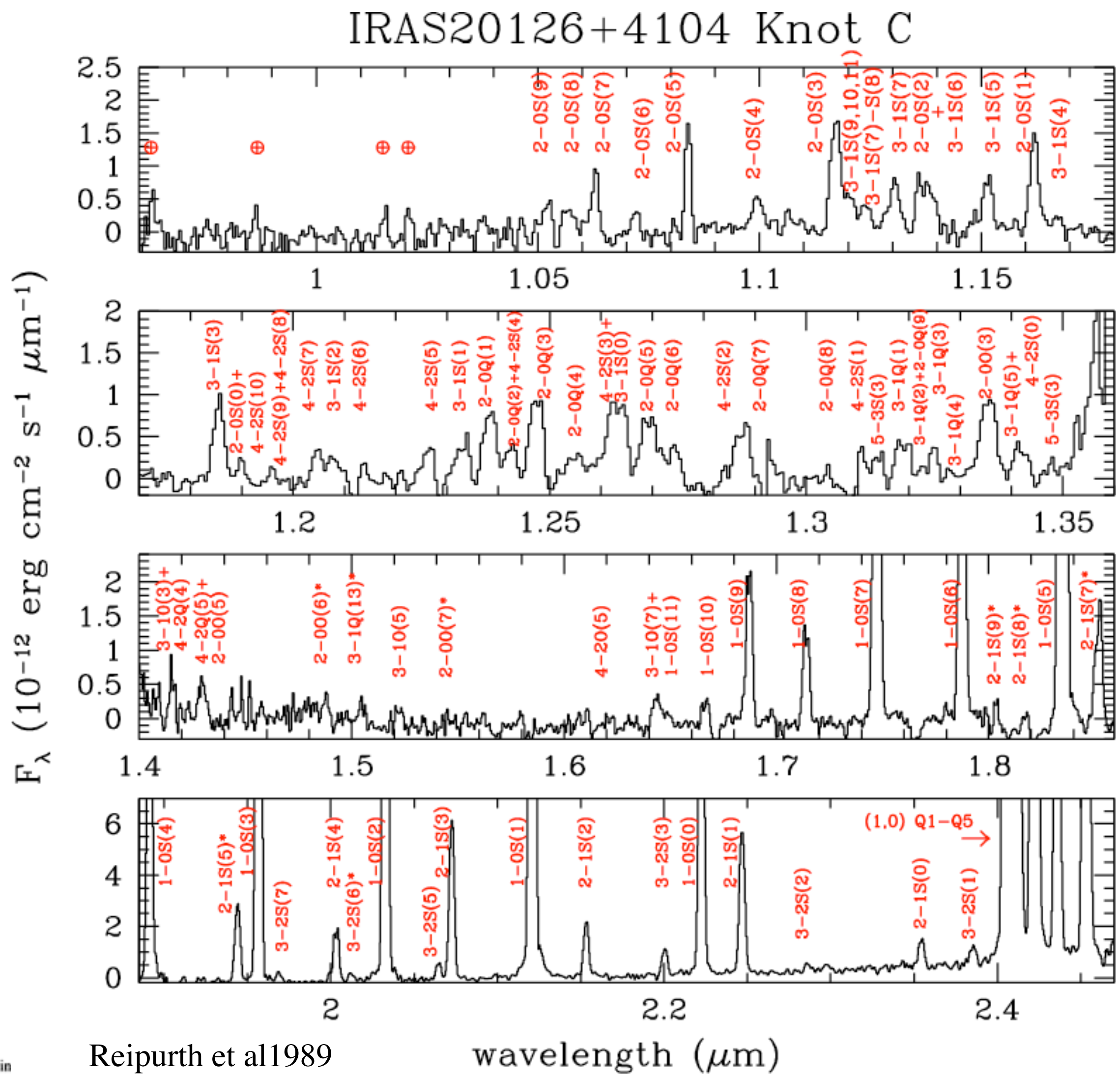


Fig. 5. Spectra of knots A-B, F, I-J in the HH 83 jet and of the bow shock in wavelength range approx. 6200 Å to 6800 Å. Note the increasing [S II] 6717/Hα ratio as one moves out along the jet, as well as the changing sulphur line ratio, indicating decreasing electron density. The bow shock is pure Hα emission



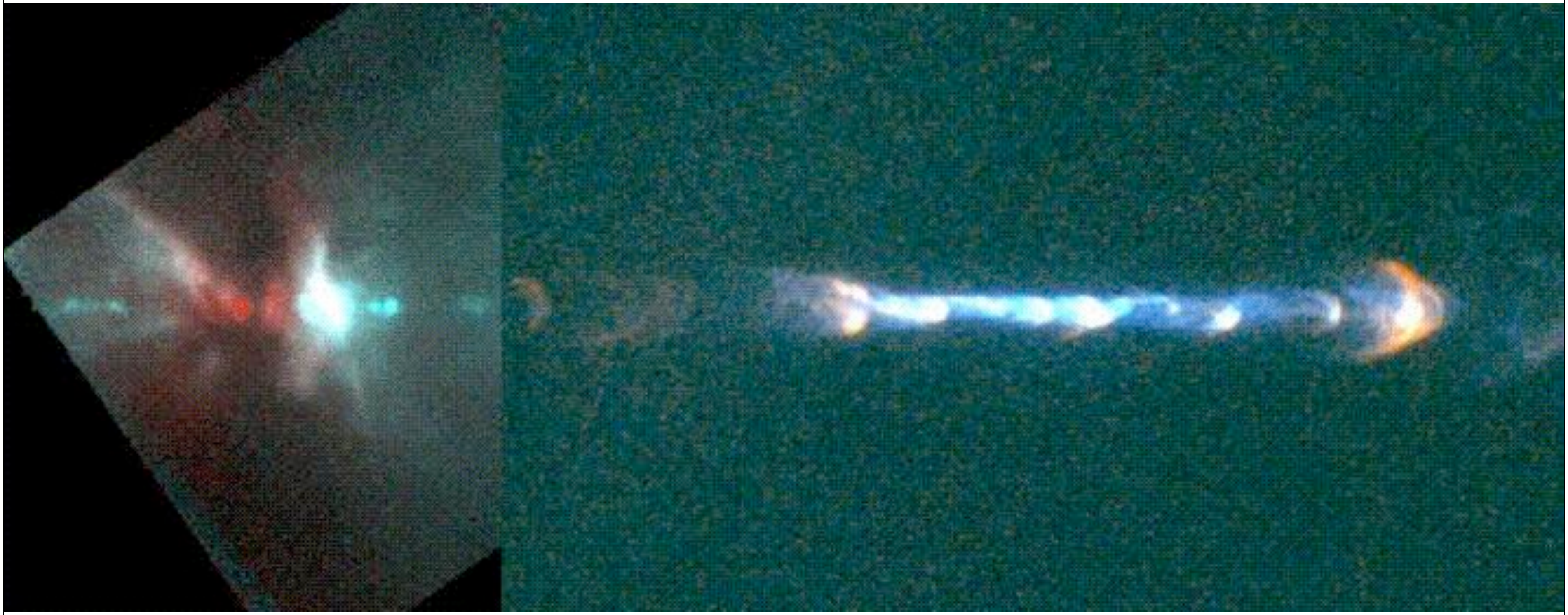
Reipurth et al1989

Carratti o Garatti et al. 2008

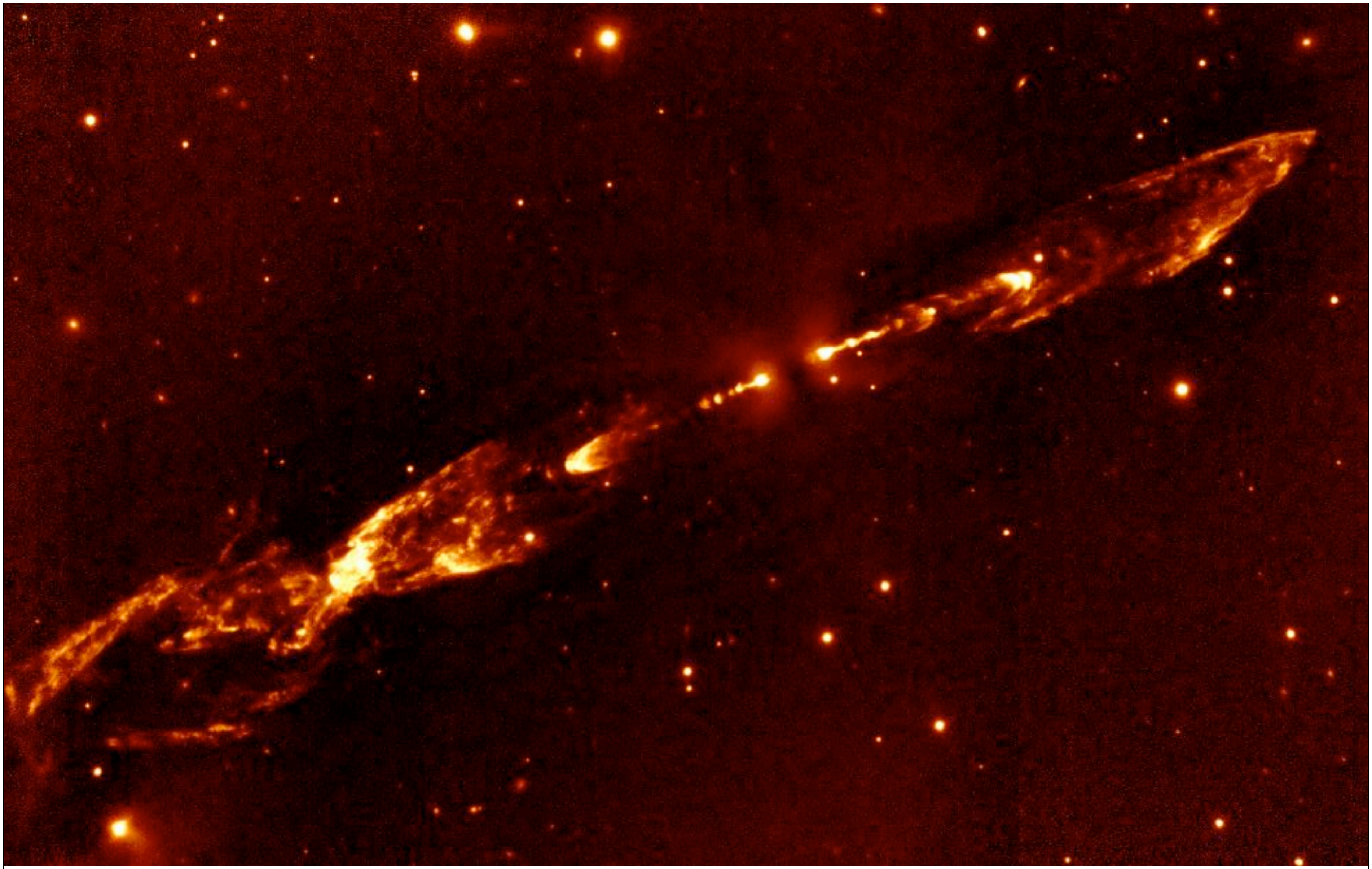
HH 111

Knots are probably internal shocks, where faster knots are crashing into slower knots

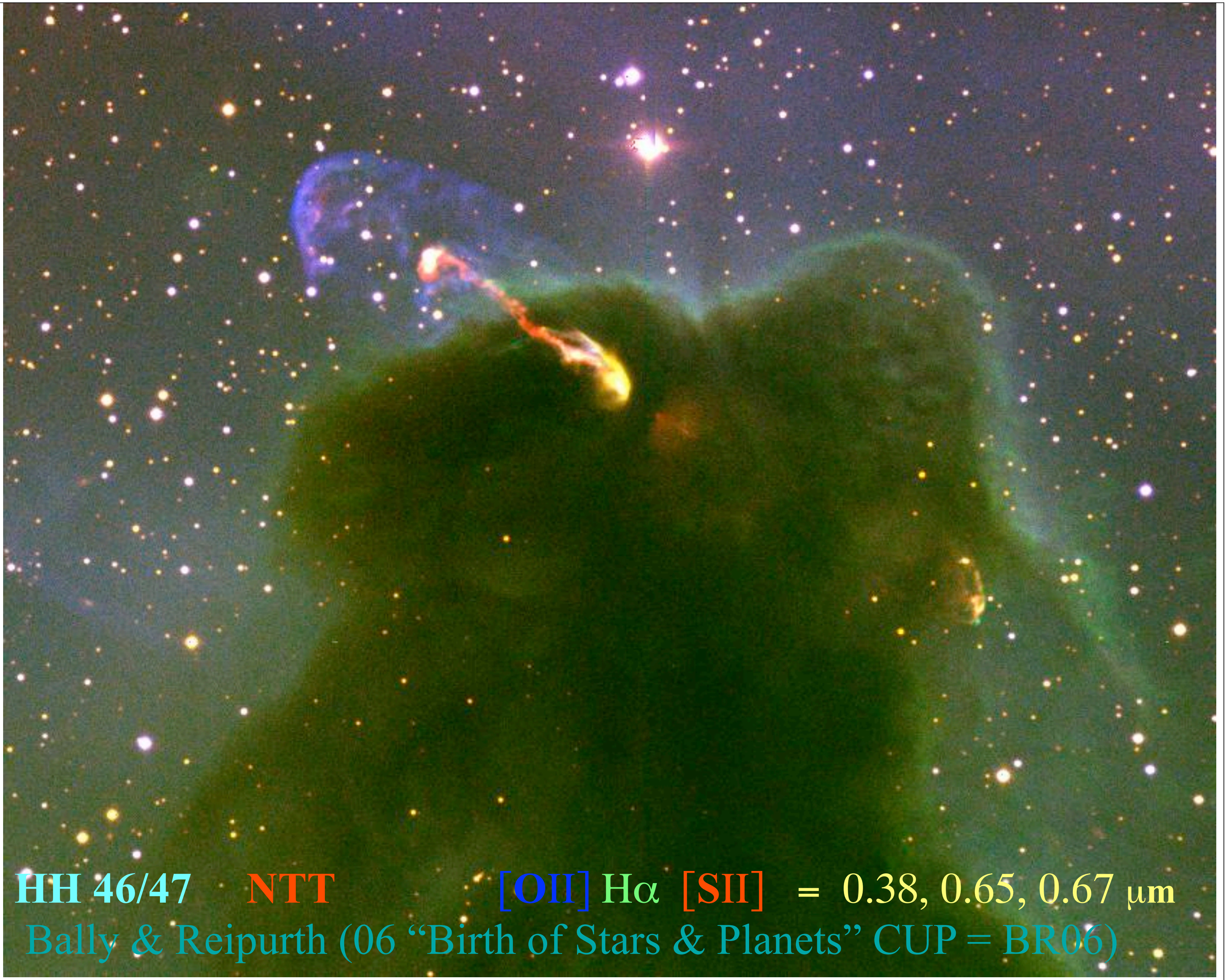
[Fe II] + K **Ha + [SII]**



NICMOS **WFPC2**

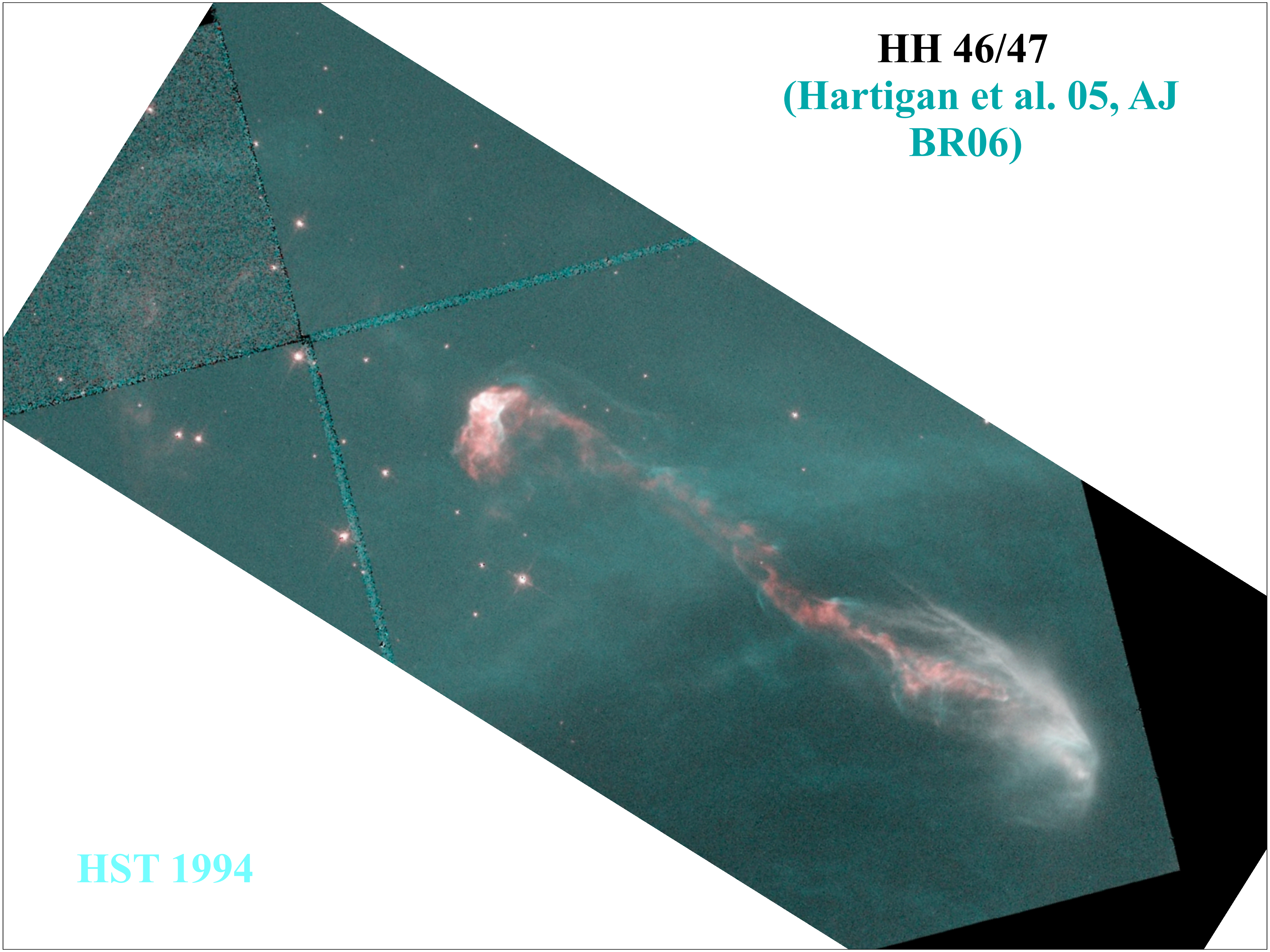


HH 212 H_2 (Mc Caughrean & Zinnecker VLT)


HH 46/47 NTT
[OII] Hα [SII] = 0.38, 0.65, 0.67 μm
Bally & Reipurth (06 "Birth of Stars & Planets" CUP = BR06)

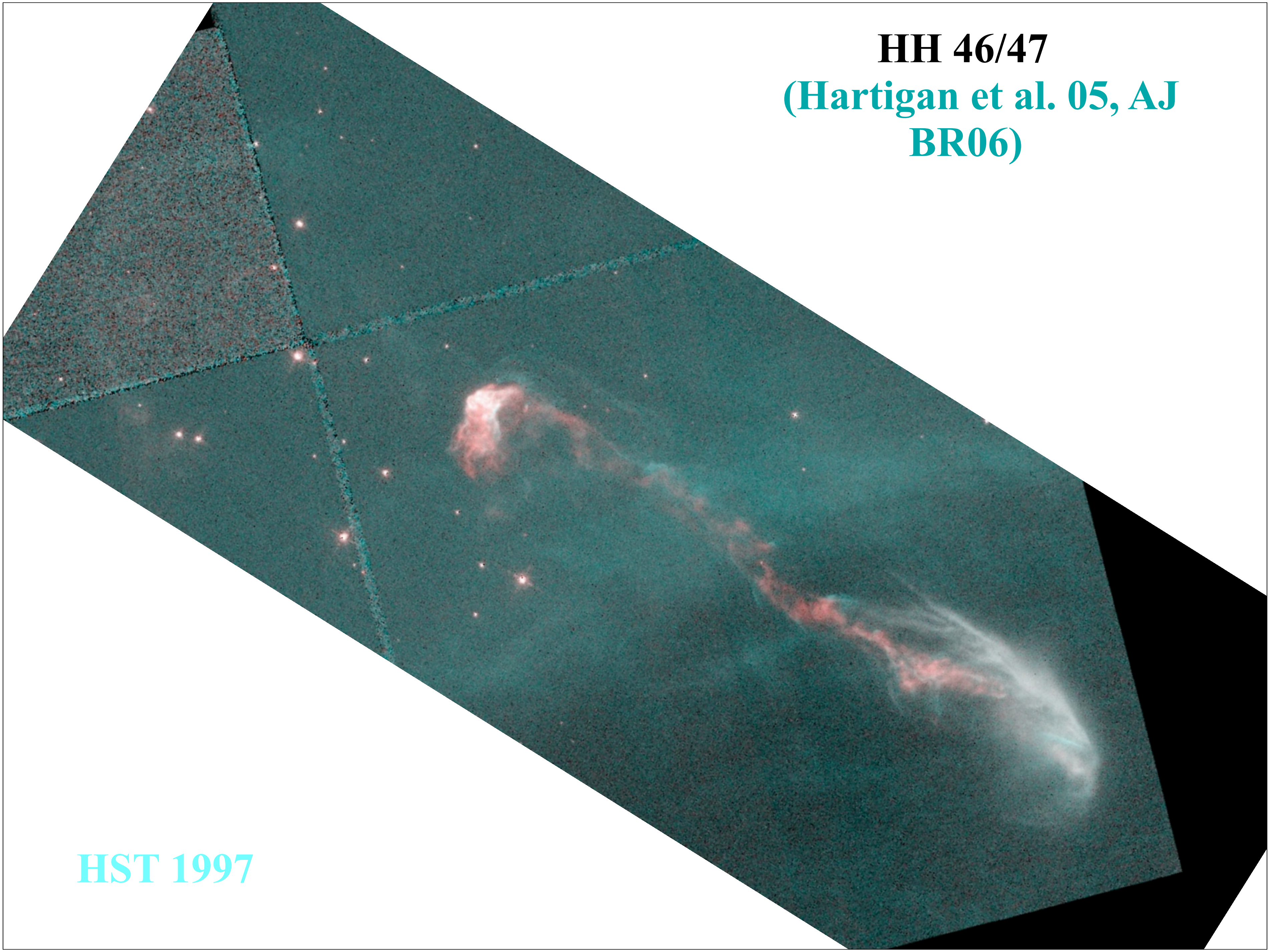
HH 46/47 Spitzer **H_2 PAH** 3.6, 4.5, 8 μm

(Noriega-Crespo 04; BR06)


HH 46/47
(Hartigan et al. 05, AJ
BR06)
HST 1994

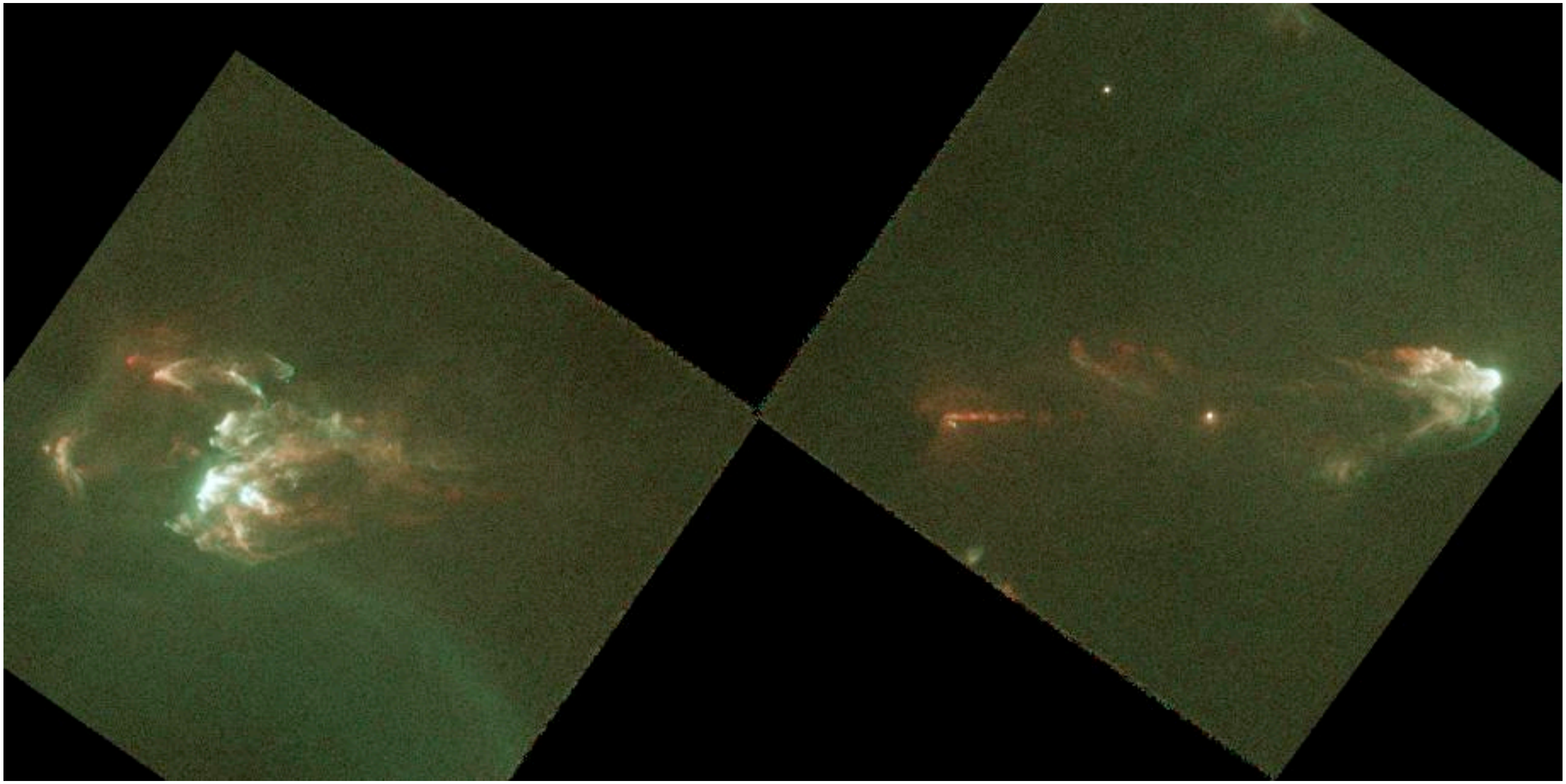
HH 46/47

(Hartigan et al. 05, AJ BR06)



HST 1997

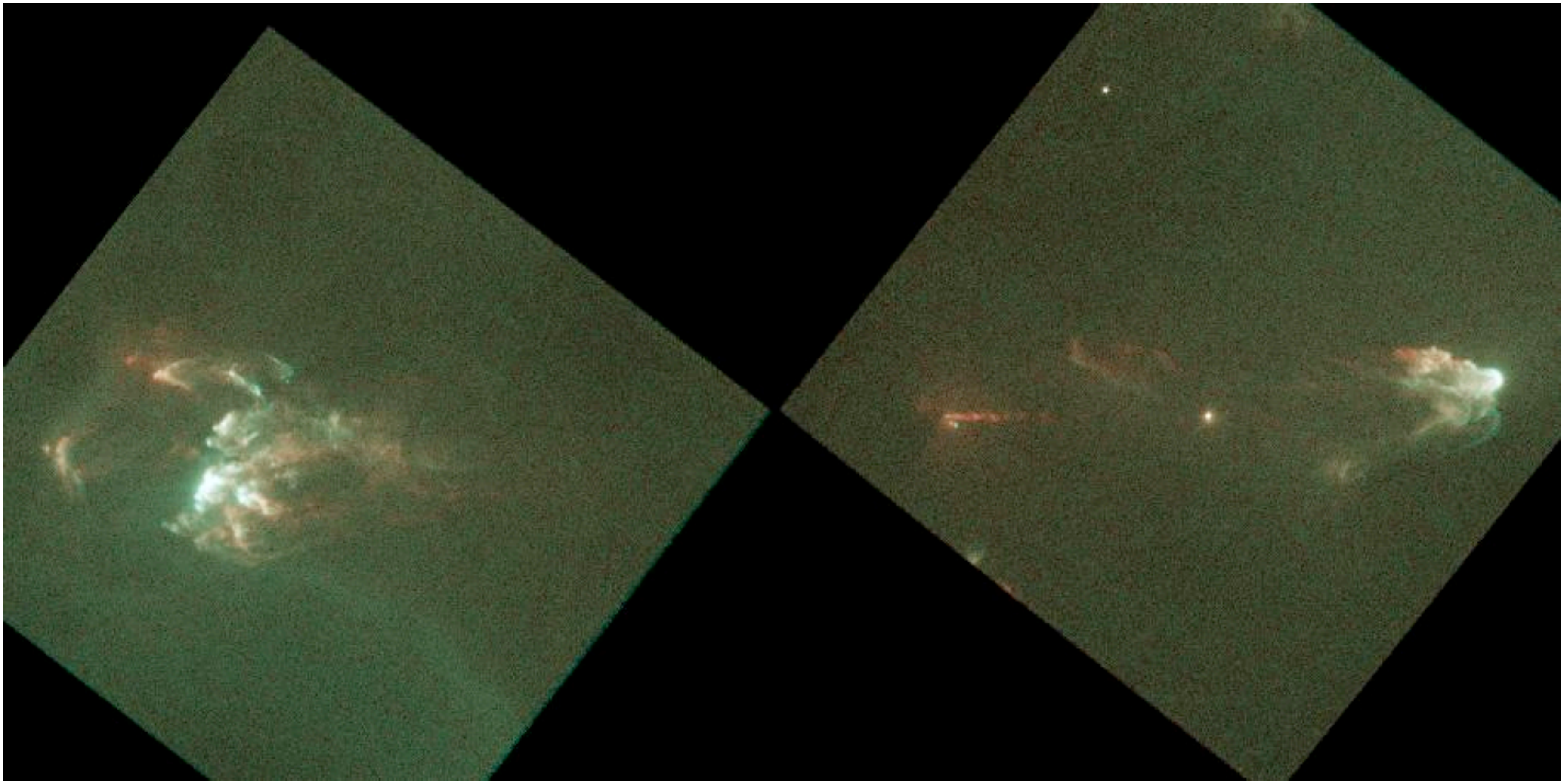
HH 2 HH 1



HST 1997 - 1994

HH 2

HH 1



HST 1997 - 1994

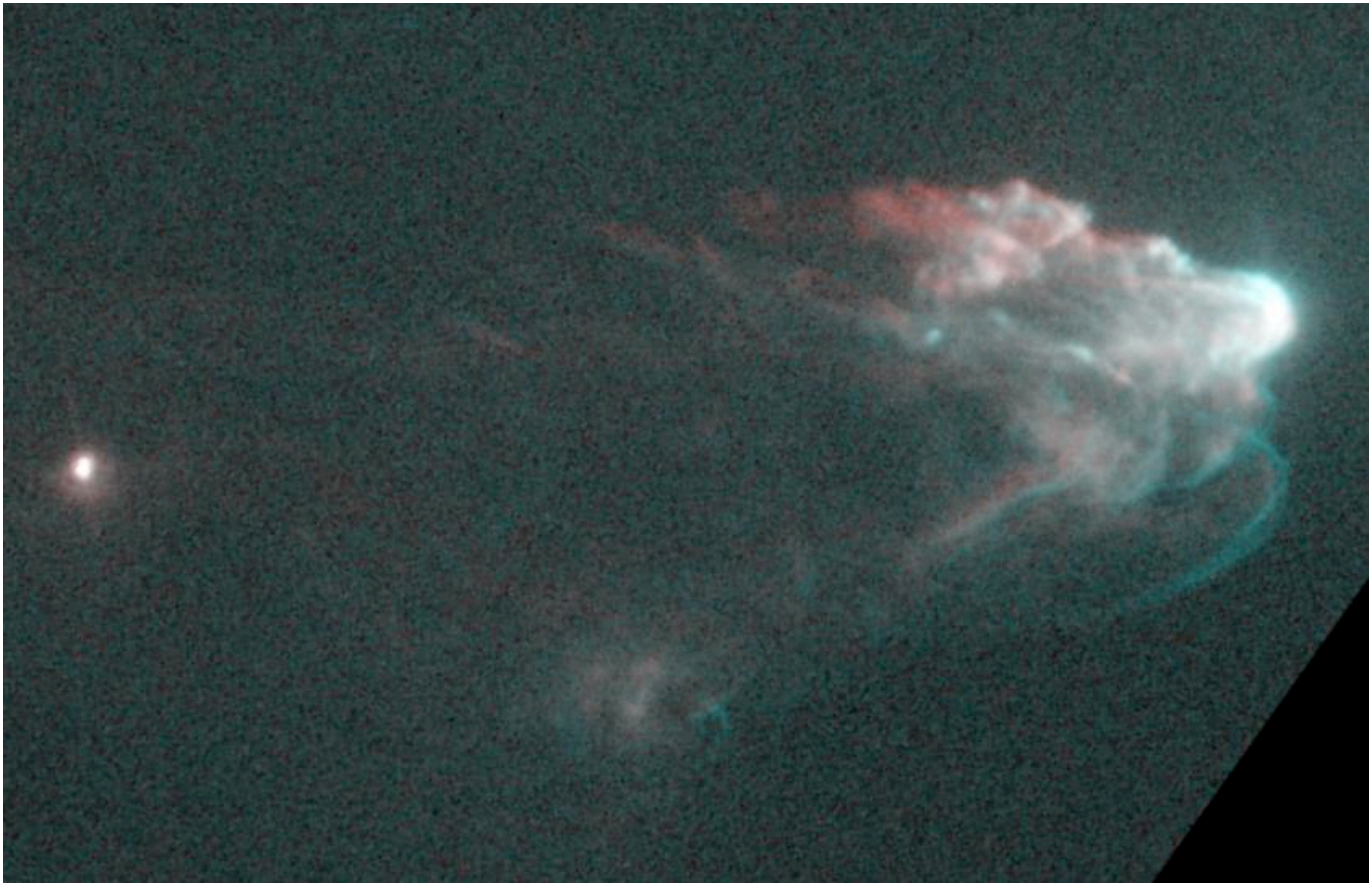
HH 1 jet

HST 1997 - 1994

HH 1 jet

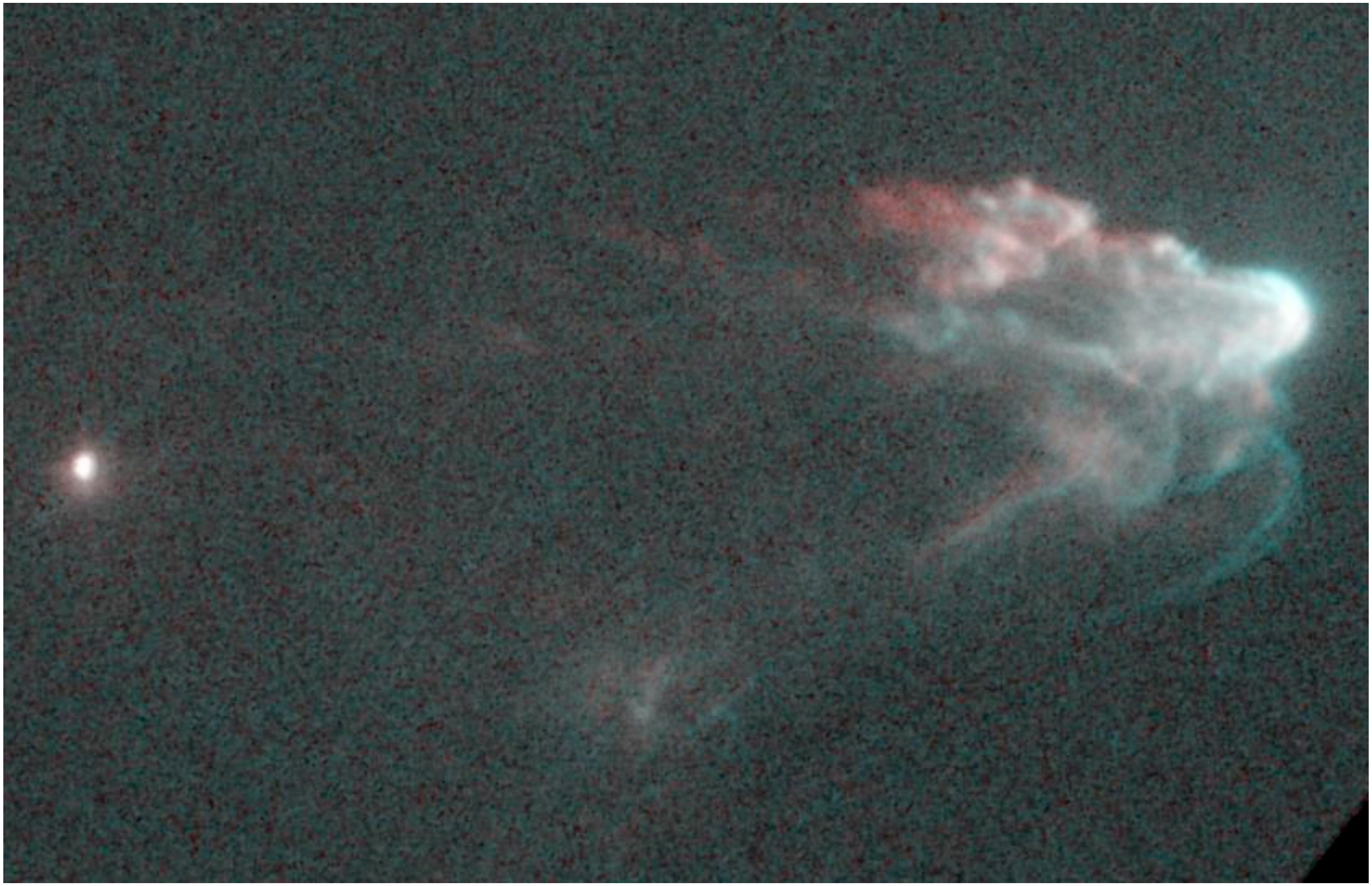
HST 1997 - 1994

HH 1



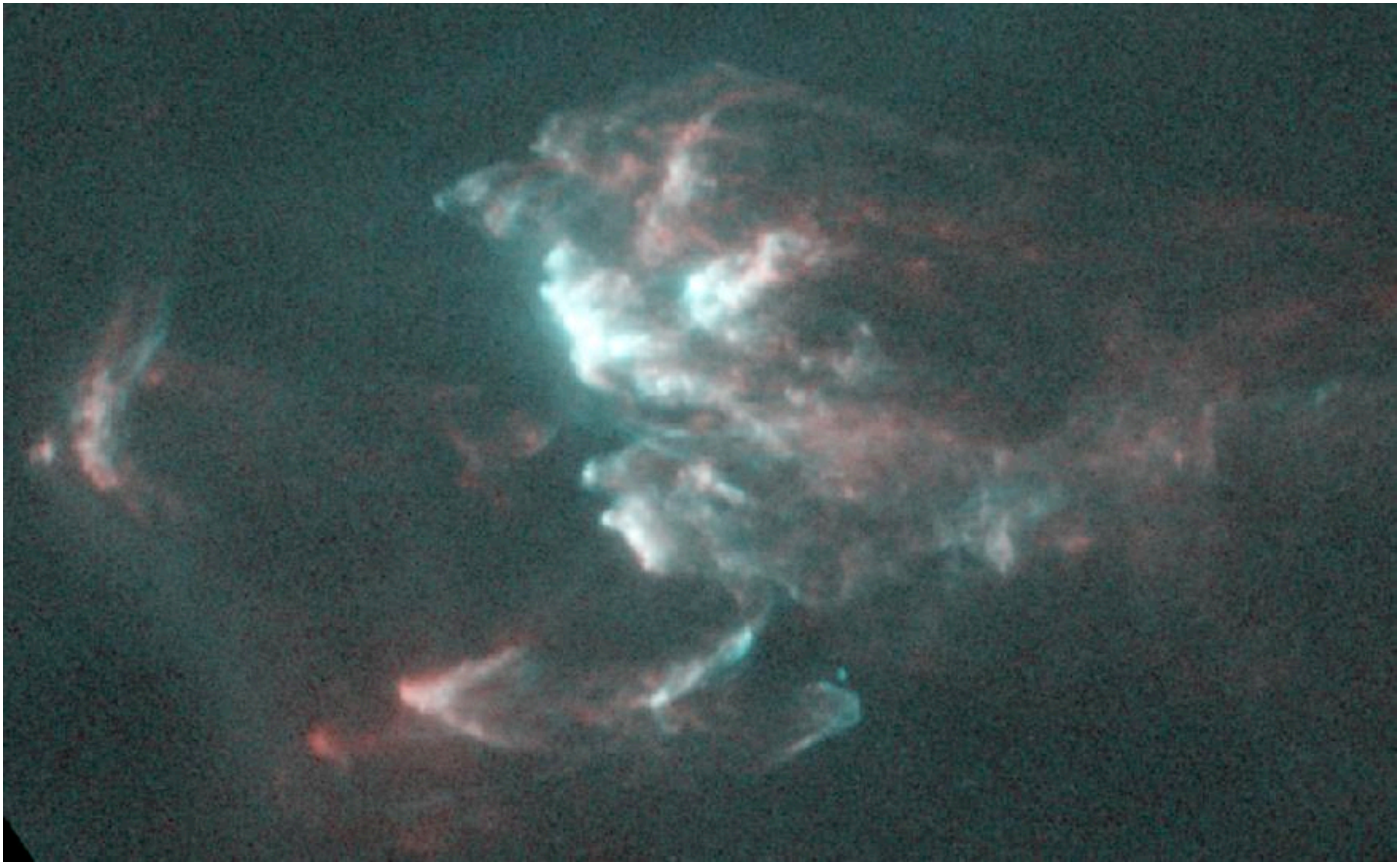
HST 1997 - 1994

HH 1



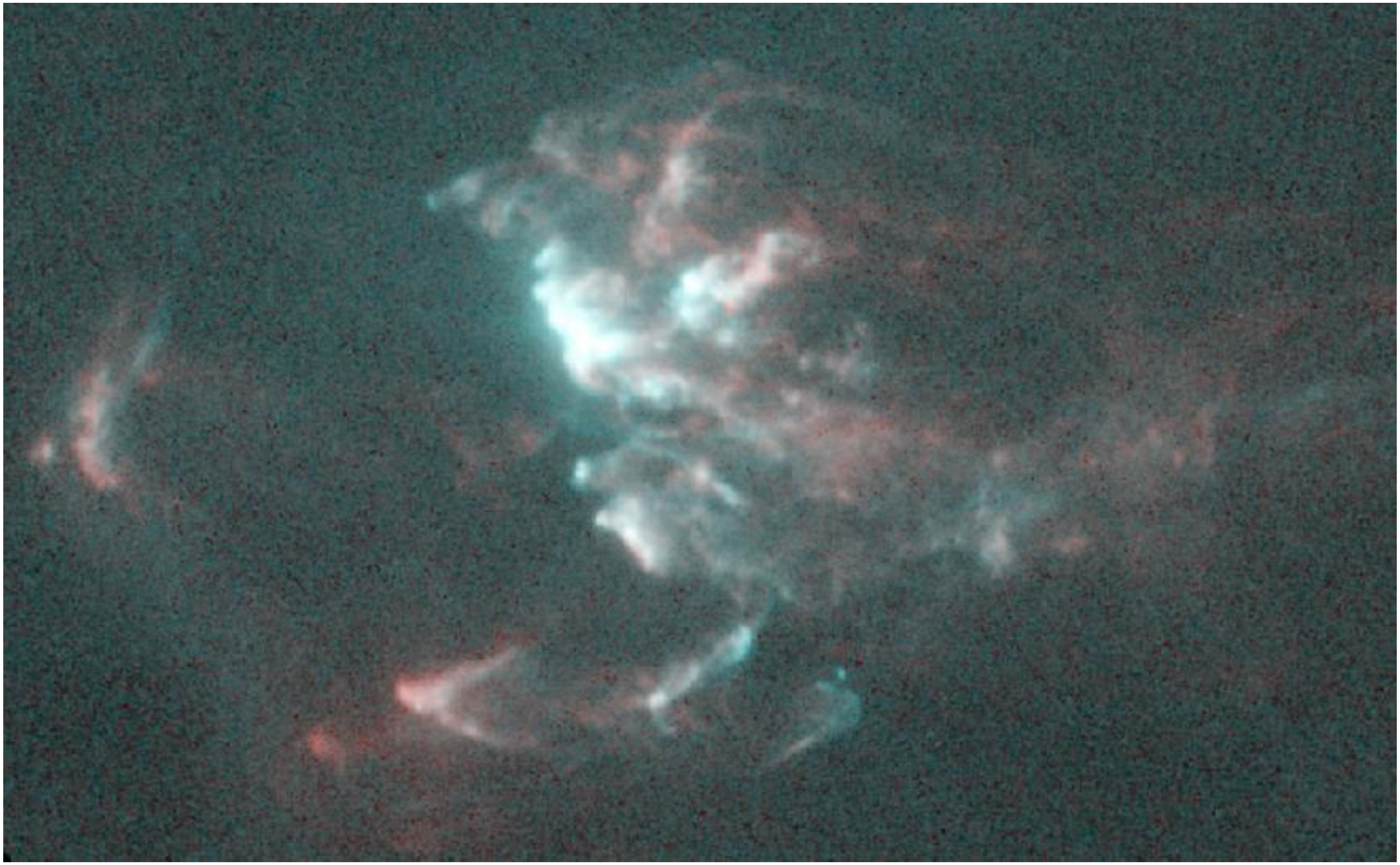
HST 1997 - 1994

HH 2



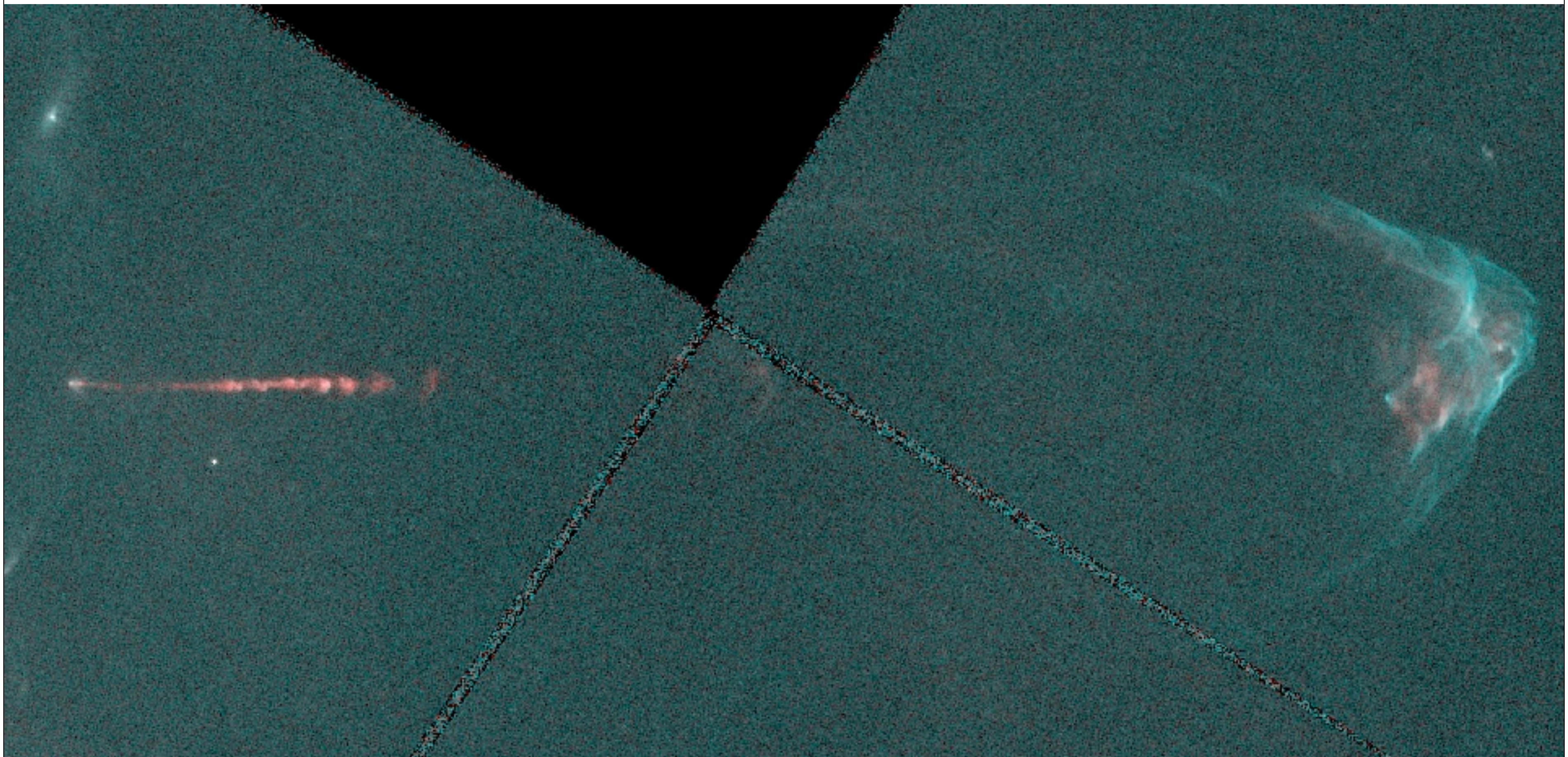
HST 1997 - 1994

HH 2



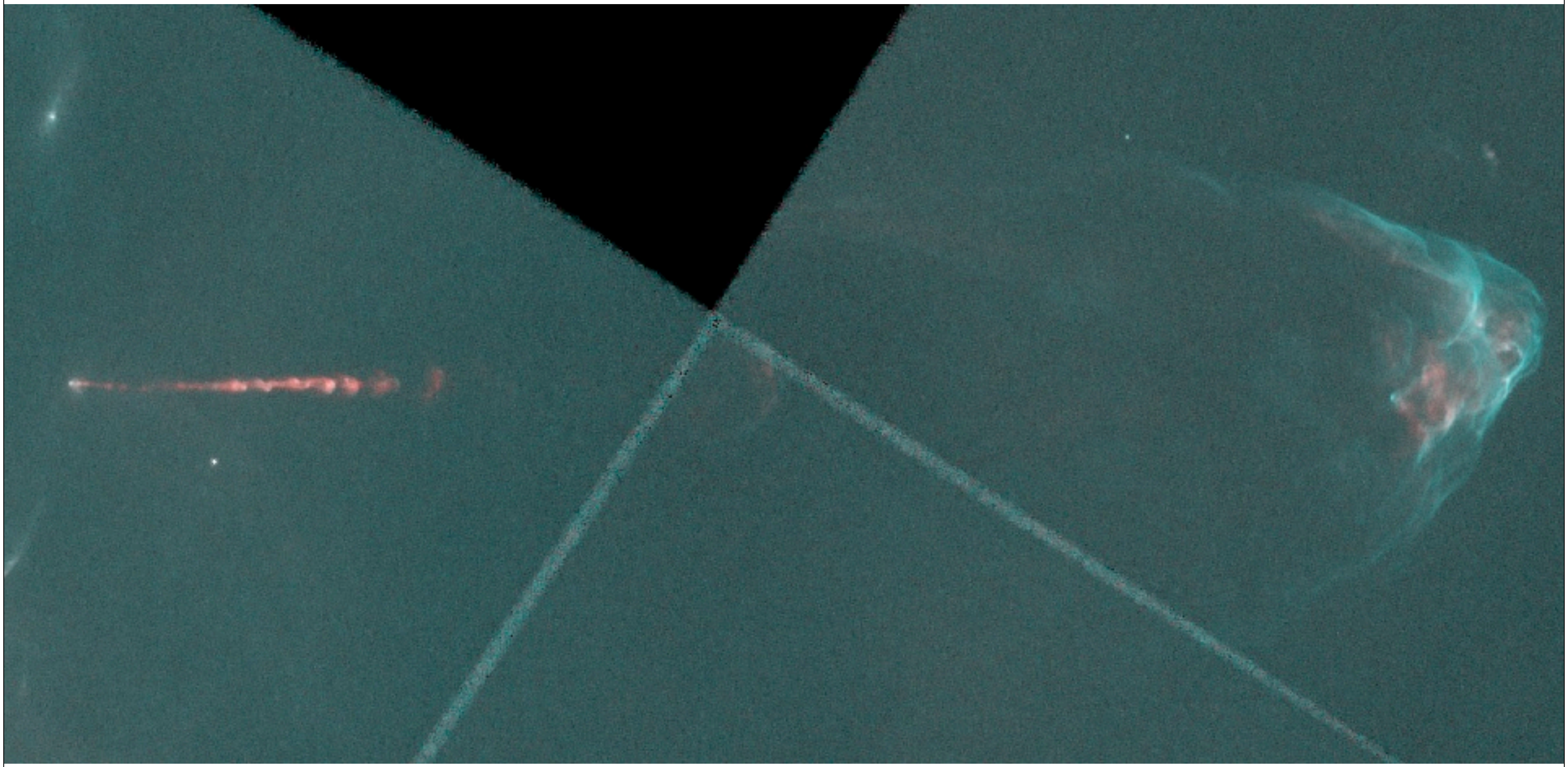
HST 1997 - 1994

HH 34



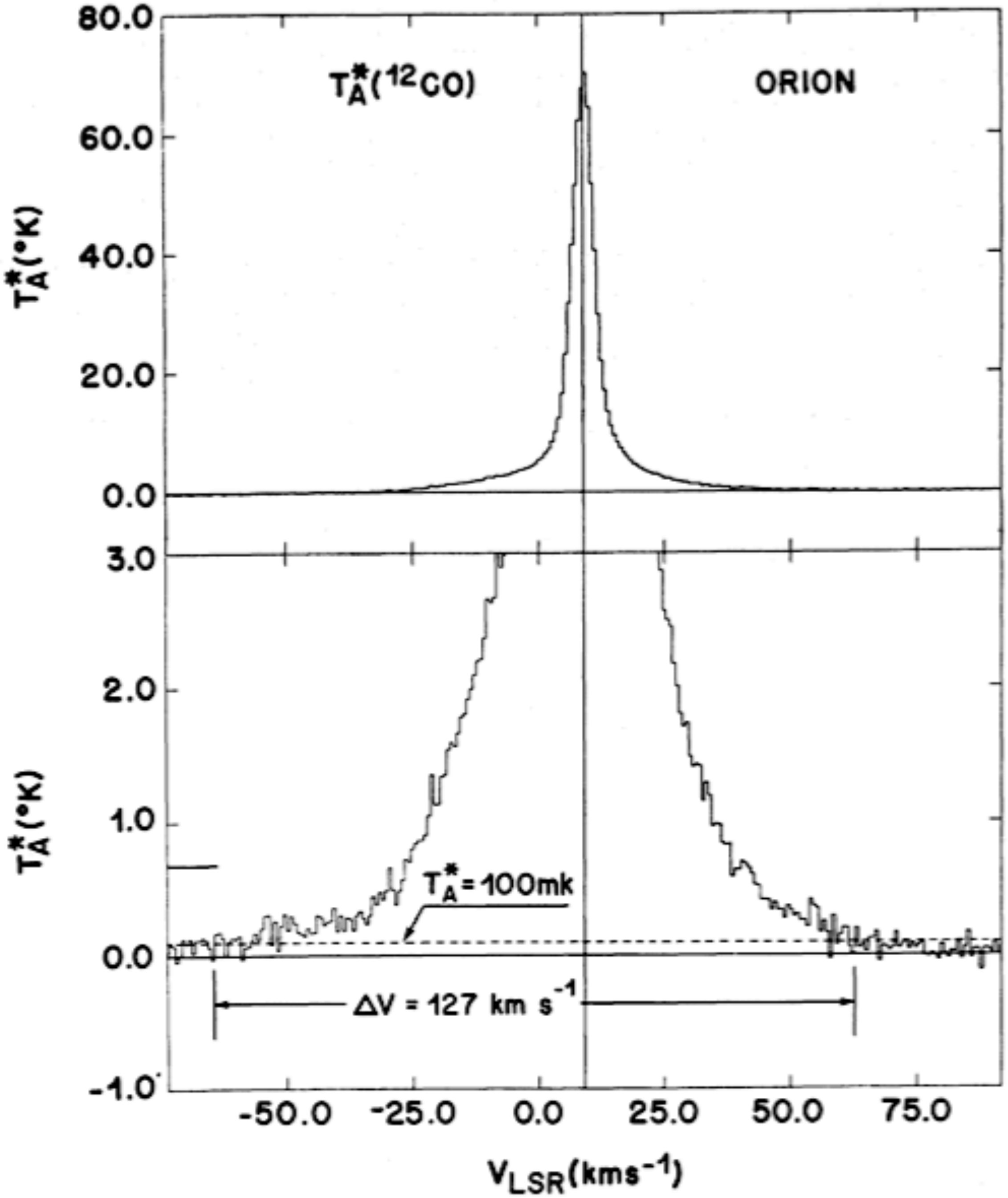
HST 1997 - 1994

HH 34



HST 1997 - 1994

Molecular Outflows



Molecular Outflows: Line Wings

Bally & Lada 1983

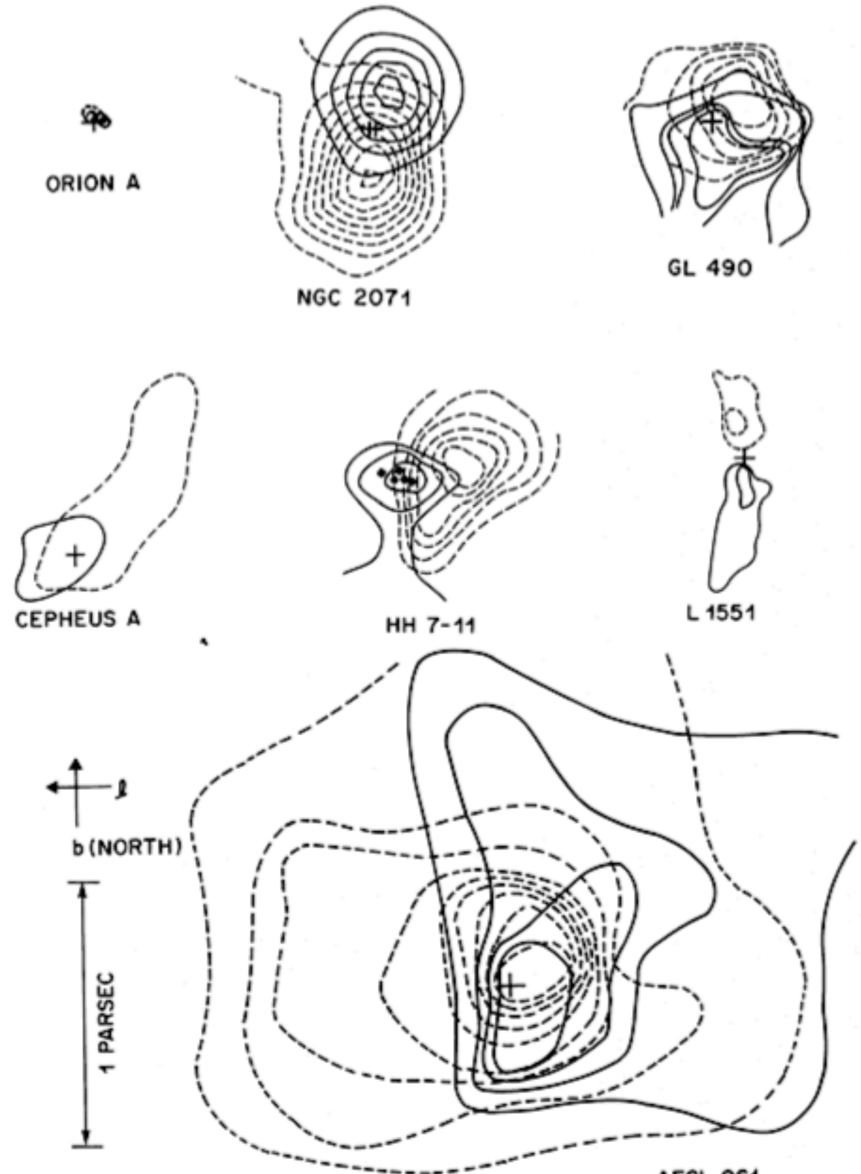


FIG. 13.—Maps of seven high-velocity molecular outflow sources in molecular cloud cores taken from the literature: NGC 2071 (Bally 1982*a*), L1551 (Snell, Loren, and Plambeck 1980), GL 490 (Lada and Harvey 1981), Cep A (Rodriguez, Ho, and Moran 1980), HH 7–11 (Snell and Edwards 1981), GL 961 (Lada and Gautier 1982), Orion A (Erickson *et al.* 1982). Solid lines are blueshifted wings, and dashed lines are the redshifted wings.

Molecular Outflows: Bipolarity

Bally & Lada
1983

Molecular Outflows: Basic Properties
Bally & Lada 1983

TABLE 4

PARAMETERS OF MAPPED MOLECULAR OUTFLOW SOURCES

Source	R_{max}[a] (pc)	R_{min}[a] (pc)	$(R_{max}R_{min})^{1/2}$ (pc)	R_{max}/R_{min}	M ($M_\odot$)	Ref.	$\dot{M}V$ ($M_\odot$ yr^{-1} km s^{-1})	$\frac{1}{2}MV^2$ (ergs)	$L_{outflow}$ ($L_\odot$)	$\langle n(H_2)\rangle$ (cm^{-3})	$\int$ Red Wing / $\int$ Blue Wing
Orion	0.04	0.04	0.04	1.0	5	1	0.52	2.0×10^{47}	2600	3.8×10^5	…
AFGL 490	0.34	0.29	0.31	1.2	14	2.3	0.04	1.5×10^{47}	115	2.3×10^3	0.70
AFGL 961	1.18	0.97	1.07	1.2	20	3.4	0.007	8.0×10^{46}	11	0.8×10^2	3.72
NGC 2071	0.49	0.28	0.37	1.8	20	3.5	0.06	2.8×10^{47}	175	1.9×10^3	2.40
Cep A	0.50	0.08	0.20	6.2	10	6	0.012	6.2×10^{46}	25	6.0×10^3	2.90
S140	0.46	0.46	0.46	1.0	64	3	0.06	2.6×10^{47}	90.0	3.2×10^3	0.91
L1551	0.42	0.08	0.18	5.2	0.3	7	0.0002	6.7×10^{43}	0.2	2.5×10^2	0.56
HH 7–11	0.40	0.21	0.29	1.9	4.0	8	0.004	1.6×10^{46}	6.5	7.9×10^2	4.26
HH 24–26	0.25	0.19	0.22	1.3	6.3	8	0.006	1.4×10^{46}	6.9	2.9×10^3	2.0
Mon R2	2.09	0.70	1.21	4.0	100	9, 10	0.02	2.3×10^{47}	24.0	2.8×10^2	1.18
Serpens	1.11	0.65	0.85	1.7	…	10	…	…	…	…	0.9
T Tauri	0.15	0.15	0.15	1.0	0.1	11	0.00003	4.2×10^{43}	0.01	1.4×10^2	…

[a]Source sizes corrected for beam size.

REFERENCES.—(1) Solomon, Huguenin, and Scoville 1981. (2) Lada and Harvey 1981. (3) Lada 1982. (4) Lada and Gautier 1982. (5) Bally 1982*a*. (6) Rodriguez, Ho, and Moran 1980. (7) Snell, Loren, and Plambeck 1980. (8) Snell and Edwards 1981. (9) Loren 1981. (10) This paper. (11) Edwards and Snell 1981.

Molecular Outflows: Mechanical Luminosity and Momentum Flux

Bally & Lada 1983

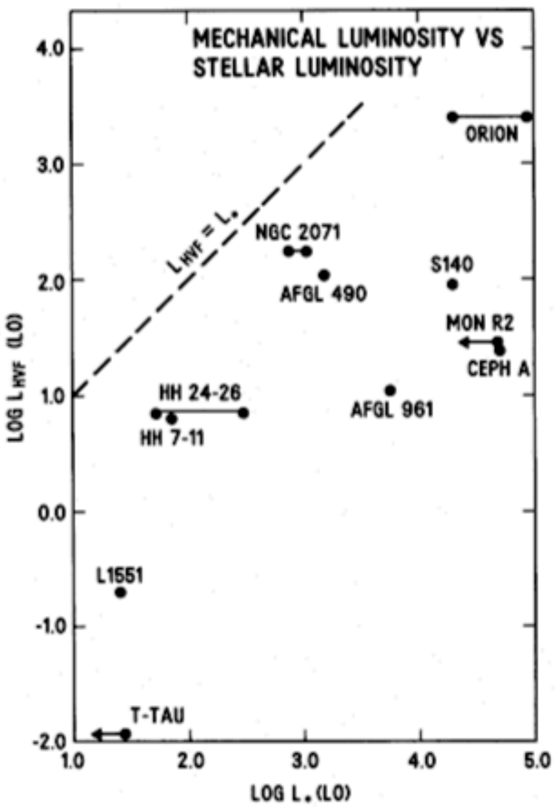


FIG. 16.—Plot of the flow mechanical luminosity vs. total bolometric luminosity of the associated infrared sources. Also shown is the relation $L_{\mathrm{HVF}} = L_\star$.

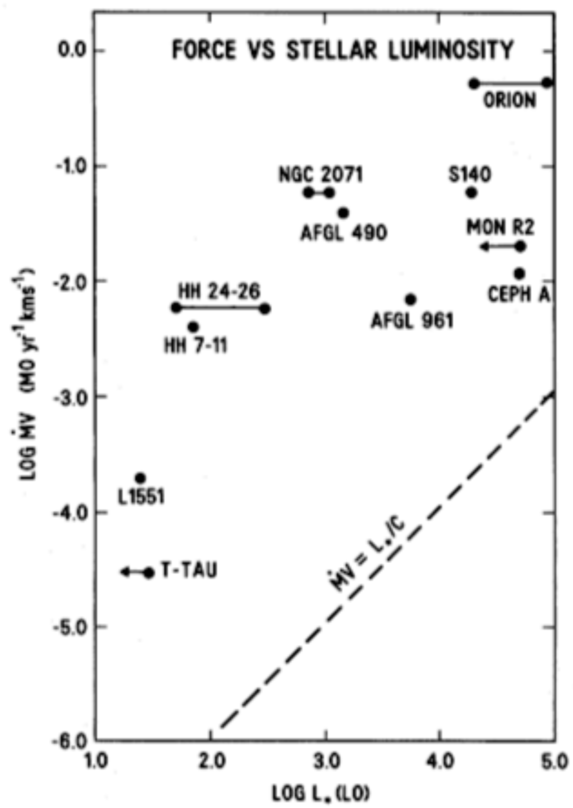
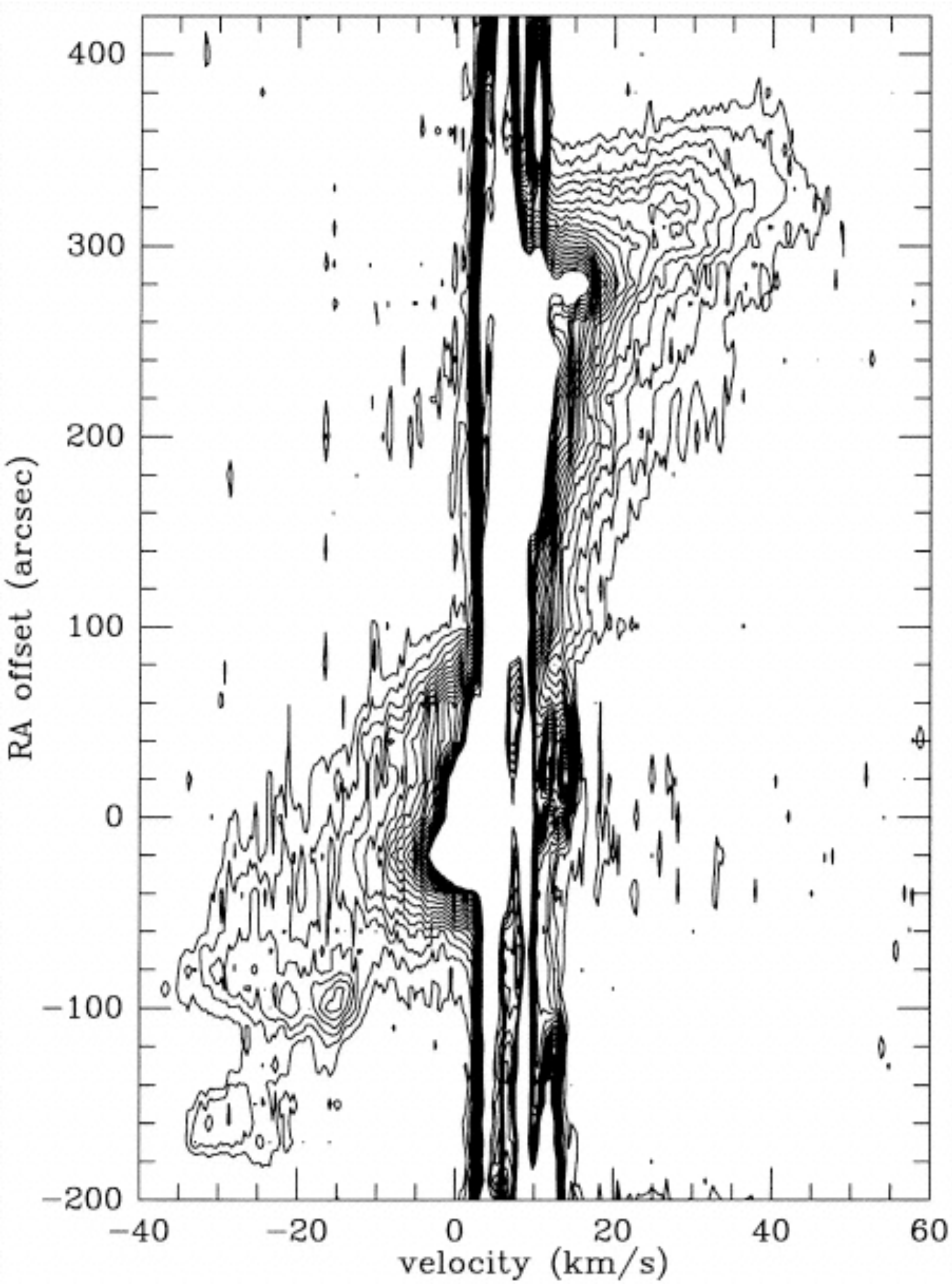


FIG. 17.—Plot of $\dot{M}V$ for the flows vs. total bolometric luminosity of the associated infrared sources. Also shown is the relation $\dot{M}V = L_\star/C$.



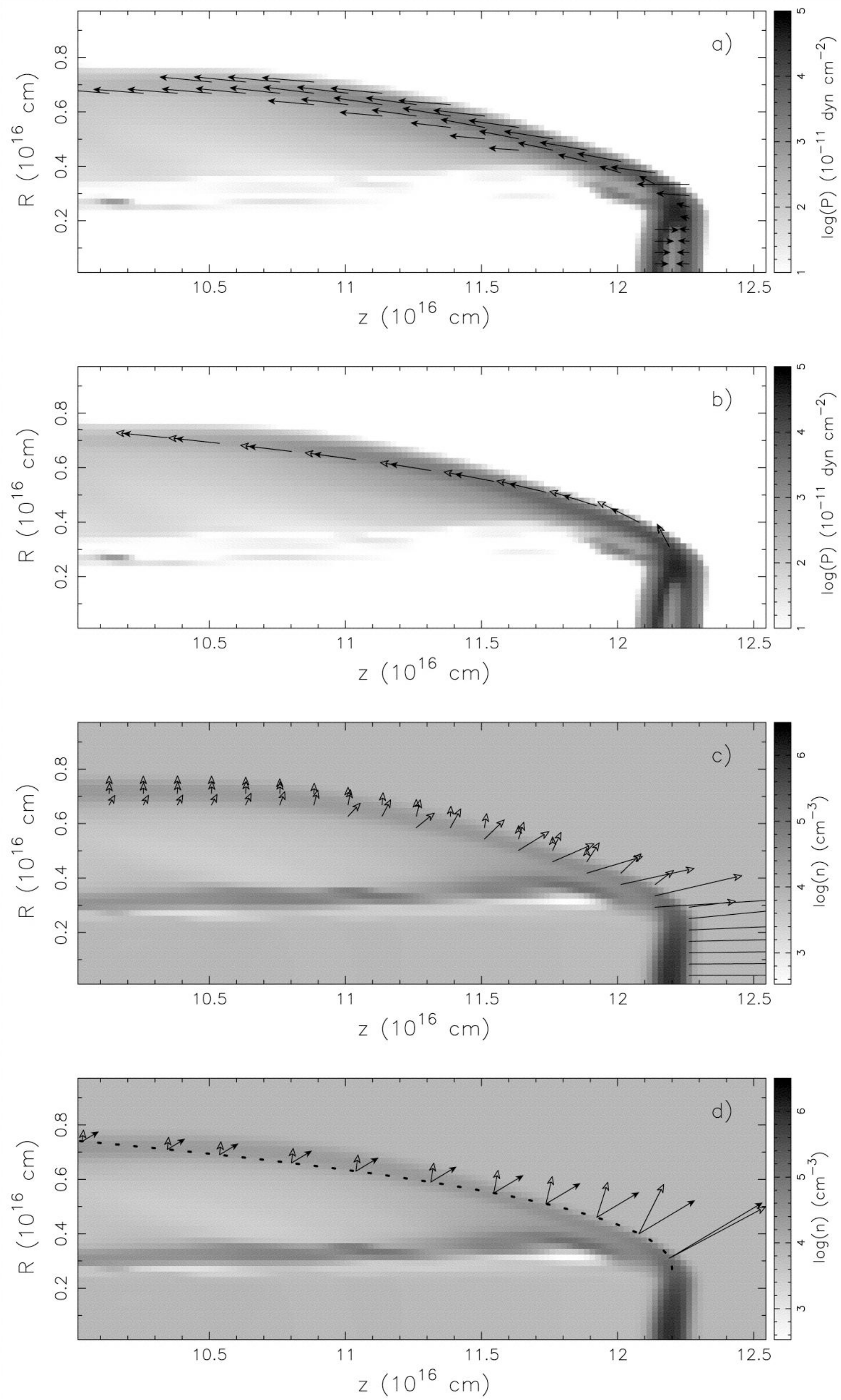
Molecular Outflow: the "Hubble Law" NGC 2264 G

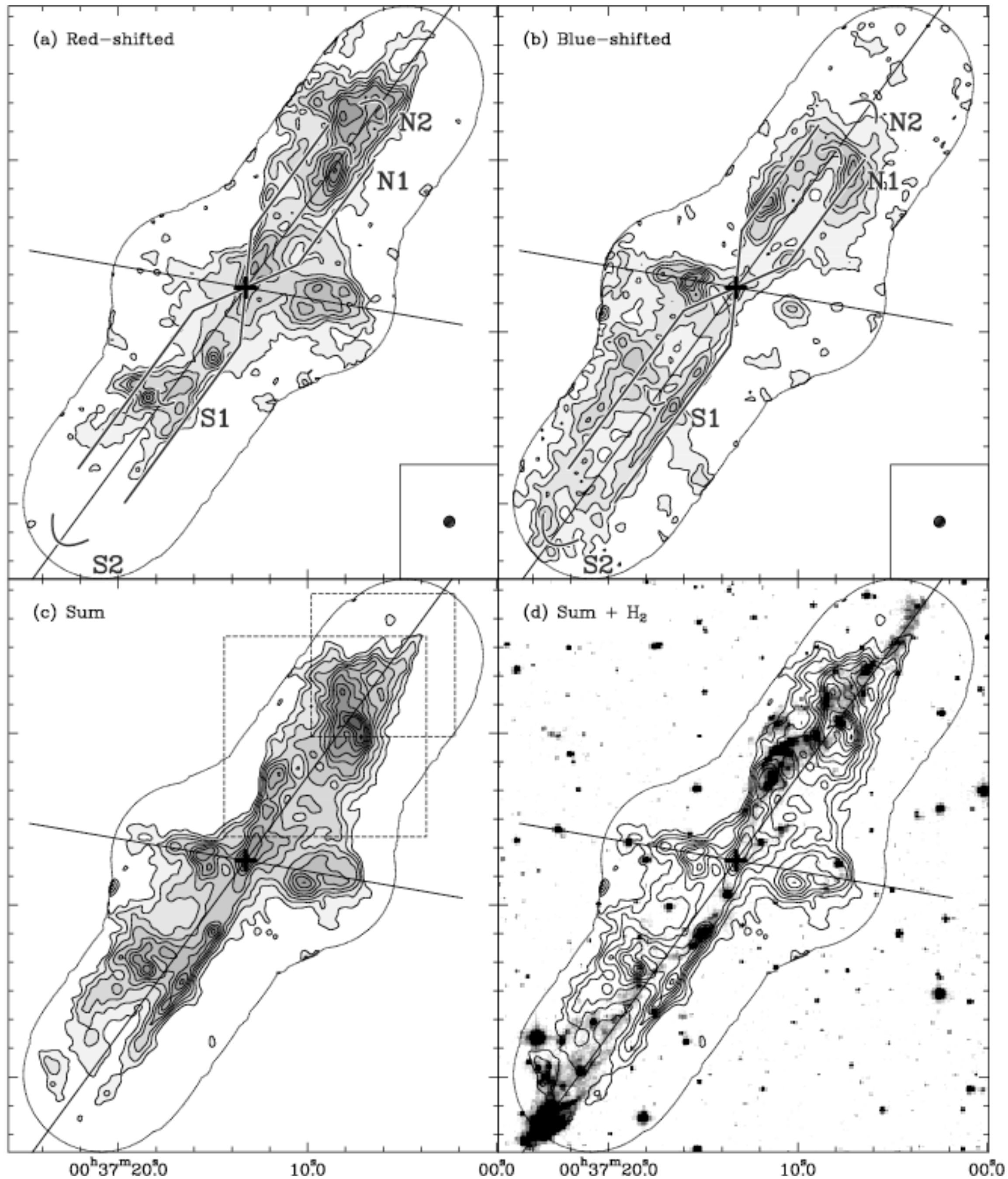
Fich & Lada
1998

Distinguishing between Wind and Jet Models Lee et al. 2001

Bow shock

Wind

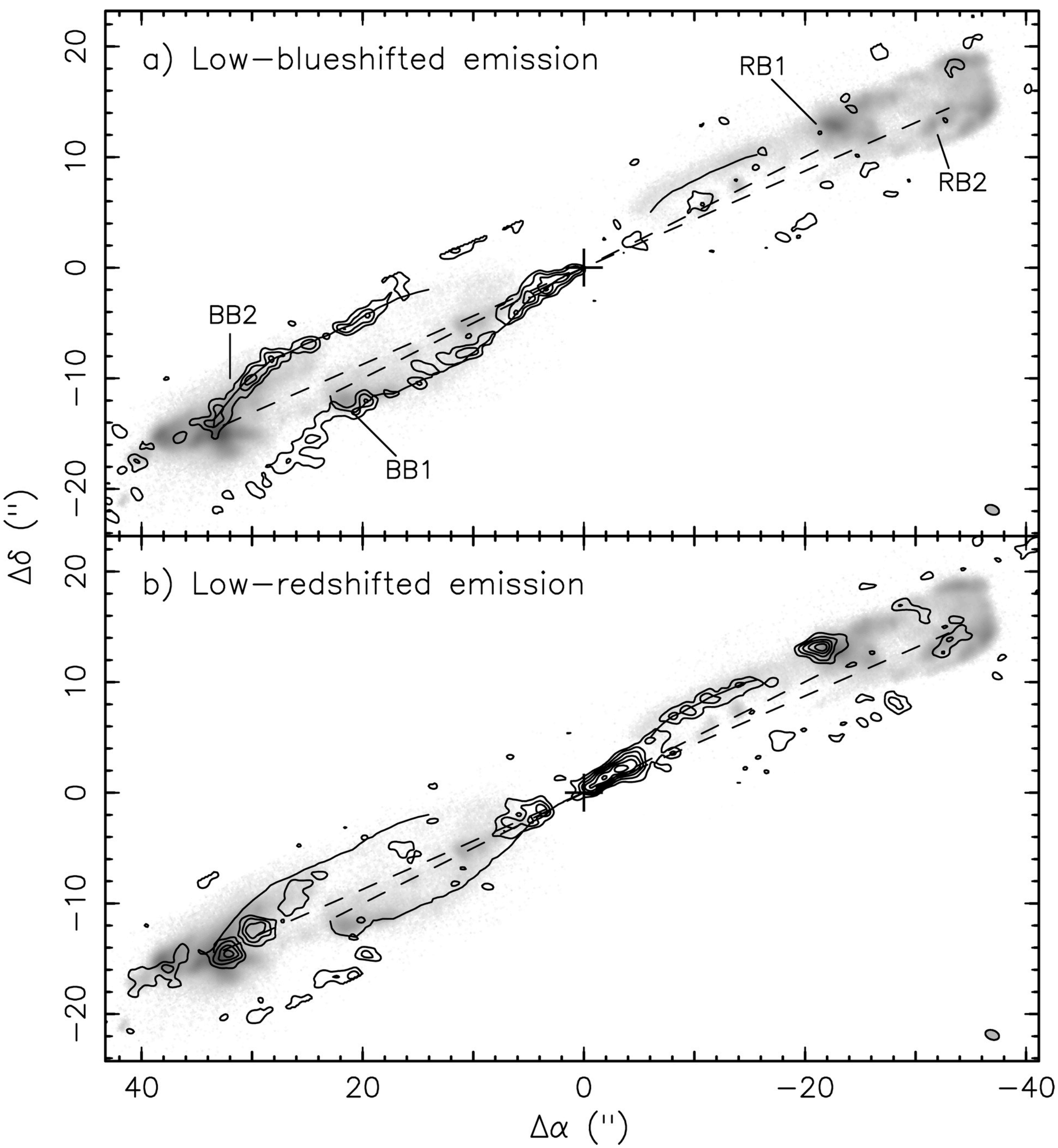




HH 288:

Contours: CO (2-1)

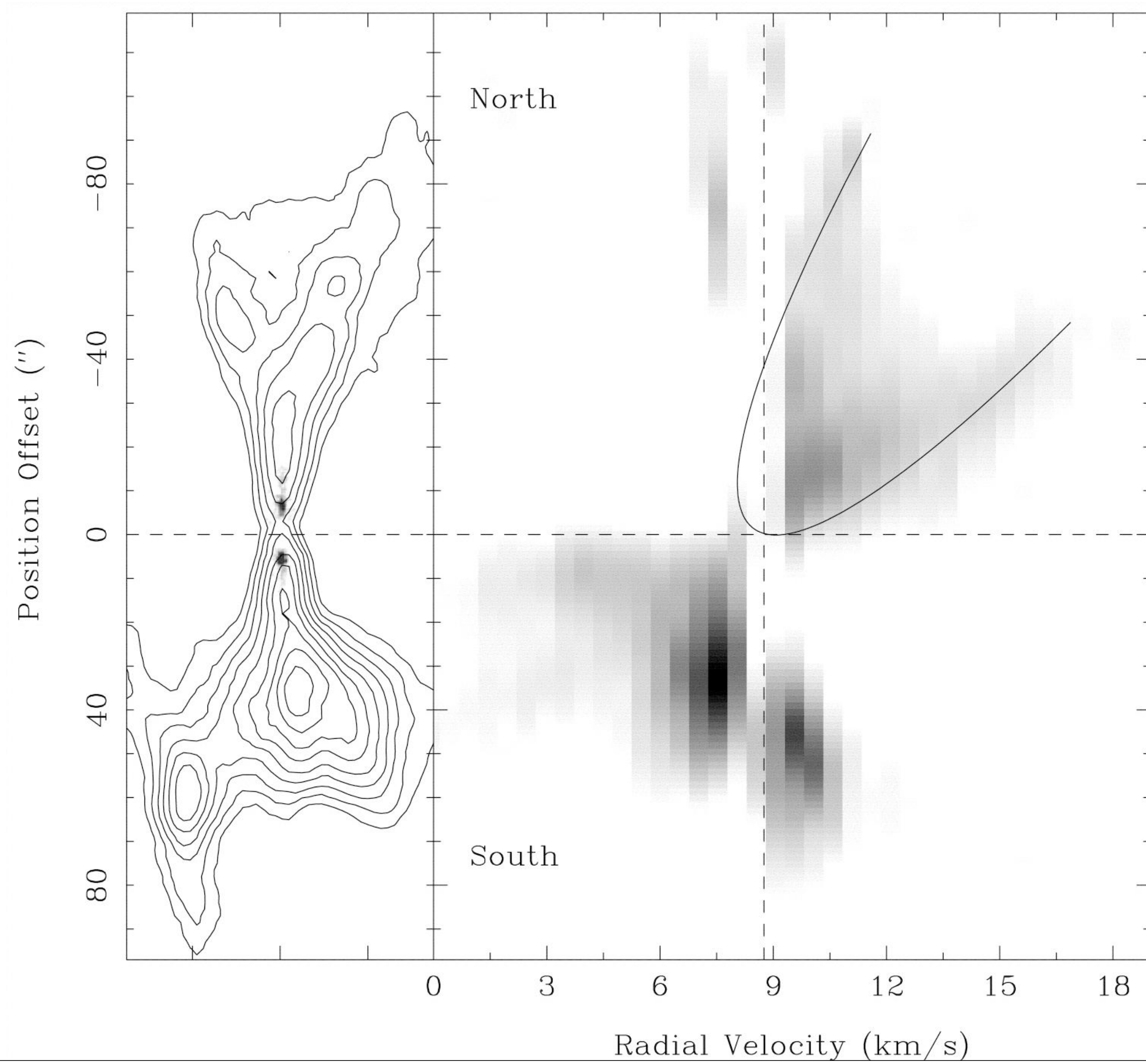
Greyscale: H_2



HH 211

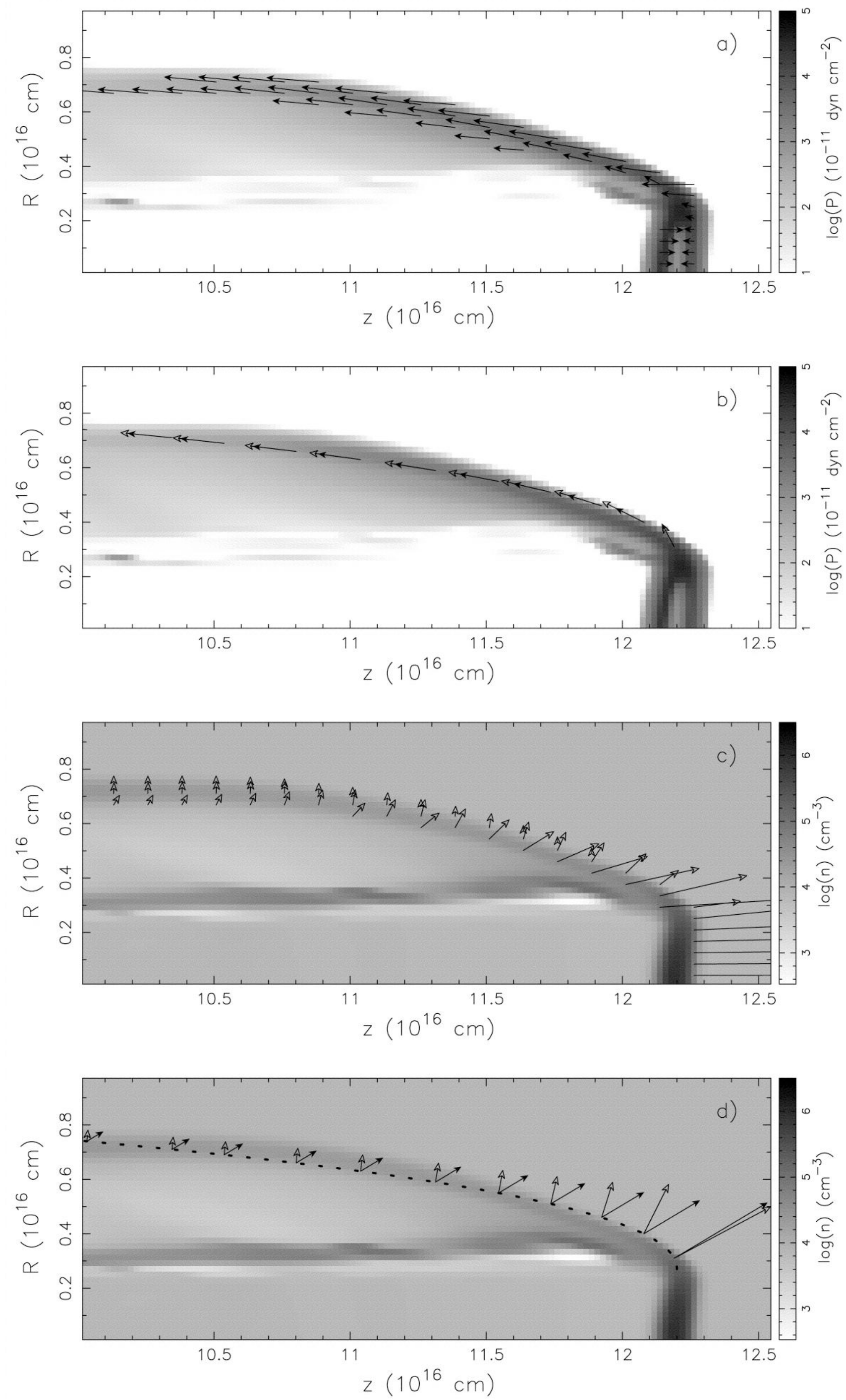
Contours: CO (2-1)

VLA 05487: example of wind (Lee et al. 2001)



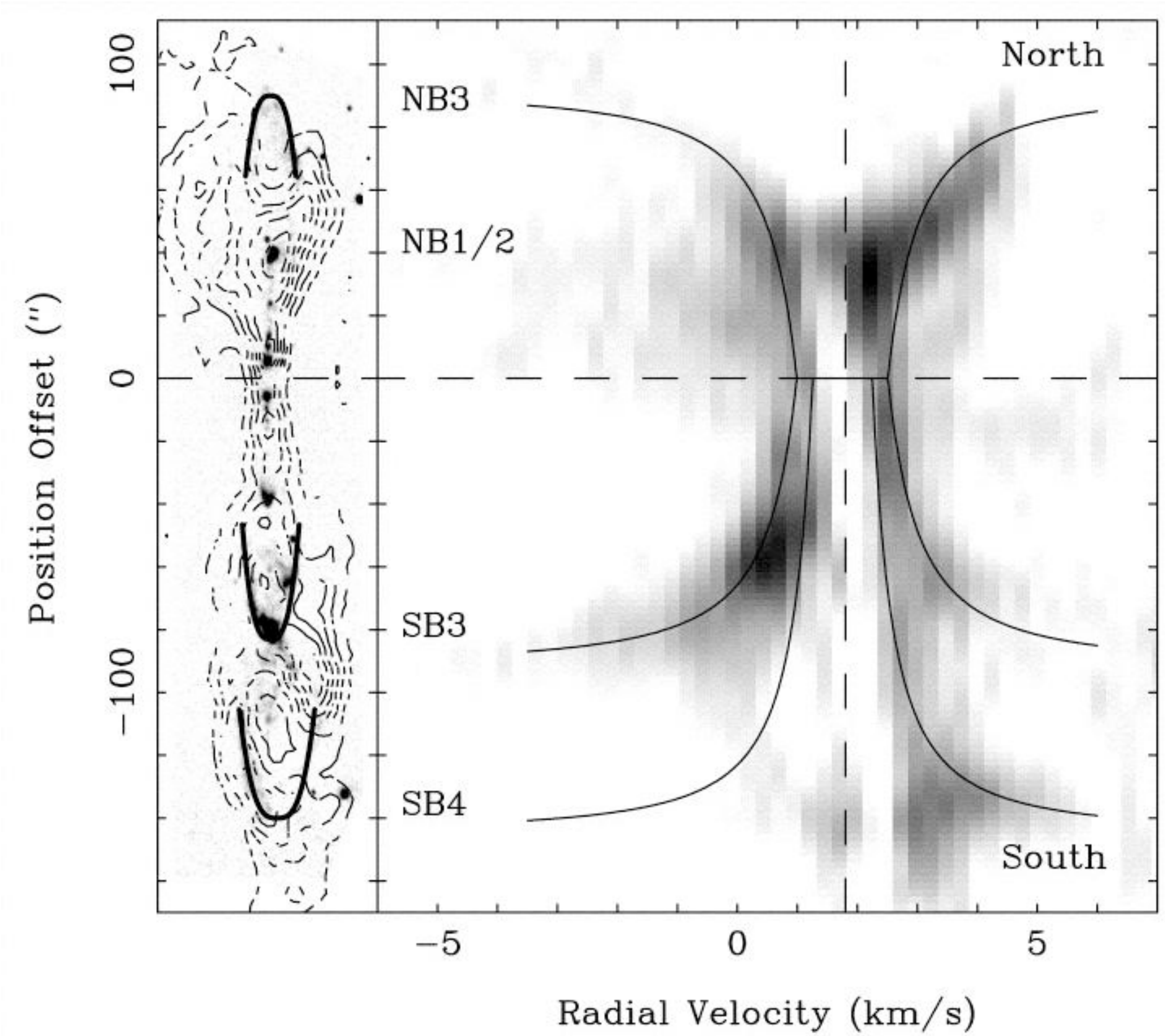
Distinguishing between Wind and Jet Models Lee et al. 2001

Bow shock

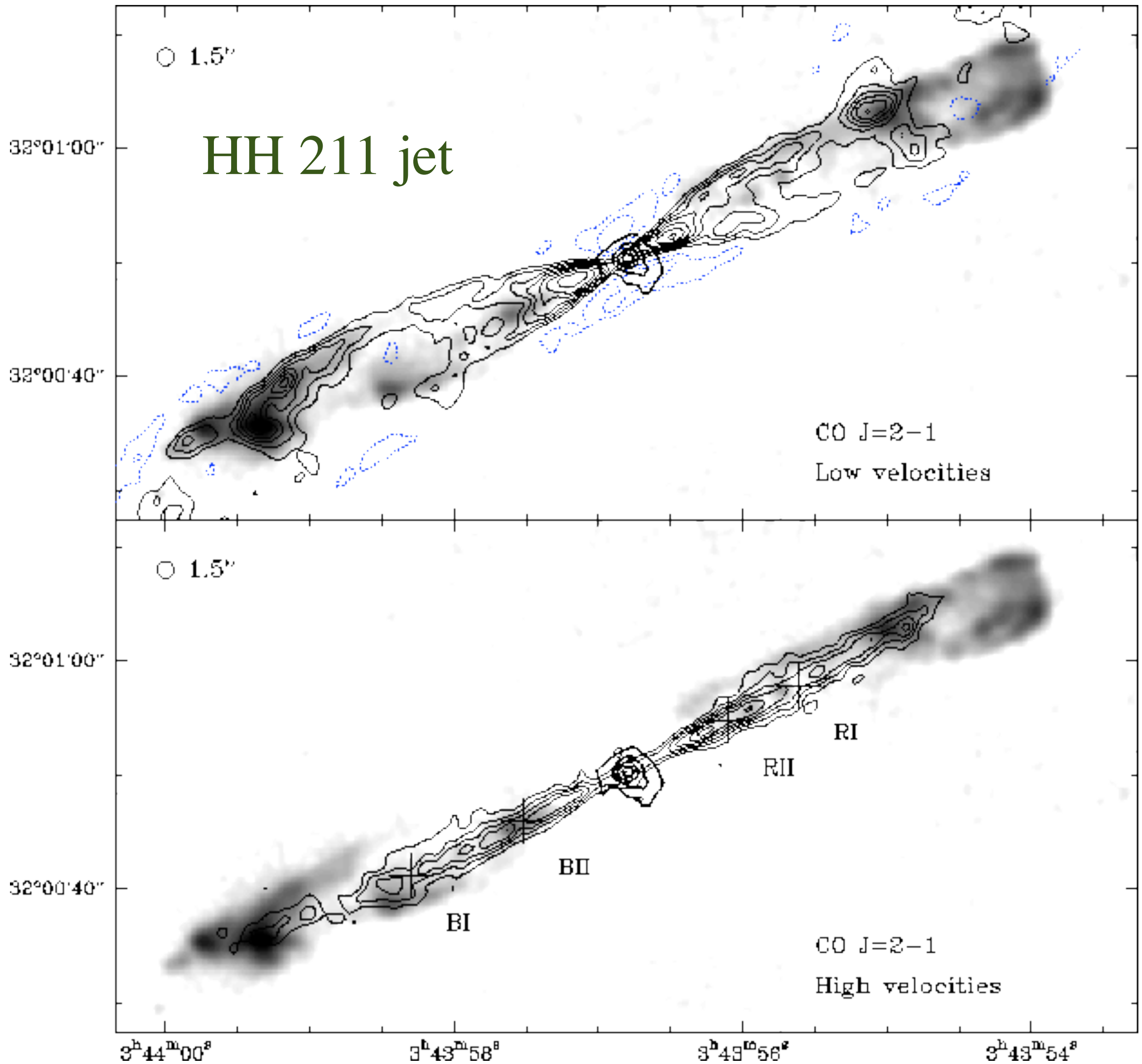


Wind

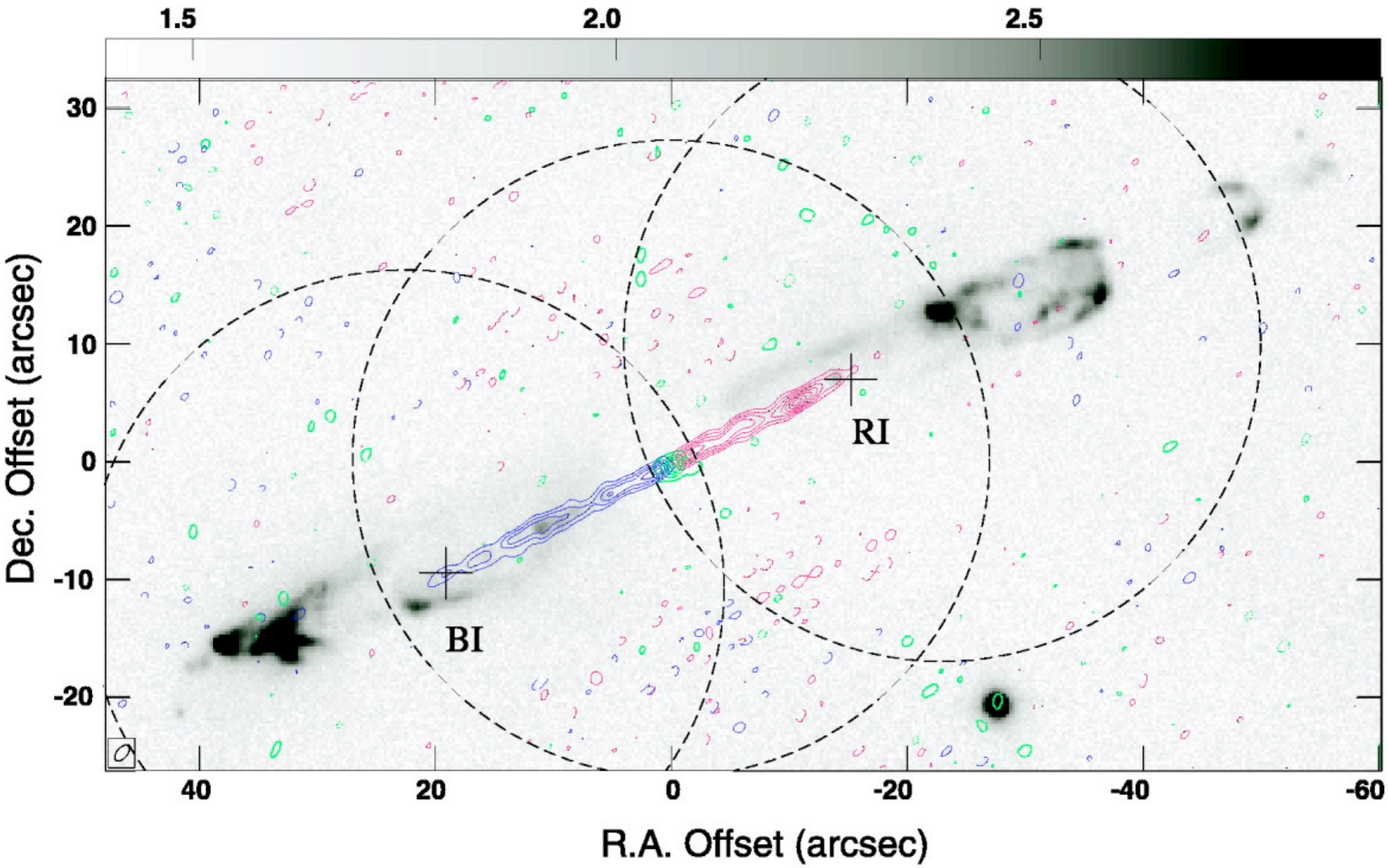
HH 212: example of jet (Lee et al. 2001)



Detecting *Jets* in Molecular Gas

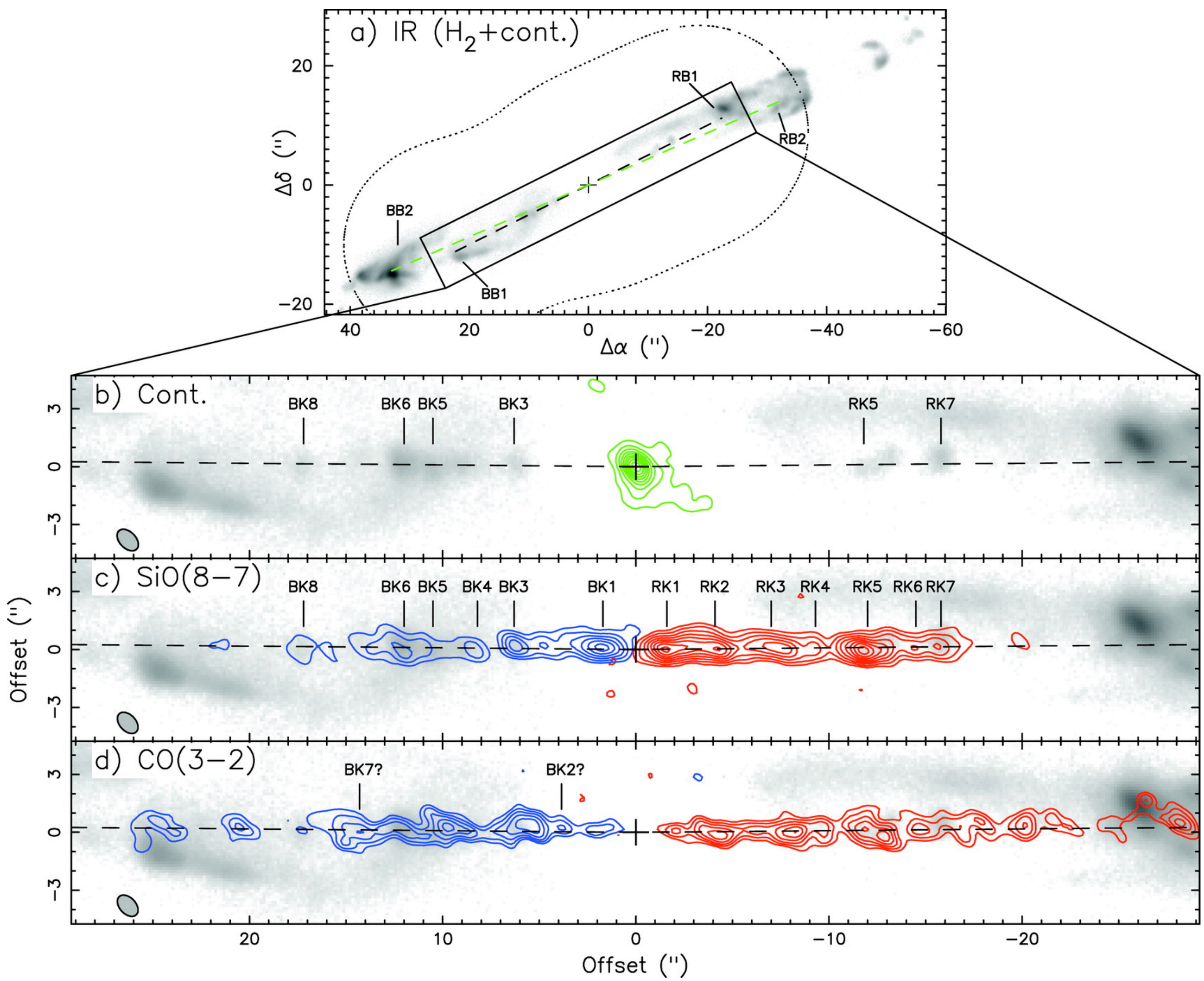


Detecting *Jets* in Molecular Gas

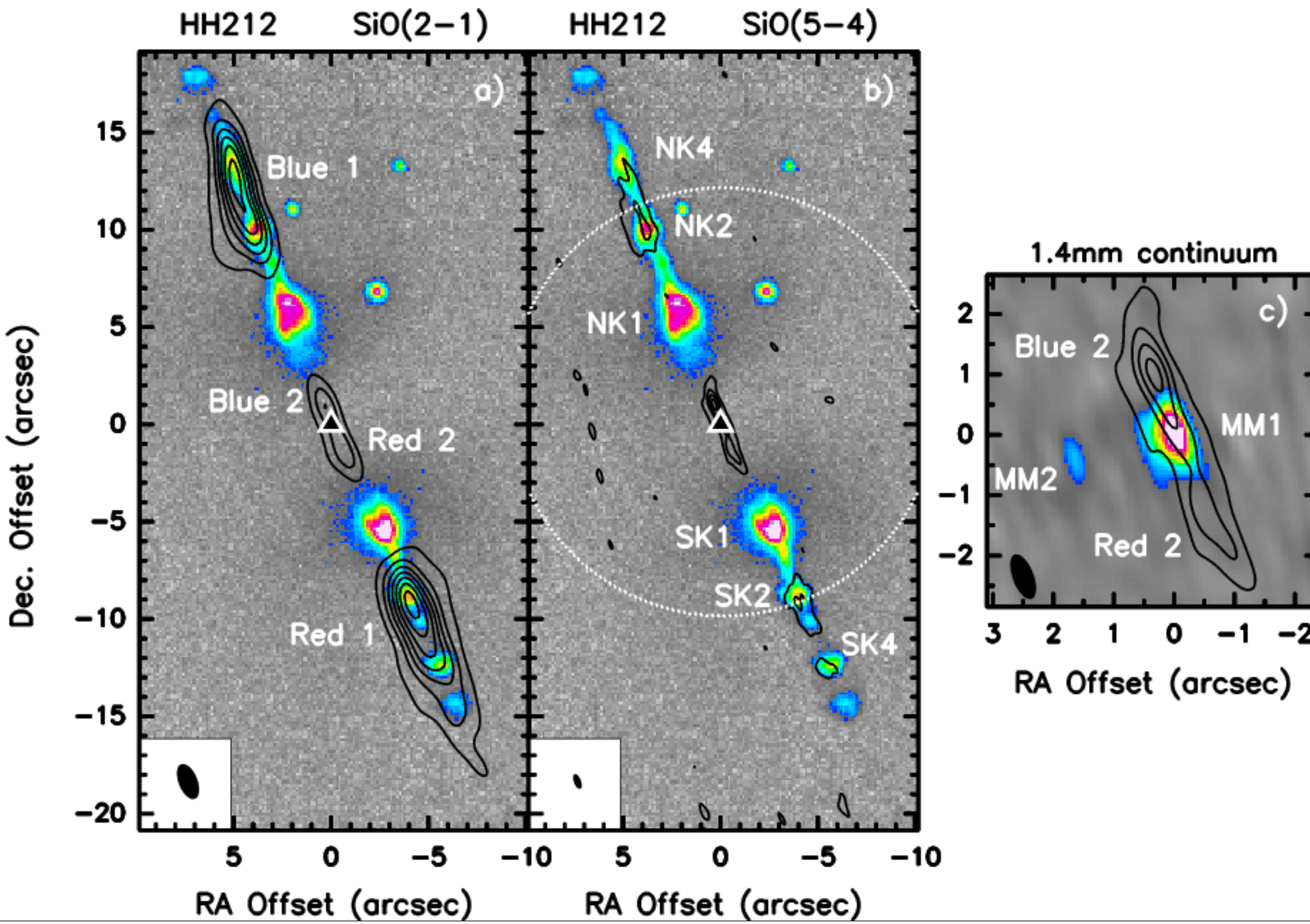


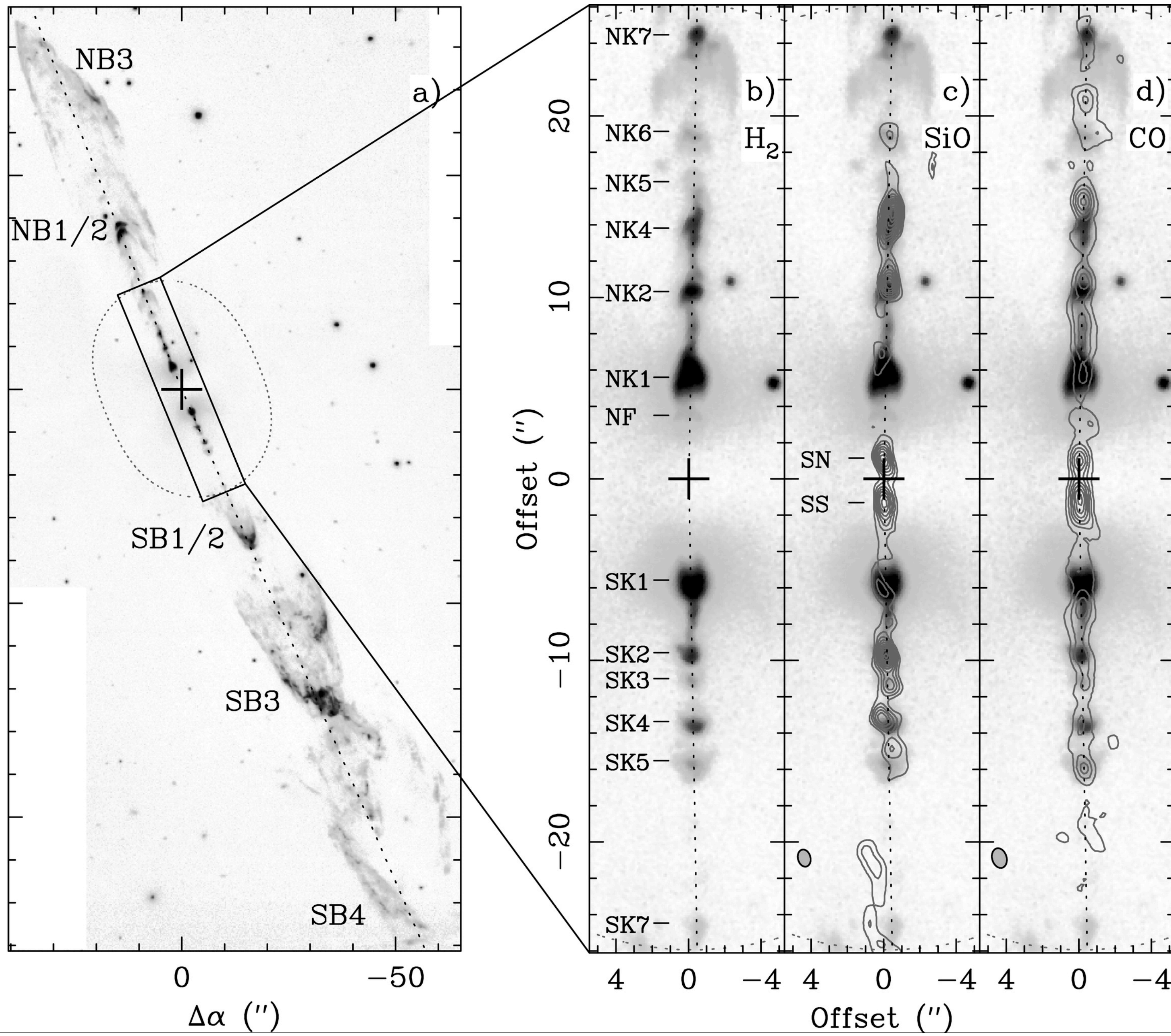
SiO mm-wave rotational lines are an excellent tracer of jets: abundance enhanced by a few orders of magnitude in jets

HH 211 Lee et al. 2007



SiO HH 212 Codella et al. 2008





HH 212 Lee et al. 2007

HH 212 Lee et al. 2007