Sternentstehung - Star Formation

Winter term 2020/2021

Henrik Beuther, Thomas Henning & Sümeyye Suri

03.11 Today: Introduction & Overview (Beuther)
10.11 Physical processes I (Beuther)
17.11 Physcial processes II (Beuther)
24.11 Molecular clouds as birth places of stars (Suri)
01.12 Molecular clouds (cont.), Jeans Analysis (Suri)
08.12 Collapse models I (Henning)
15.12 Collapse models II (Henning)
------------ Christmas break -------------
12.01 Protostellar evolution (Beuther)
19.01 Pre-main sequence evolution & outflows/jets (Beuther)
26.01 Accretion disks I (Henning)
02.02 Accretion disks II (Henning)
09.02 High-mass star formation, clusters and the IMF (Suri)
16.02 Extragalactic star formation (Henning)
23.02 Examination week, no star formation lecture

Book: Stahler & Palla: The Formation of Stars, Wileys

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2021.html

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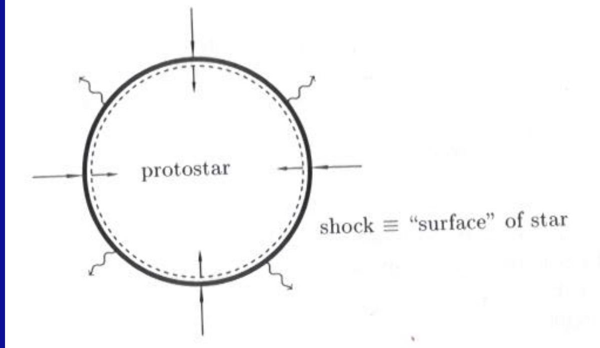
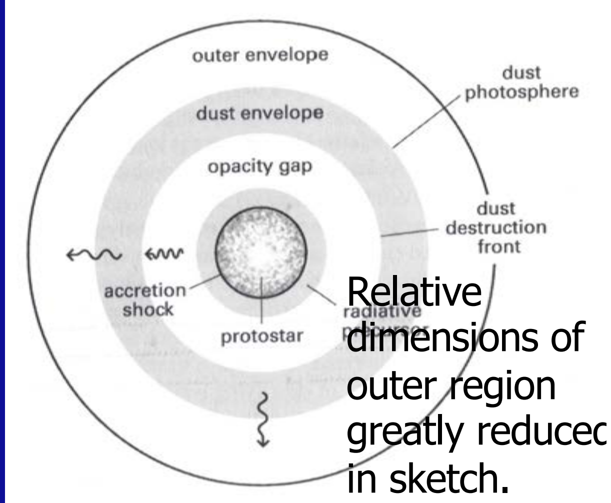
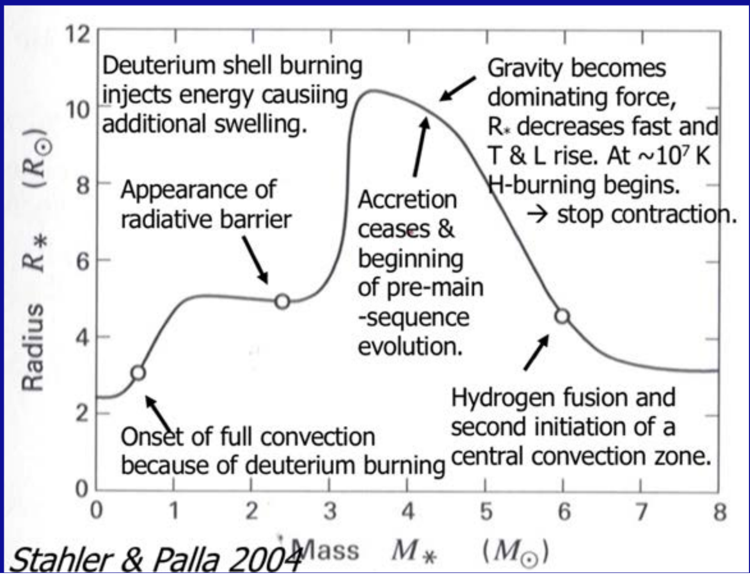
Summary last week

- Protostellar evolution, 1st and 2nd core, accretion luminosity
- Envelope structure
- Convection, entropy profile of protostar
- Structure of protostar
- Definition: protostar vs. pre-main sequence star

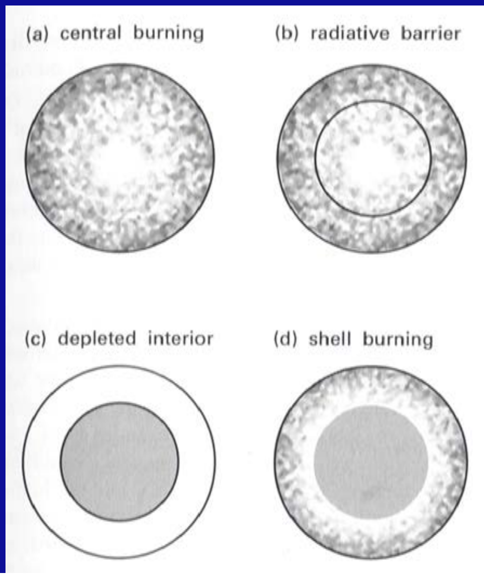




Relative dimensions of outer region greatly reduced in sketch.



Stahler & Palla 2004



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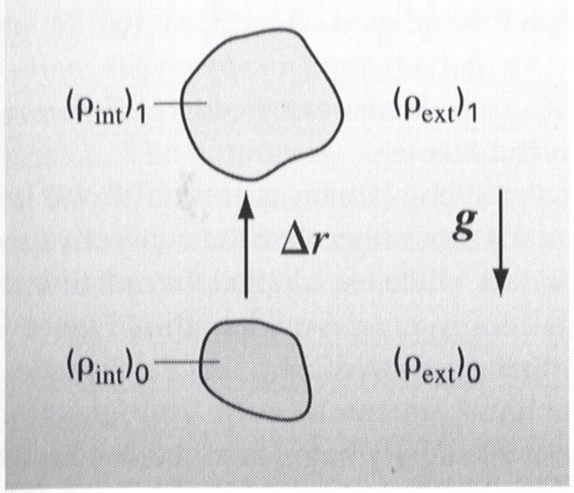


Topics today

- Pre-main-sequence evolution

- General outflow properties

- Jet launching

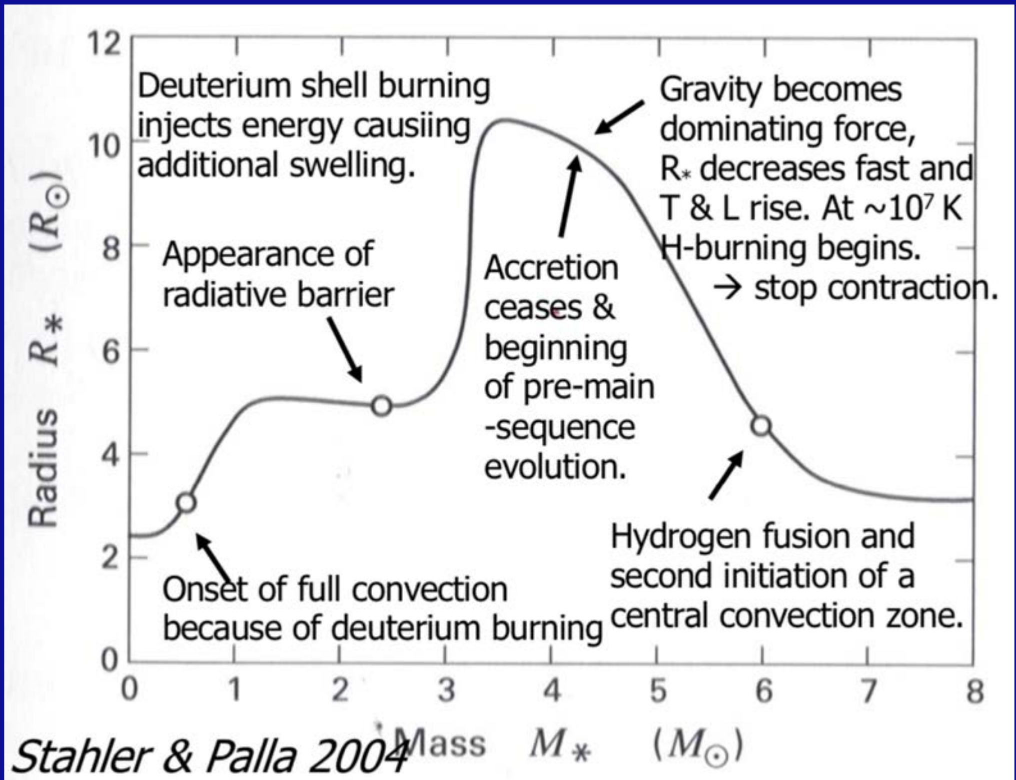
- Outflow driving and entrainment

Protostellar vs. pre-main sequence evolution (mainly for low-mass protostars)

- Accretion ceases → protostar contracts → gain energy by gravity

→ Main luminosity not accretion but due to gravitational contraction.

→ Identify this point with end of protostellar and beginning of pre-main sequence phase (low-mass stellar evolution)



Further contraction until H-burning I

- Different evolution for low- and high-mass pre-main sequence stars:

  - <u>Low-mass:</u>

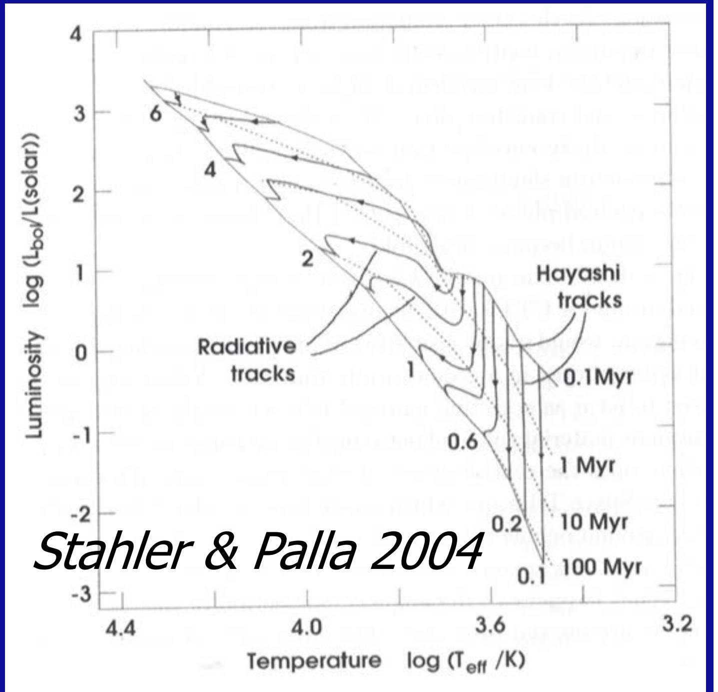
    - still convective, still remaining deuterium burning

    - Hayashi tracks: Shrinking releases grav. energy & $T_{surface}$ approx. constant

    - $L = 4\pi R^2 \sigma_B T_{eff}^4 \propto R_*^2$ → L decreases → L falls below L_{crit}.
      → Radiative core forms again with a
      shrinking outer convective layer.

    - During further slow contraction internal energy, temperature & luminosity rise again until hydrogen burning starts → ZAMS.

    - Stars below ~$0.4 M_{sun}$ reach the ZAMS still fully convective.



Stahler & Palla 2004

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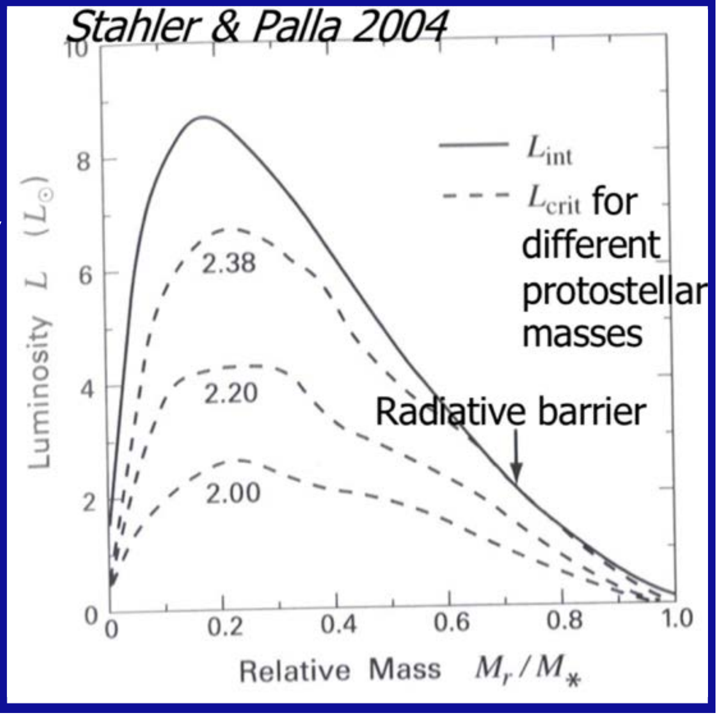


Further contraction until H-burning II

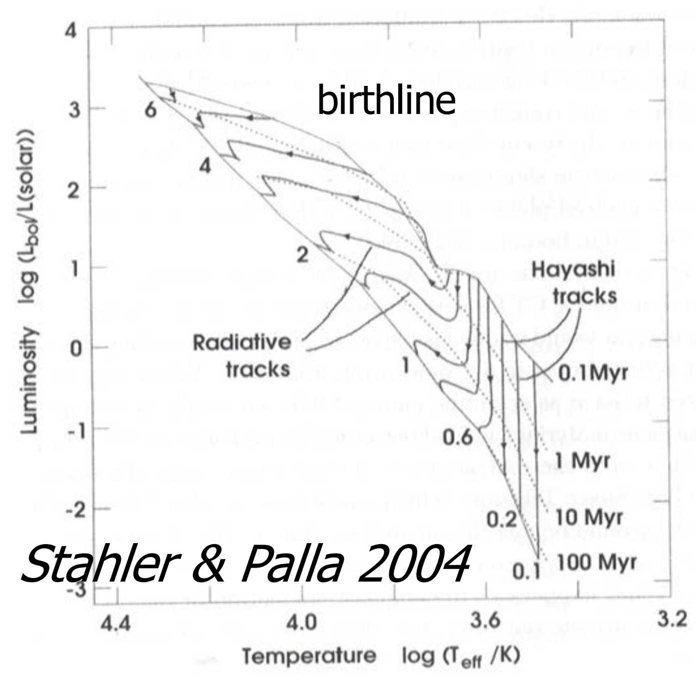
- Different evolution for low- and high-mass pre-main sequence stars

  - <u>Intermediate- to high-mass:</u>

    - More massive not convective anymore but fully radiative
      → no phase of decreasing luminosity (although they also shrink).

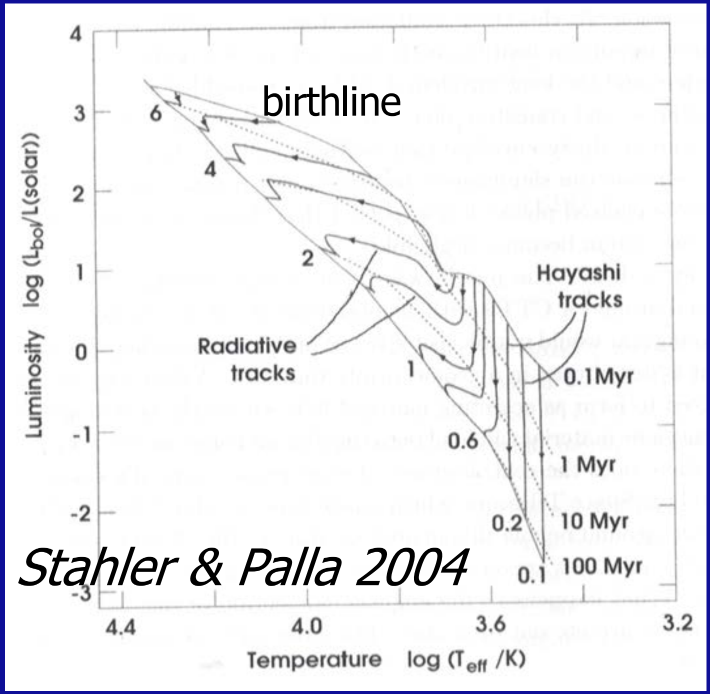
      → Always gain luminosity and temperature via gravitational energy (and decreasing deuterium shell burning)

      → Hydrogen ignites → ZAMS.



Stahler & Palla 2004

Hertzsprung Russel (HR) diagram I

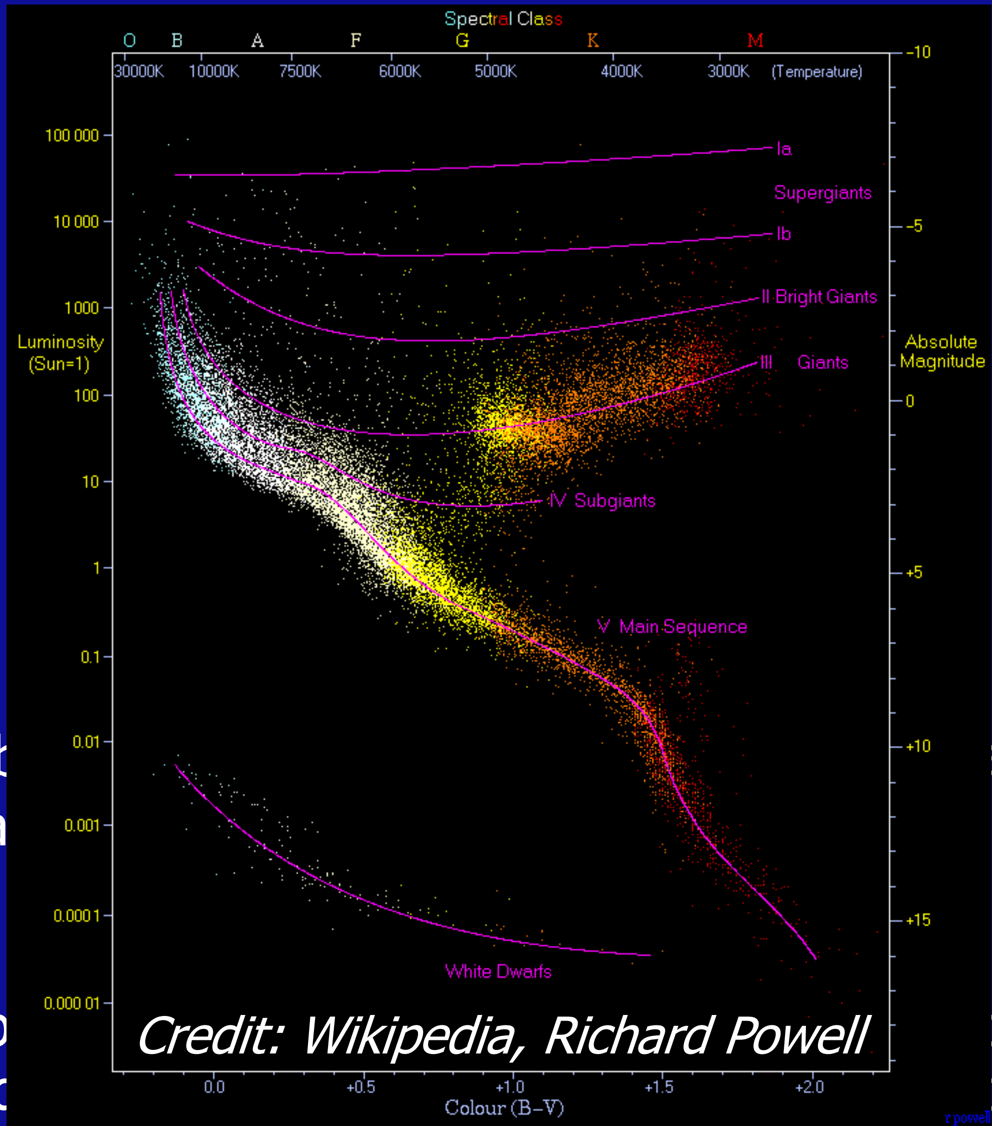


- Birthline first observationally → locus where stars first appear in the HR diagram emanating from their dusty natal envelope.

- Theoretically: birthline the time where the main accretion has stopped → pre-main sequence star gains the main luminosity from grav. contraction.

→ Approx. coincedes with quasi-static contraction in still convective phase

Hertzsprung Russel (HR) diagram I



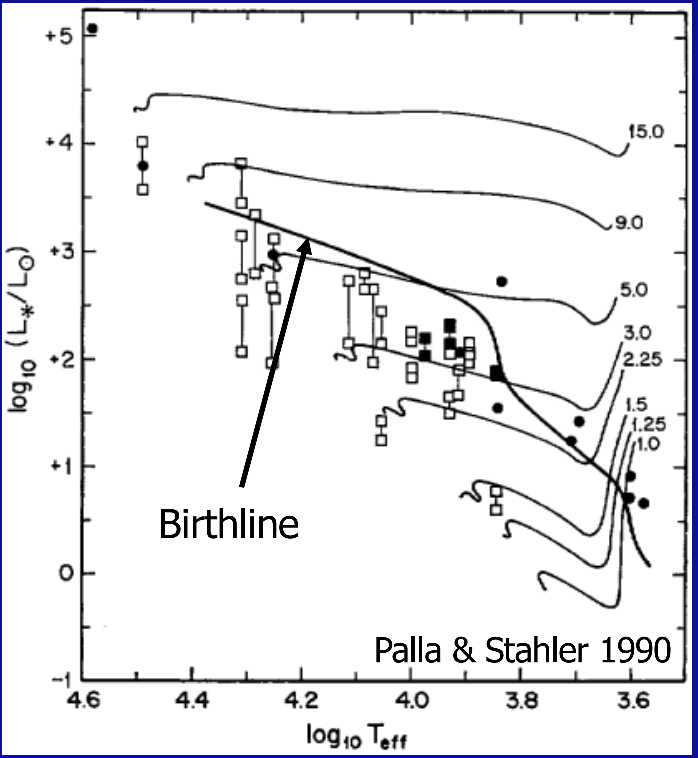
Credit: Wikipedia, Richard Powell

- Birthline first ob… appear in the HR diagram emana…

- Theoretically: b… on has stopped
  → pre-main se… om grav. contraction.

  → Approx. coincedes with quasi-static contraction in still convective phase

Hertzsprung Russel (HR) diagram II

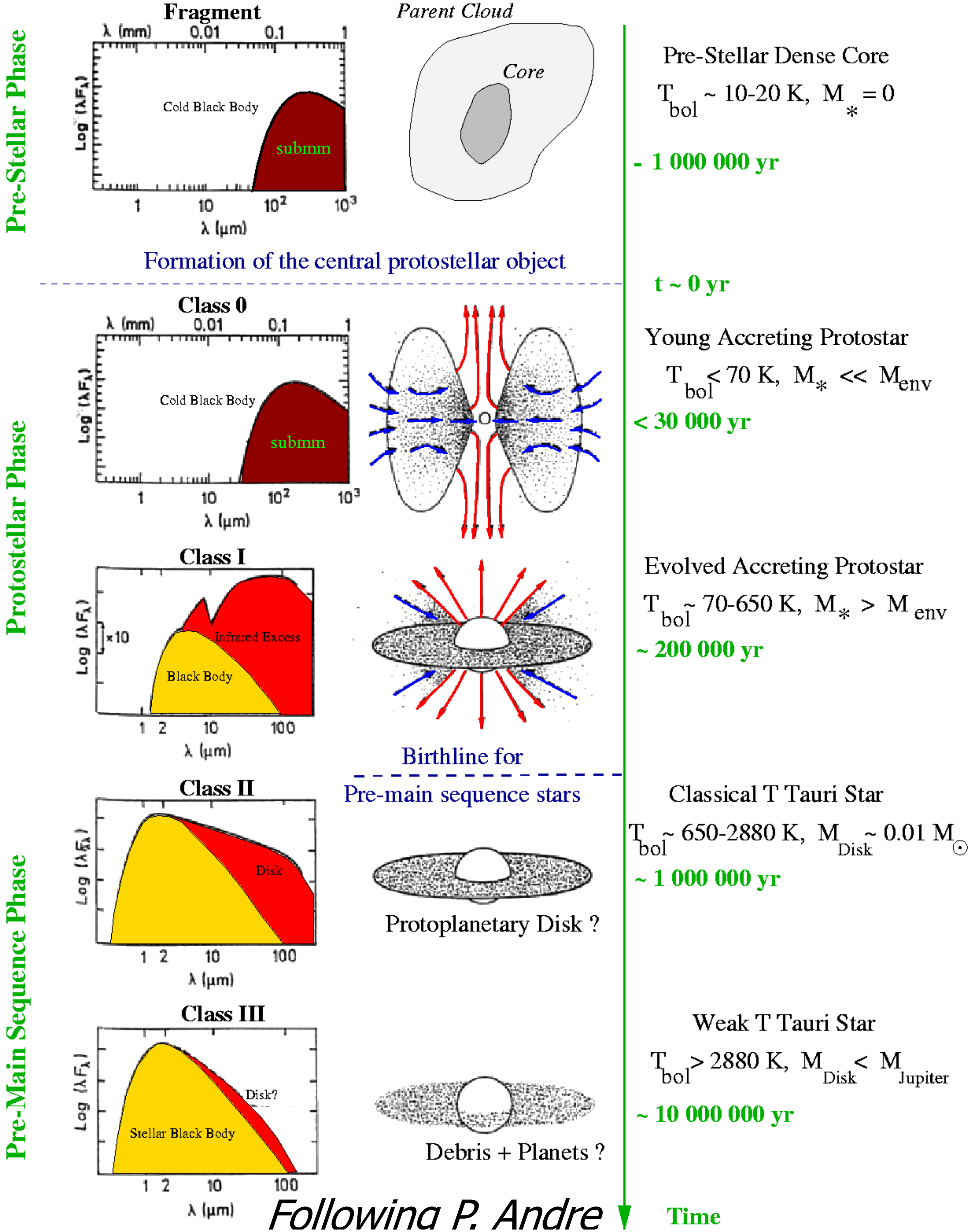


- Intermediate-mass protostars fully radiative when stopping accretion
  → no vertical Hayashi part but direct horizontal radiative tracks

- High-mass stars: short Kelvin-Helmholtz contraction time-scale
  → start nuclear H-burning - entering the ZAMS – before accretion ends

- no (visible) pre-main sequence evolution since H-burning starts still deeply embedded in their natal cores

Observable spectral energy distributions (SEDs)



Following P. Andre

Topics today

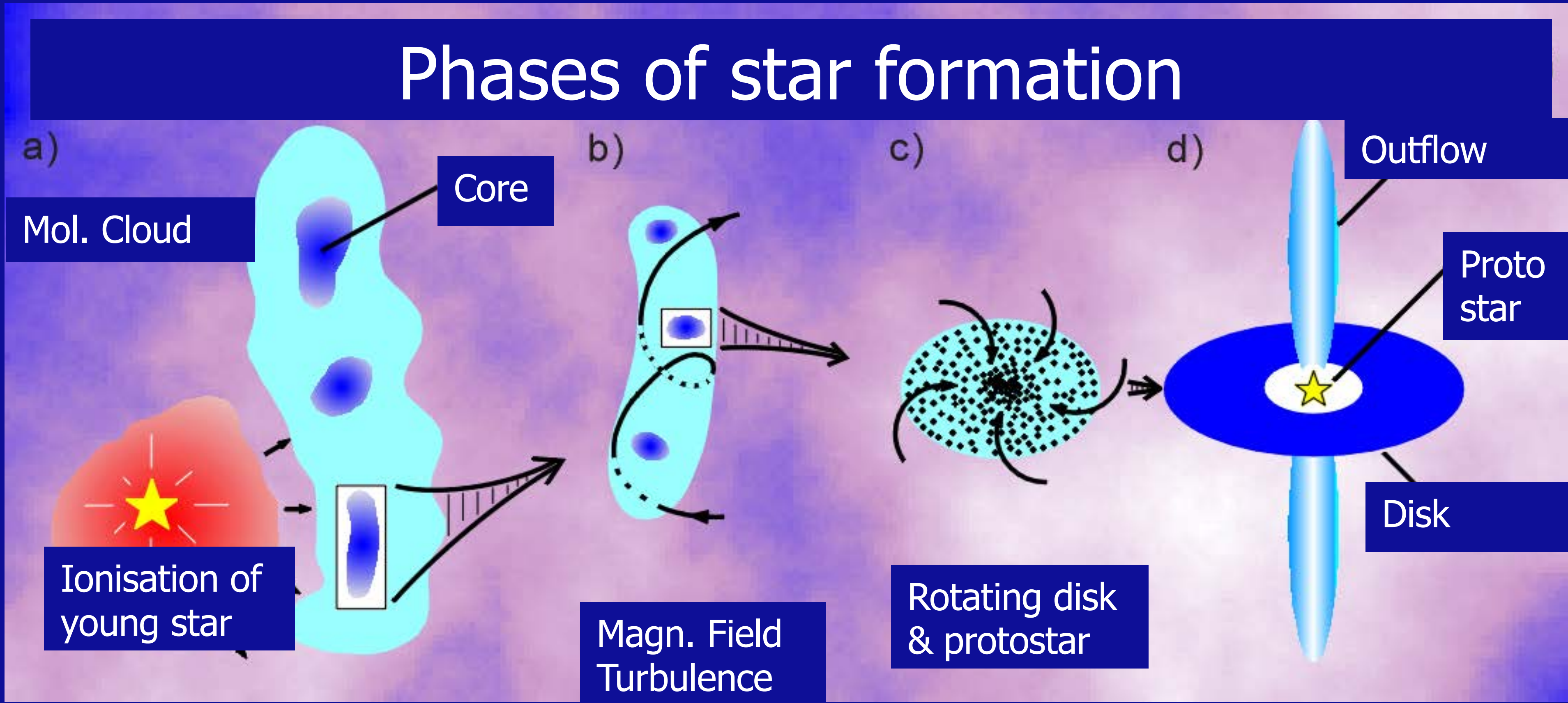
- Pre-main-sequence evolution

- General outflow properties

- Jet launching

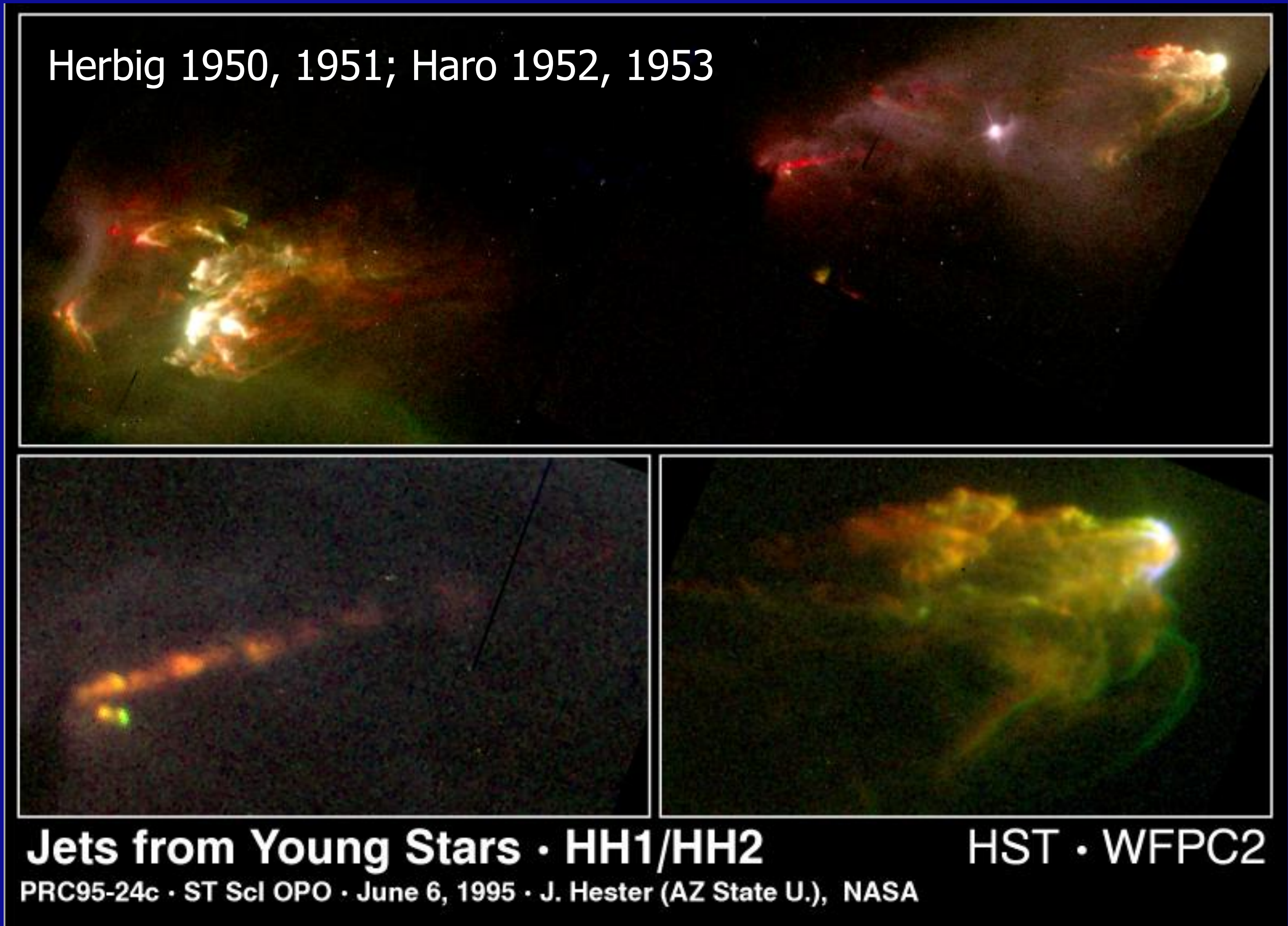
- Outflow driving and entrainment

Star formation paradigm



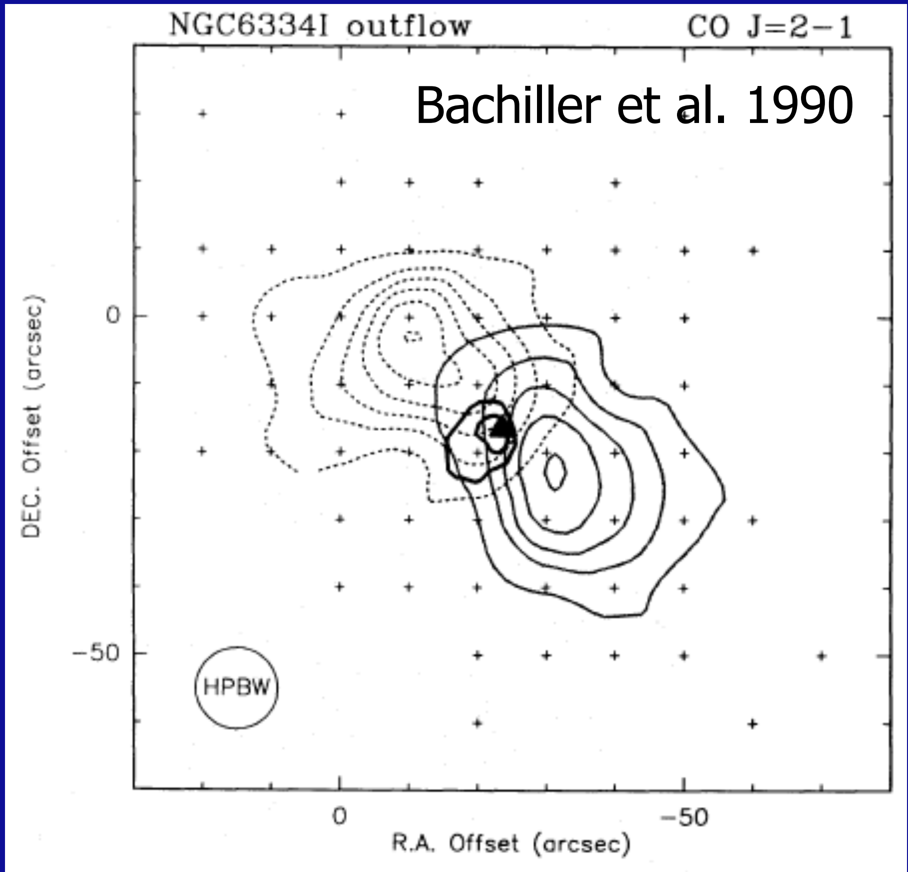
https://www.mpifr-bonn.mpg.de/473576/starform

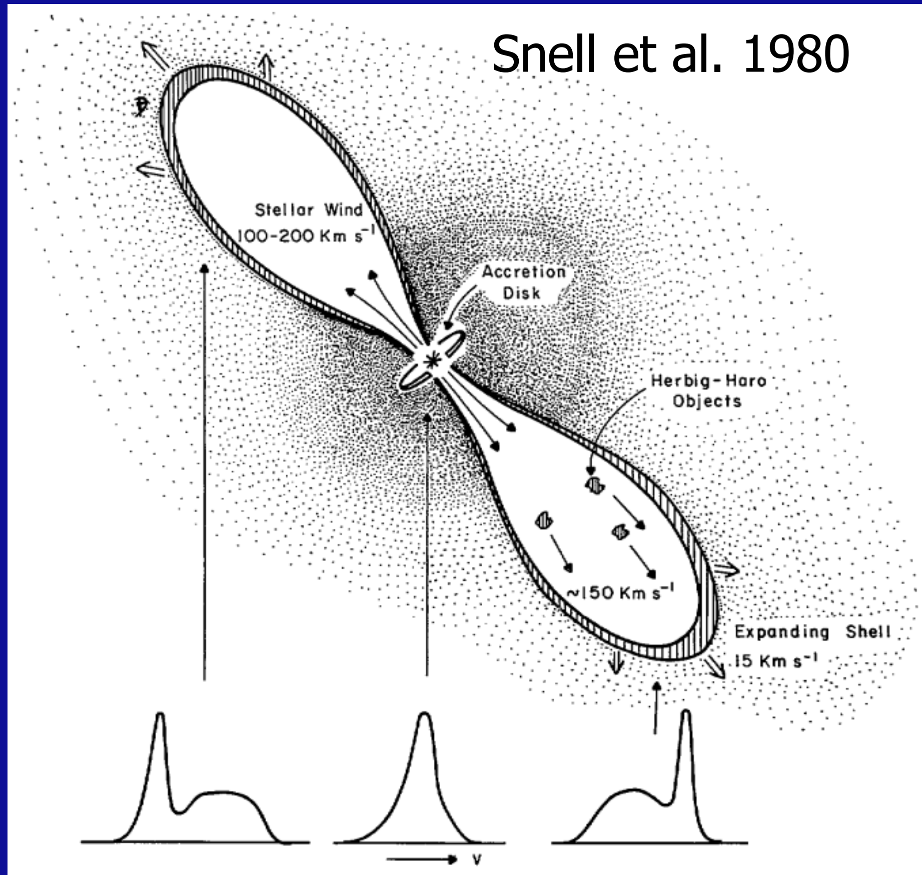
Discovery of outflows I



Initially thought to be embedded protostars but soon spectra were recognized as caused by shock waves → jets and outflows indicated

Discovery of outflows II

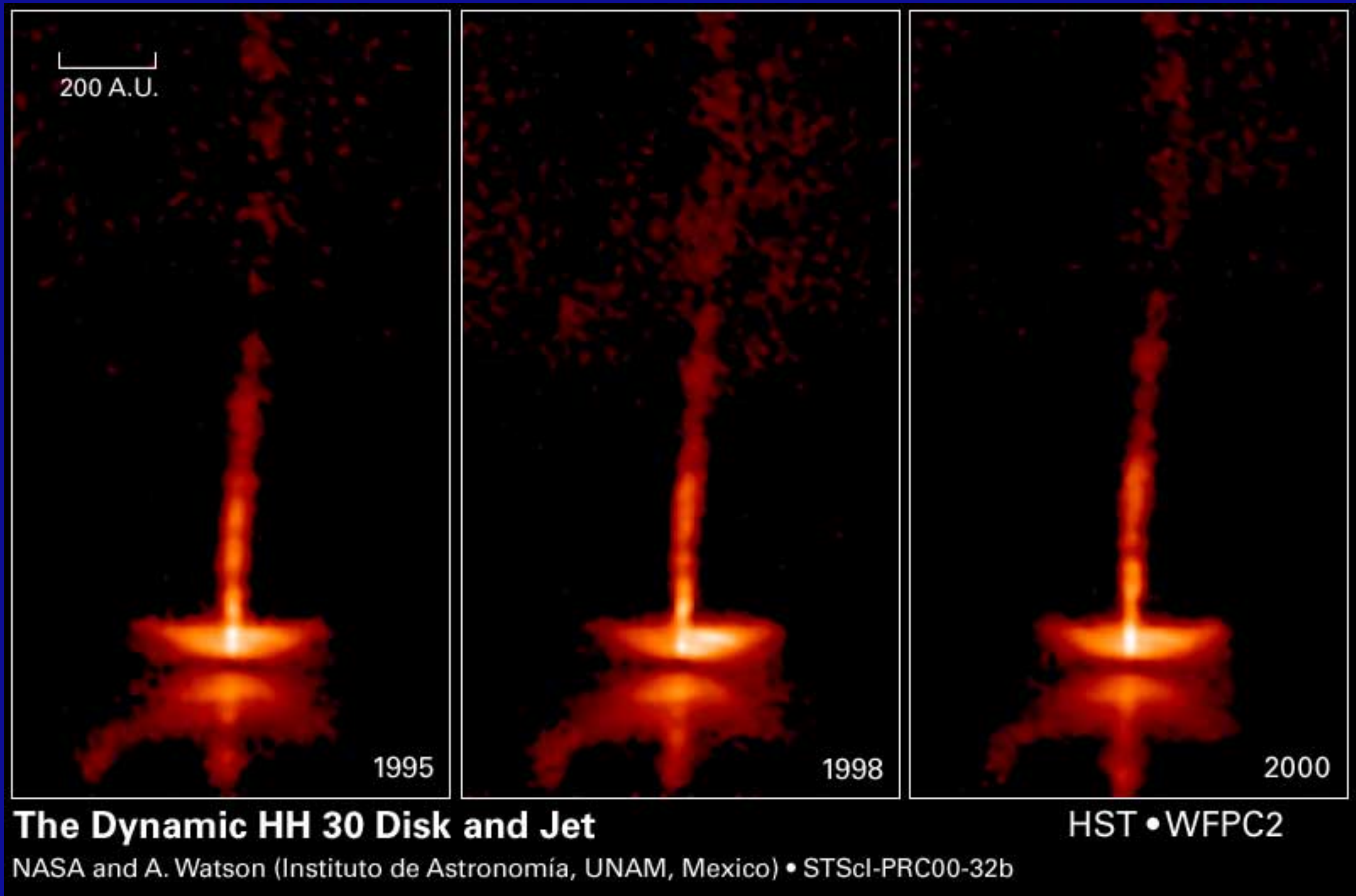




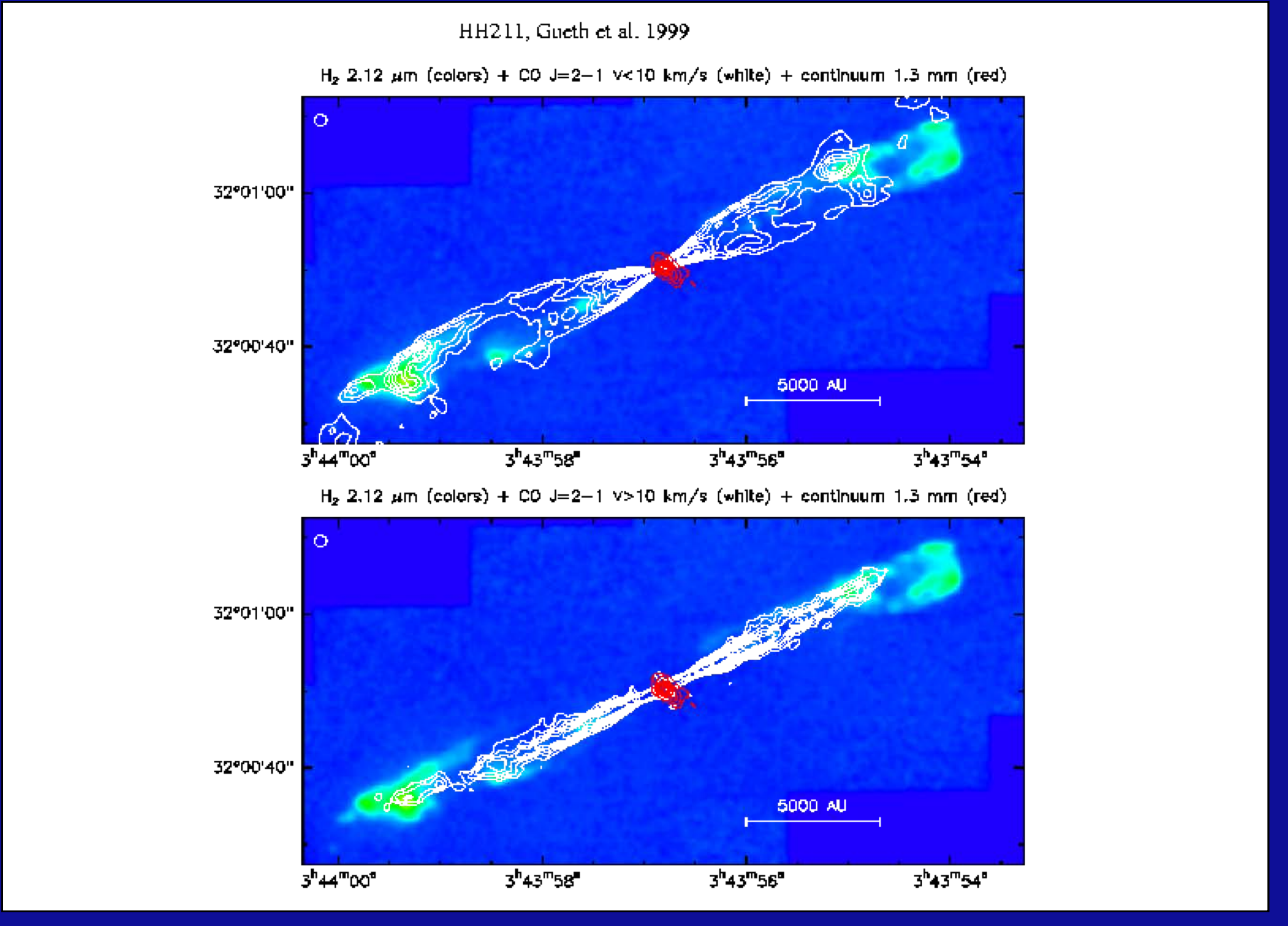
- In the mid to late 70th, first CO non-Gaussian line wing emission detected (Kwan & Scovile 1976).

- Bipolar structures, extremely energetic, often associated with HH objects

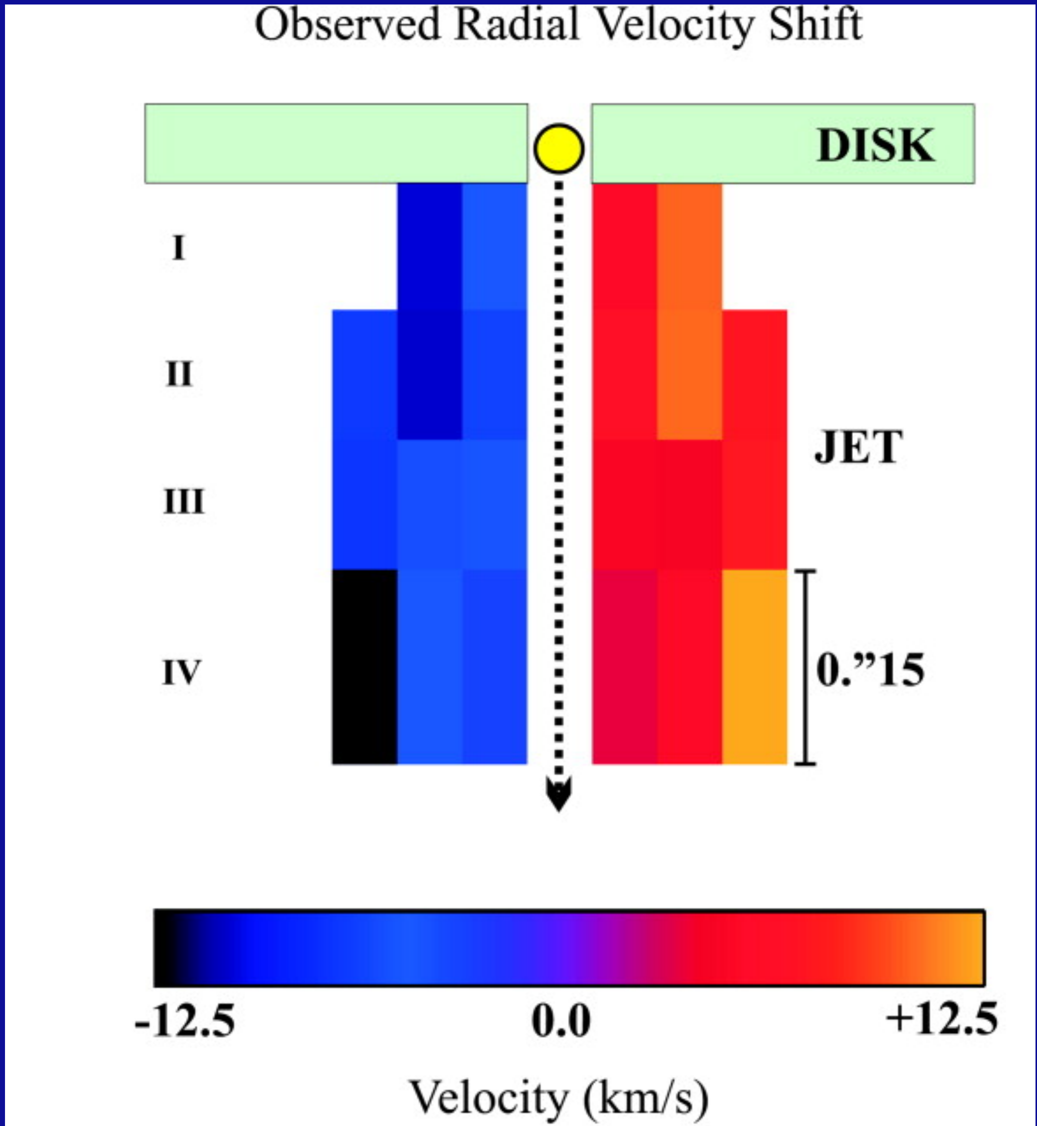
HH30, a disk-outflow system



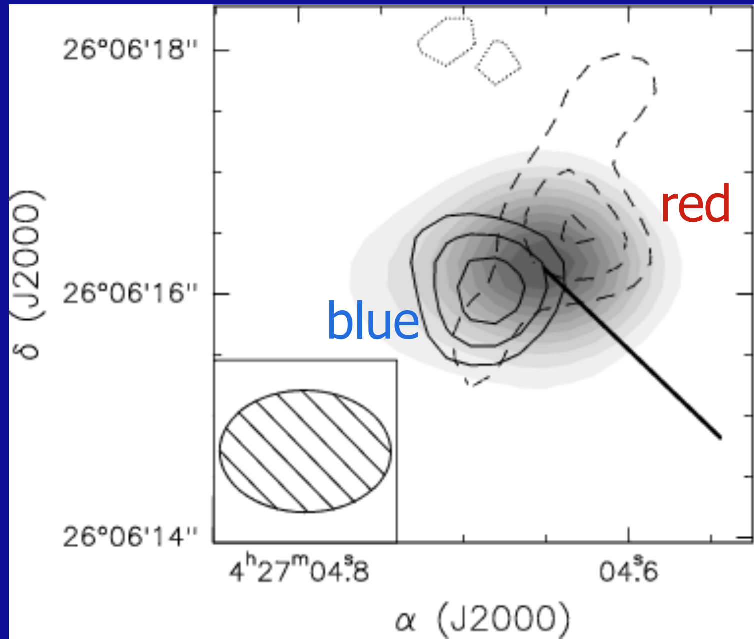
The prototypical molecular outflow HH211



Jet rotation in DG Tau



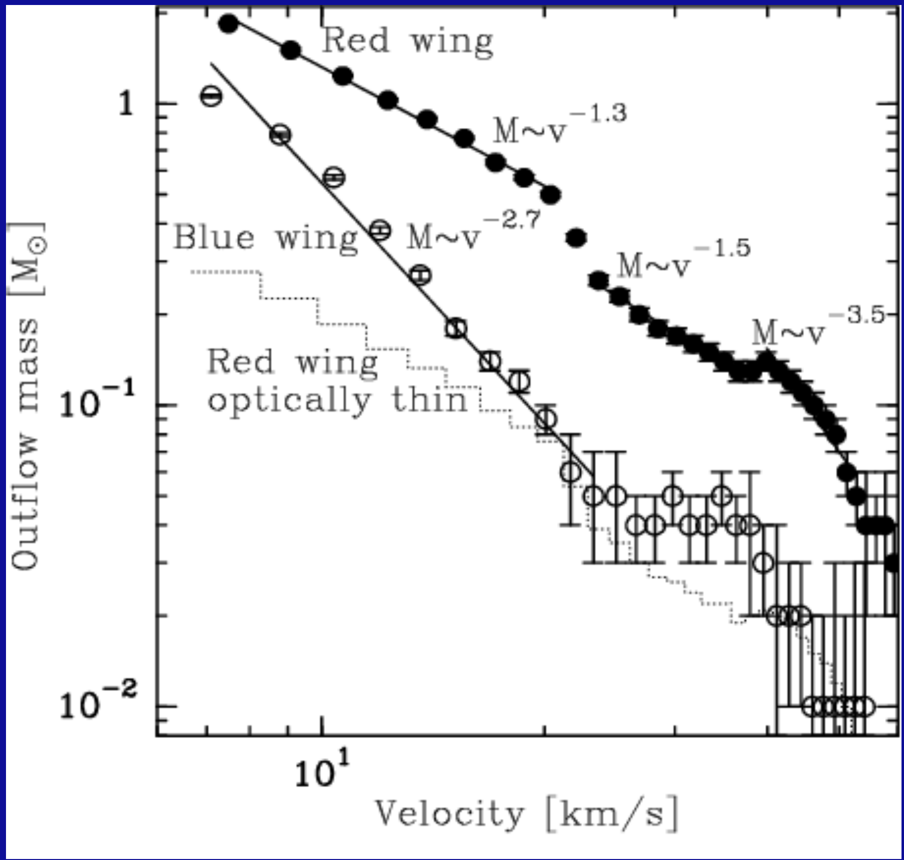
Bacciotti et al. 2002



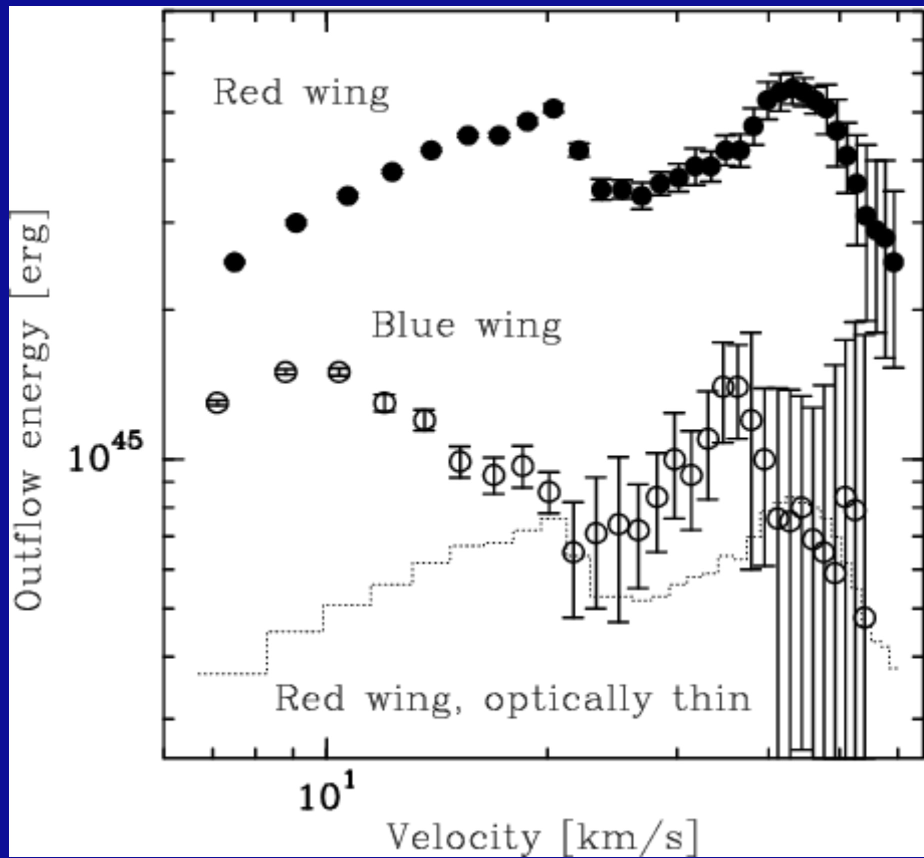
Testi et al. 2002

Corotation of disk and jet

Mass vs.velocity, energy vs. velocity



$E \sim v^2$

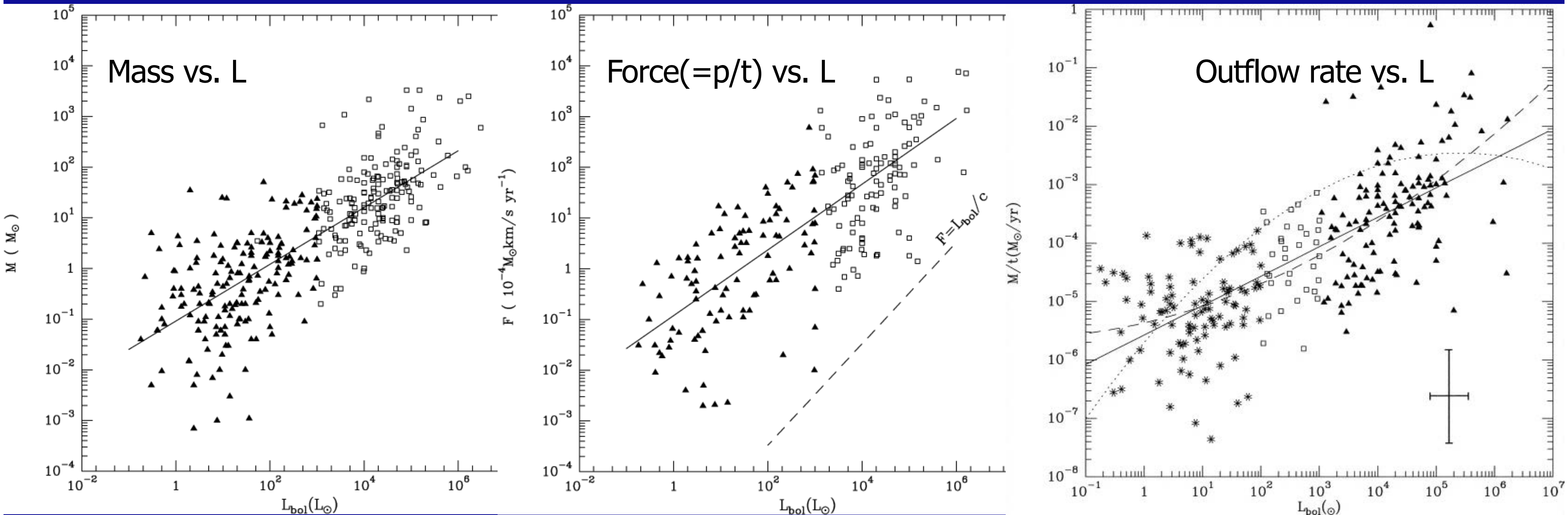


- Mass-velocity relation exhibits broken power-law, steeper further out.
- Energy at high velocities of the same magnitude than at low velocities.

Lebron et al. 2006

General outflow properties

- Jet velocities 100-500 km/s <==> Outflow velocities 10-50 km/s
- Estimated dynamical ages between 10^3 and 10^5 years
- Size between 0.1 and 1 pc
- Force provided by stellar radiation too low (middle panel)
  → non-radiative processes necessary!



Wu et al. 2004, 2005

Impact on surrounding cloud

- Entrain large amounts of cloud mass with high energies.

- Partly responsible to maintain turbulence in cloud.

- Can disrupt the cores to stop any further accretion.

- May trigger collapse in neighboring cores.

- Via shock interactions heat the cloud.

- Alter the chemical properties.

Topics today

- Pre-main-sequence evolution

- General outflow properties

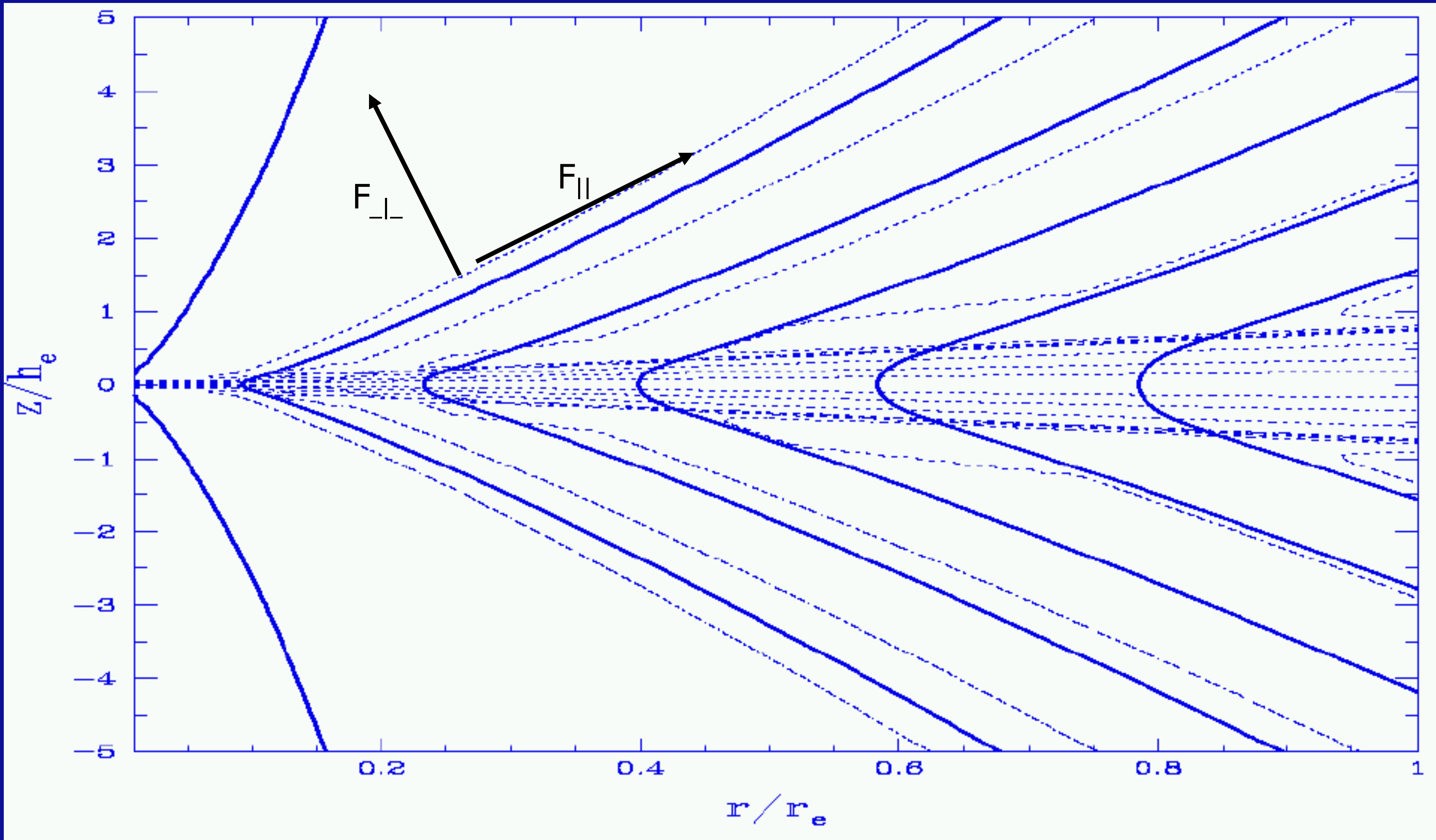
- Jet launching

- Outflow driving and entrainment

Jet launching from accretion disks

"magnetic accretion-ejection structures" (Ferreira et al 1995-1997):

1) disk material diffuses across magnetic field lines, 2) is lifted upwards by MHD forces, then
3) couples to the field and 4) becomes accelerated magnetocentrifugally and 5) collimated



Magnetic field lines (thick) and streamlines (dashed)

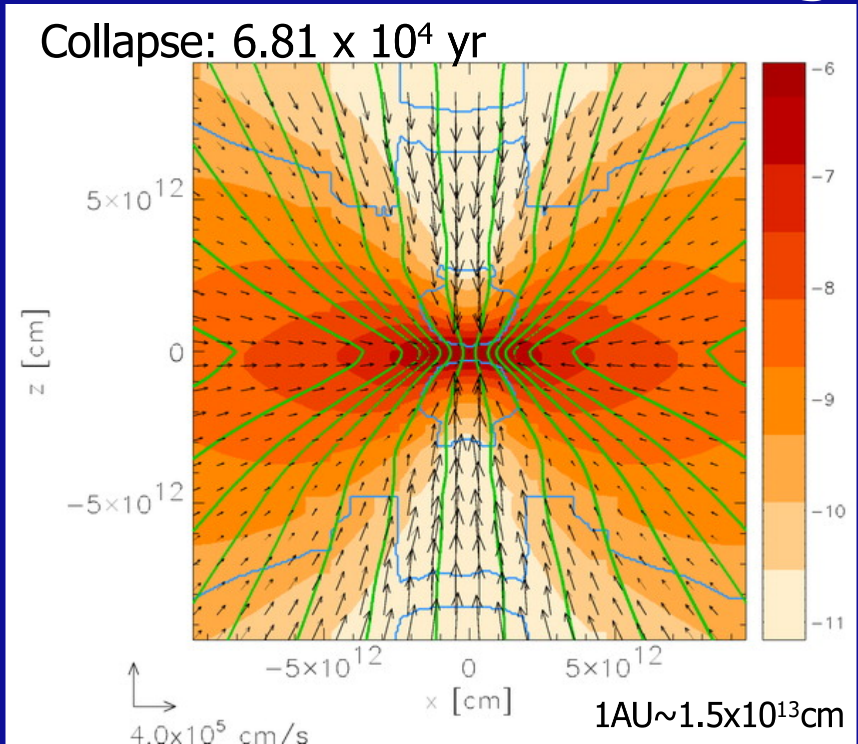
Jet launching

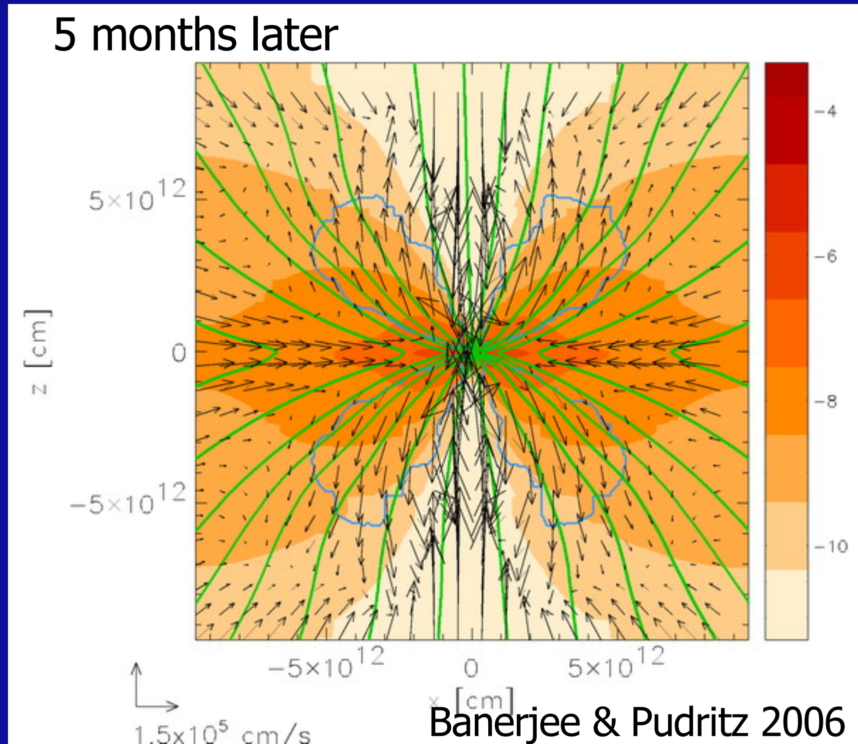
- Consensus: Jets are driven by magnetocentrifugal winds from magnetic field lines anchored in rotating circumstellar disks.

Disk winds ← → X-winds

Launching over larger disk area?	← →	Launching from a small area close to disk truncation?

Jet-launching: Disk winds I





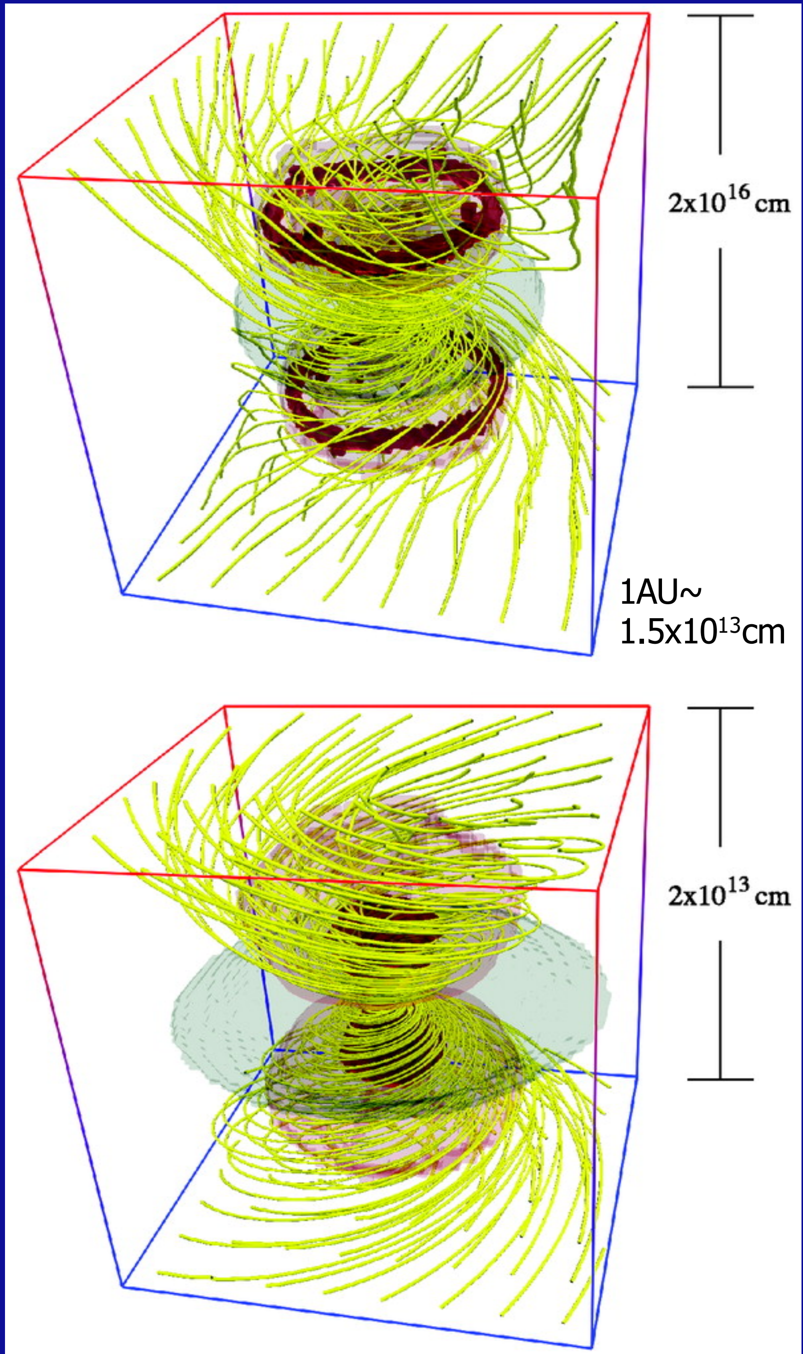
- Infalling core pinches magnetic field.

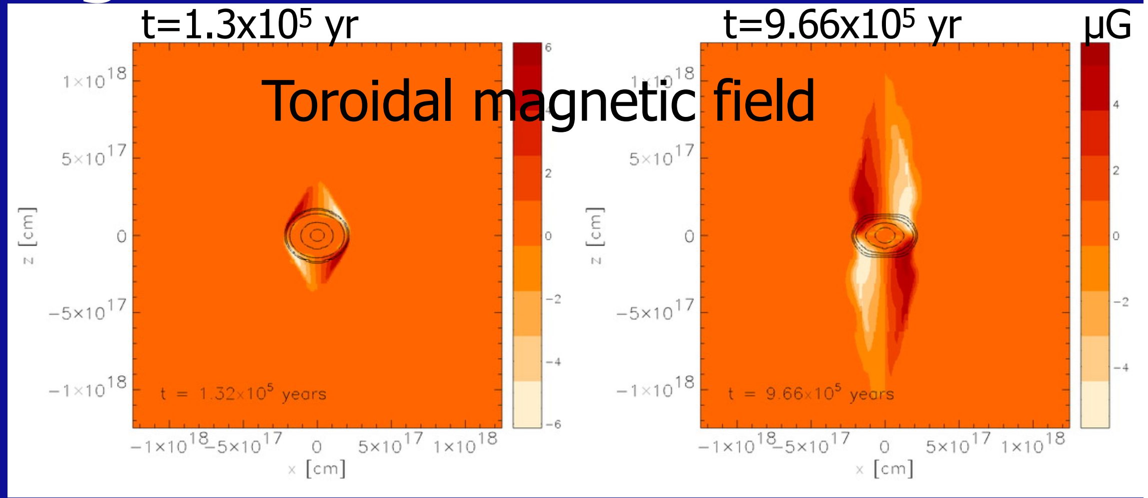
- If poloidal magnetic field component B_p has angle larger 30° from vertical
  → centrifugal forces launch matter-loaded wind along field from disk

- Wind transports away from 60 to 100% of disk angular momentum.

Review: Pudritz et al. 2006

Jet-launching: Disk winds II



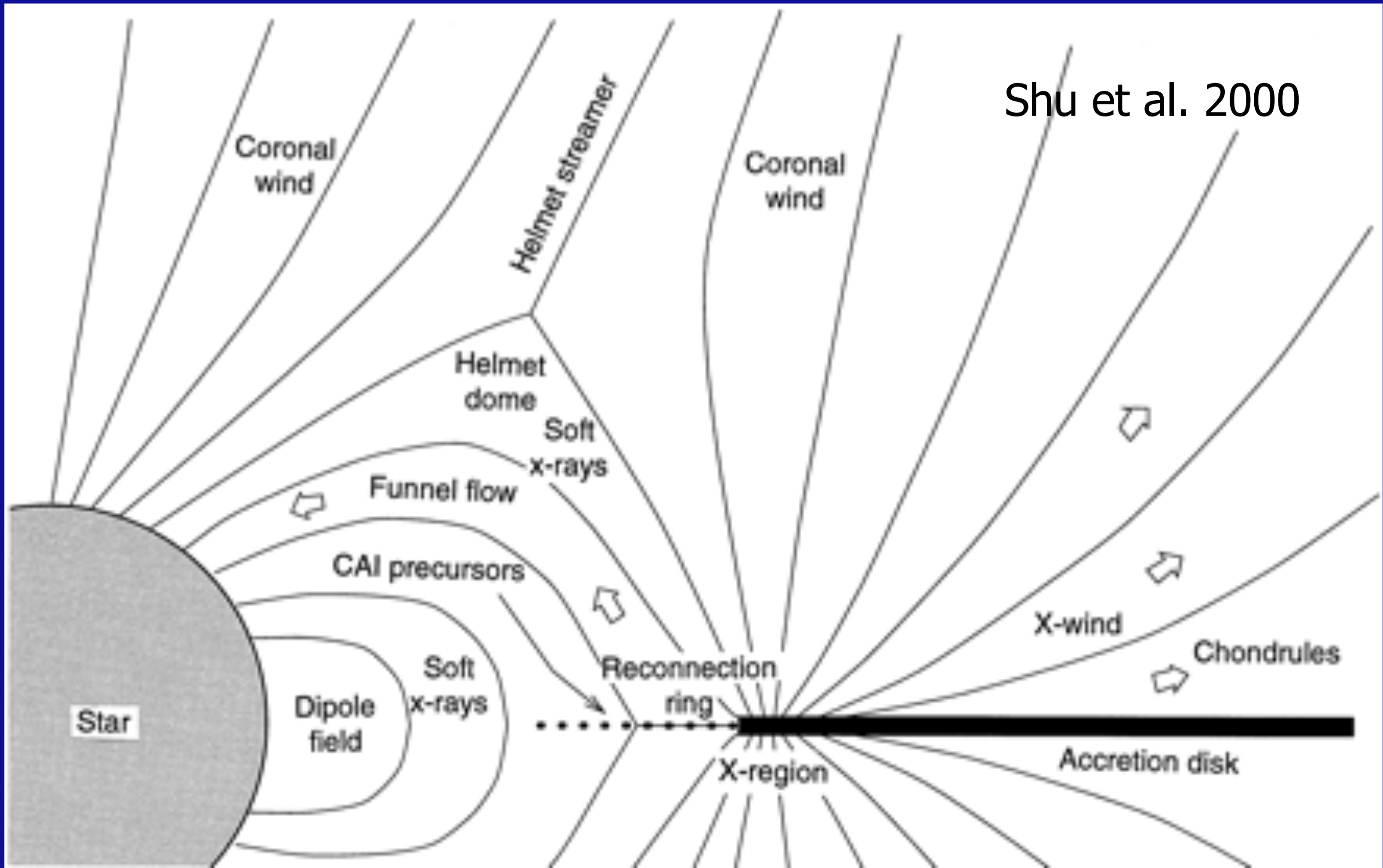


- On larger scales, a strong toroidal magnetic field B_ϕ builds up during collapse.

- At large radii (outside Alfven radius r_A, the radius where kin. energy equals magn. energy) B_ϕ/B_p much larger than 1
  → collimation via Lorentz-force $F_L \sim j_z B_\phi$

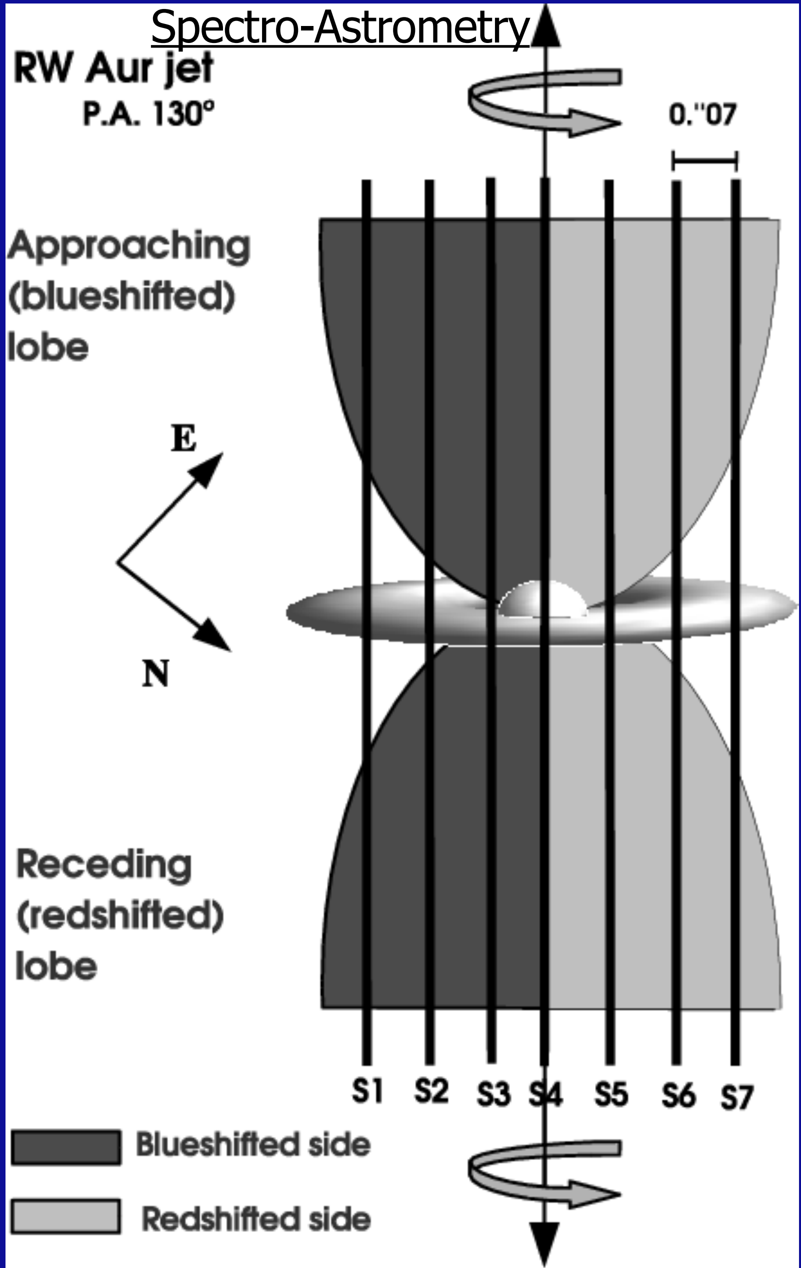
Banerjee & Pudritz 2006

X-winds

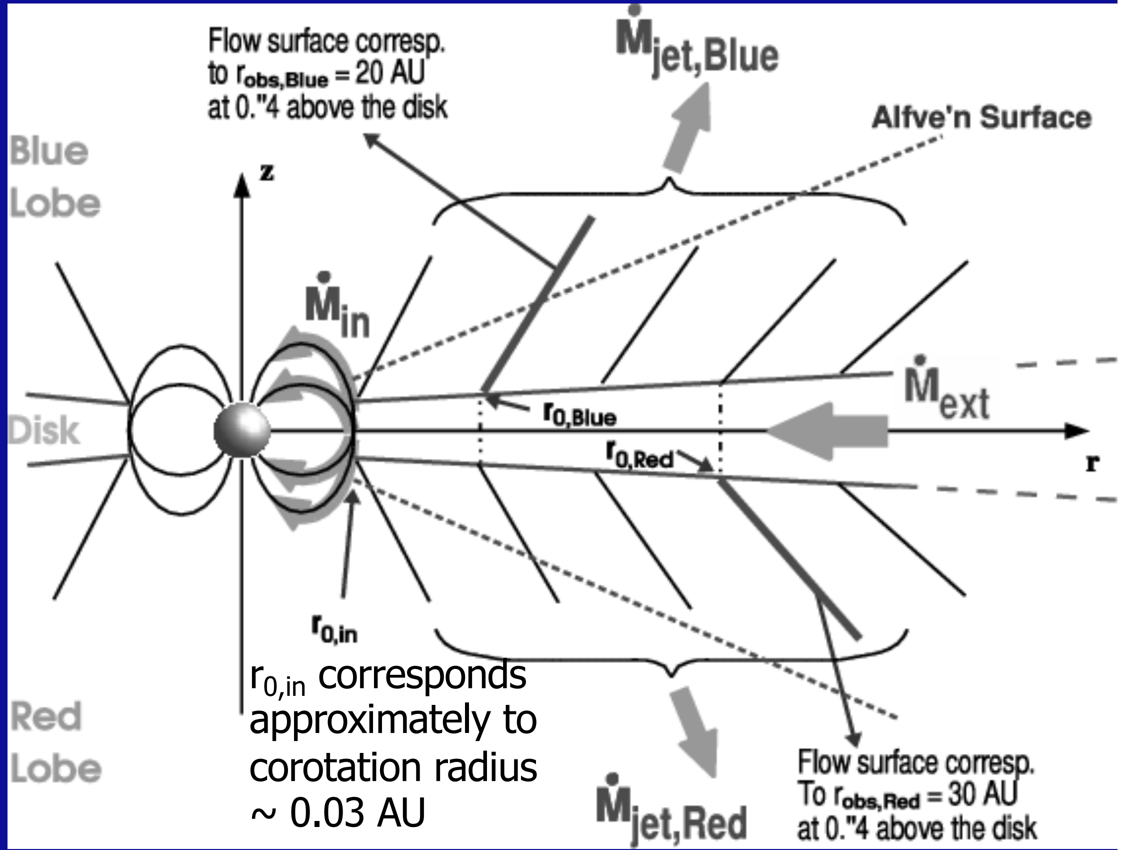


- The wind is launched magneto-centrifugally from the inner co-rotation radius of the accretion disk (~0.03AU)

Jet-launching points and angular momenta



Woitas et al. 2005



- From toroidal and poloidal velocities
  → footpoints r_0, where gas comes from
  → outer r_0 for the blue and red wing are about 0.4 and 1.6 AU (lower limits)
  → consistent with disk winds
- About 2/3 of the disk angular momentum may be carried away by jet.

Topics today

- Pre-main-sequence evolution

- General outflow properties

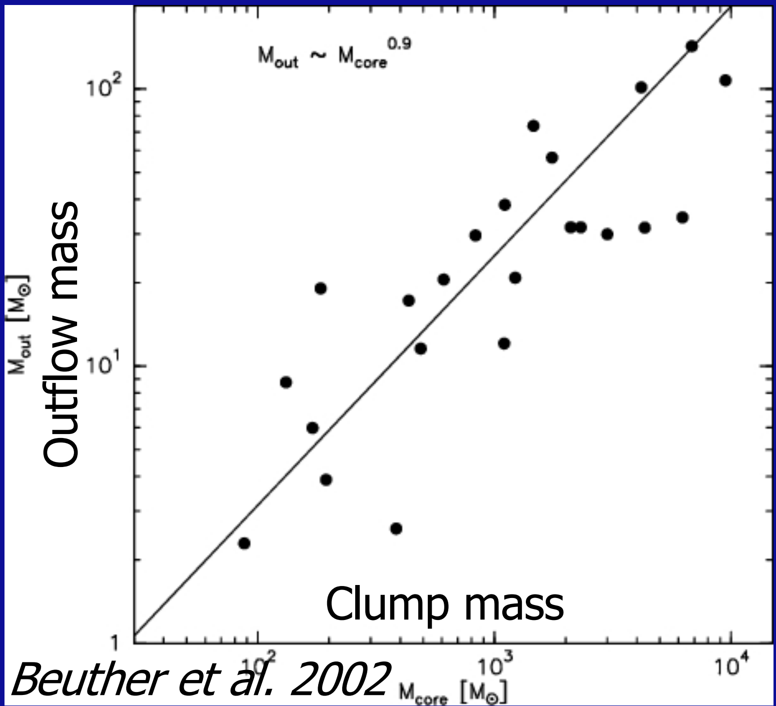
- Jet launching

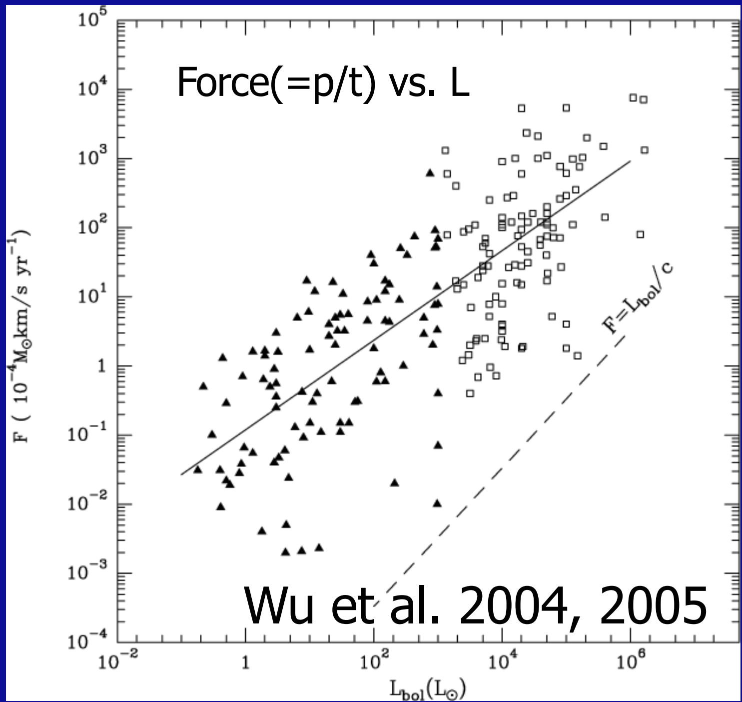
- Outflow driving and entrainment

Outflow driving I

- Molecular outflow masses usually much larger than stellar masses
  → outflow-mass not directly from star-disk but swept-up entrained gas.

- Force observed in outflow cannot be explained just by force excerted from central object → other outflow driving and entrainment processes required.

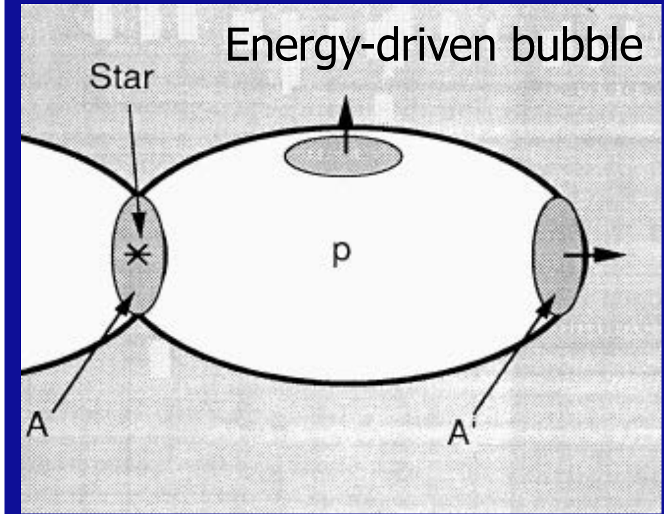




Outflow driving II

Momentum-driven vs. energy-driven molecular outflows

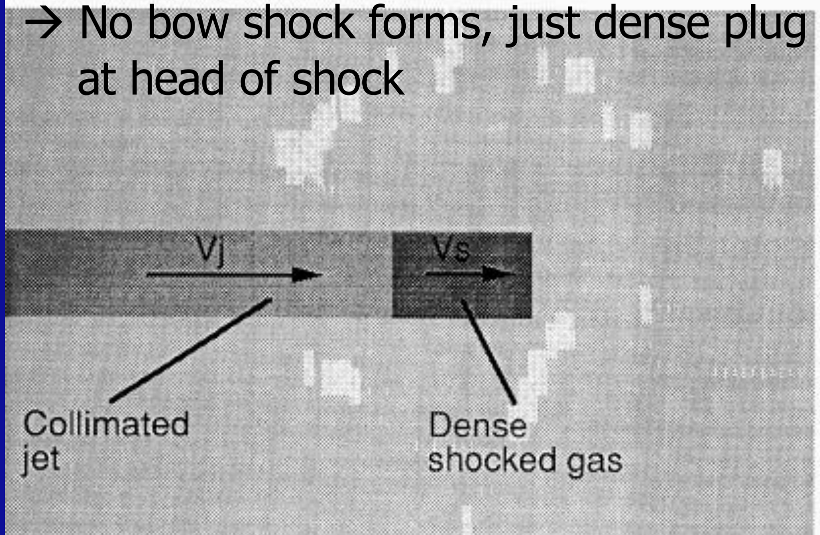
Energy-driven bubble

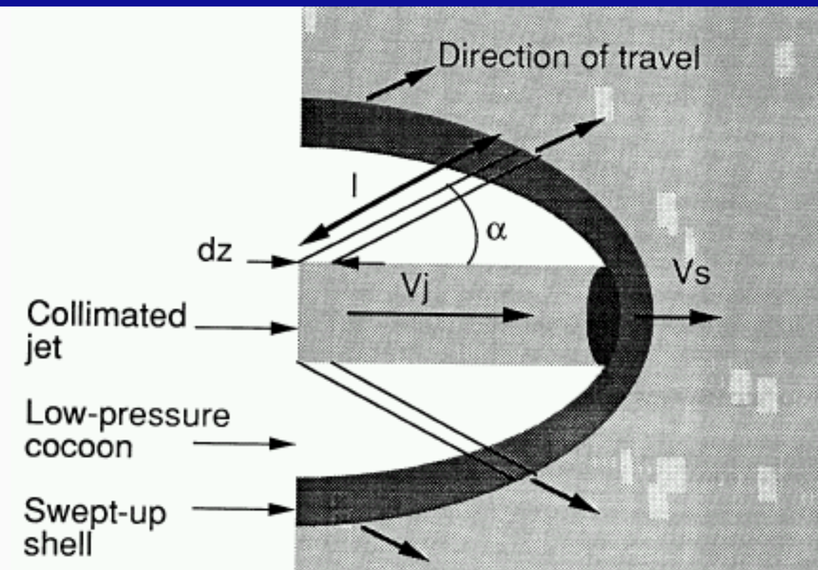


- Energy-driven: jet-energy conserved in pressurized bubble that gets released adiabatically as the bubble expands.
  → large transverse velocities which are not observed
  → momentum conservation better!

Completely radiative shock → only dense plug at front
Completely adiabatic shock → large bow shocks with mainly transverse motions
Both wrong → Hence intermediate solution with highly dissipative shock required → forward motion and bow shock!
→ This can accelerate the ambient gas!

Completely radiative shock
→ No bow shock forms, just dense plug at head of shock





Highly dissipative shock: Forward motion AND bow-shock for gas entrainment.

Masson et al. 1993

Outflow entrainment models I

Basically 4 outflow entrainment models are discussed in the literature:

<u>Turbulent jet entrainment model</u>

- Working surfaces at the jet boundary layer caused by Kelvin-Helmholtz instabilities form viscous mixing layer entraining molecular gas.
  → The mixing layer grows with time and whole outflow gets turbulent.

- Broken power-law of mass-velocity relation is reproduced, but velocity decreases with distance from source → opposite to observations

<u>Jet-bow shock model</u>

- Jet impacts on ambient gas → bow shocks are formed at head of jet.
  → High pressure gas is ejected sideways
  → broader bow shock entraining the ambient gas.
  → Episodic ejection produces chains of knots and shocks.

- Numerical modeling reproduces many observables, e.g. Hubble-law (outflow velocity increases with distance).

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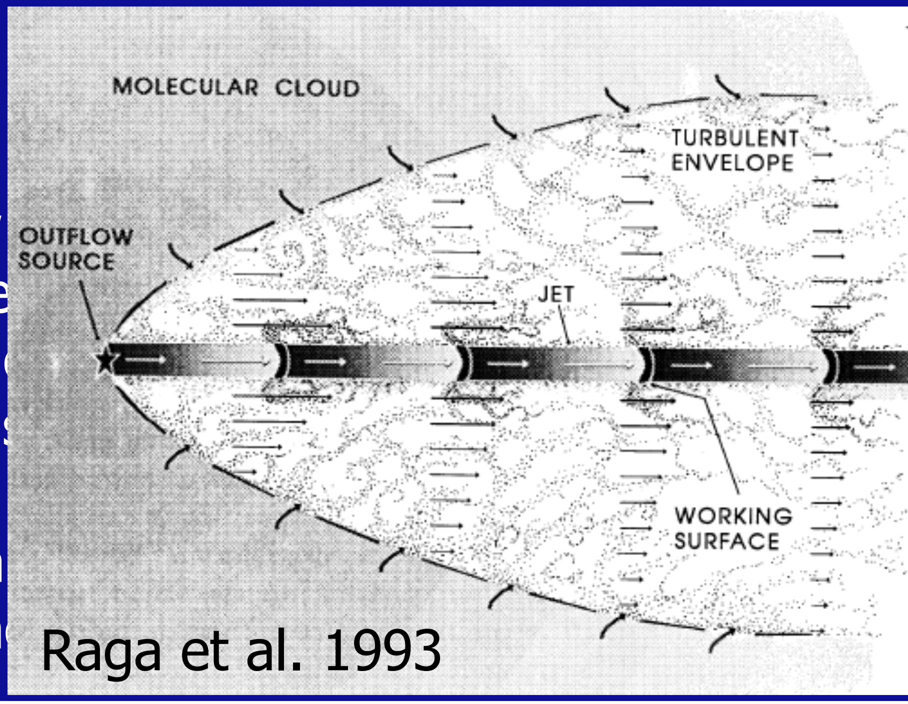

Raga et al. 1993

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Jet-

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  → … d side
  → … ng the
  → … chains

- N … es ma
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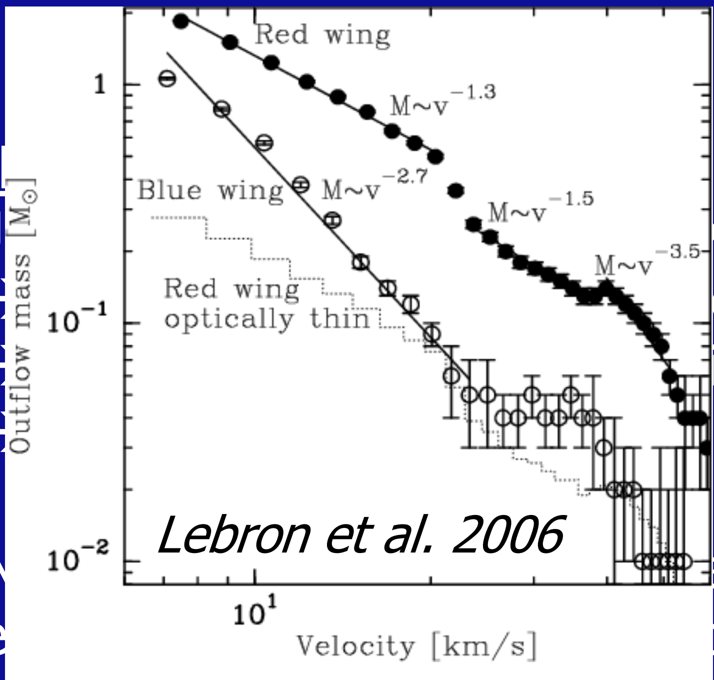
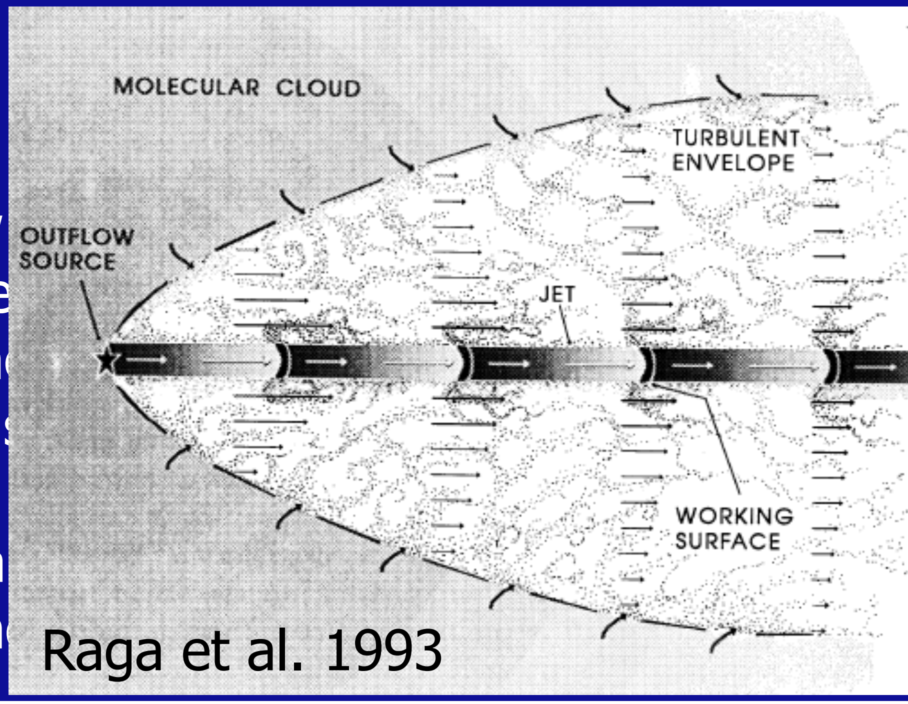


Lebron et al. 2006



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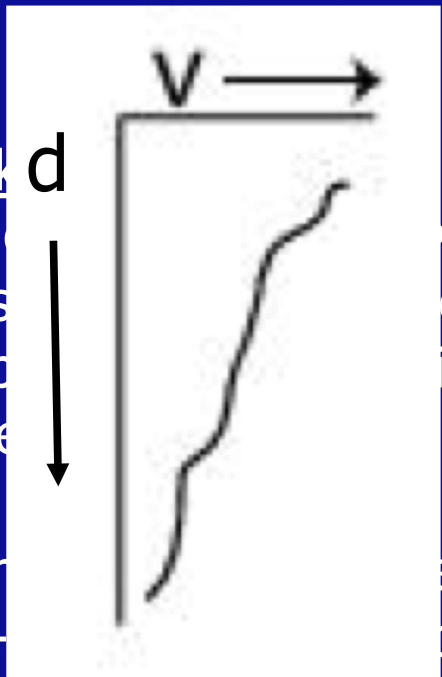

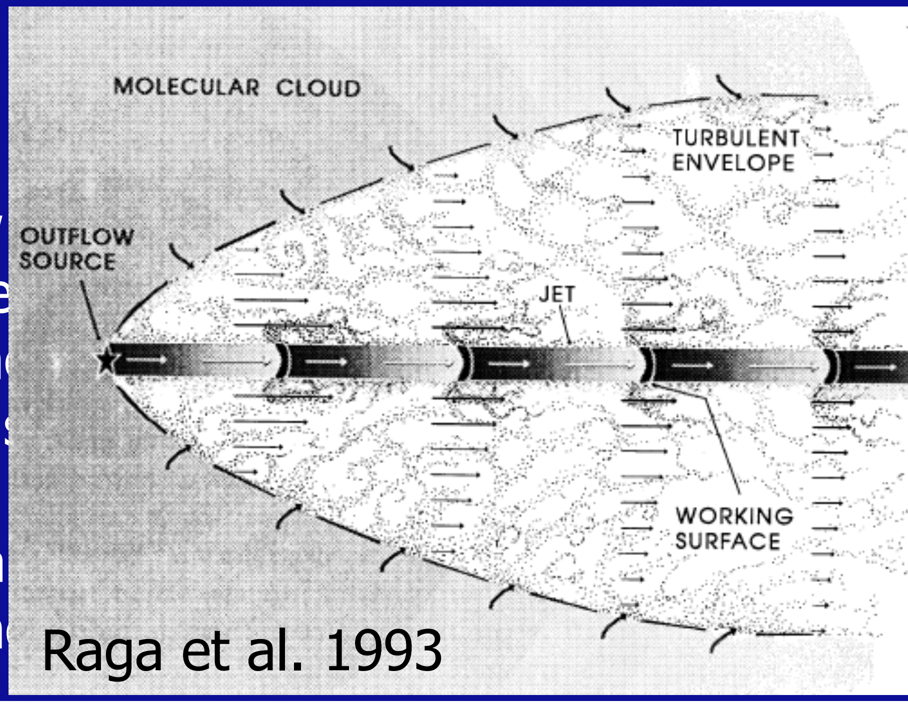

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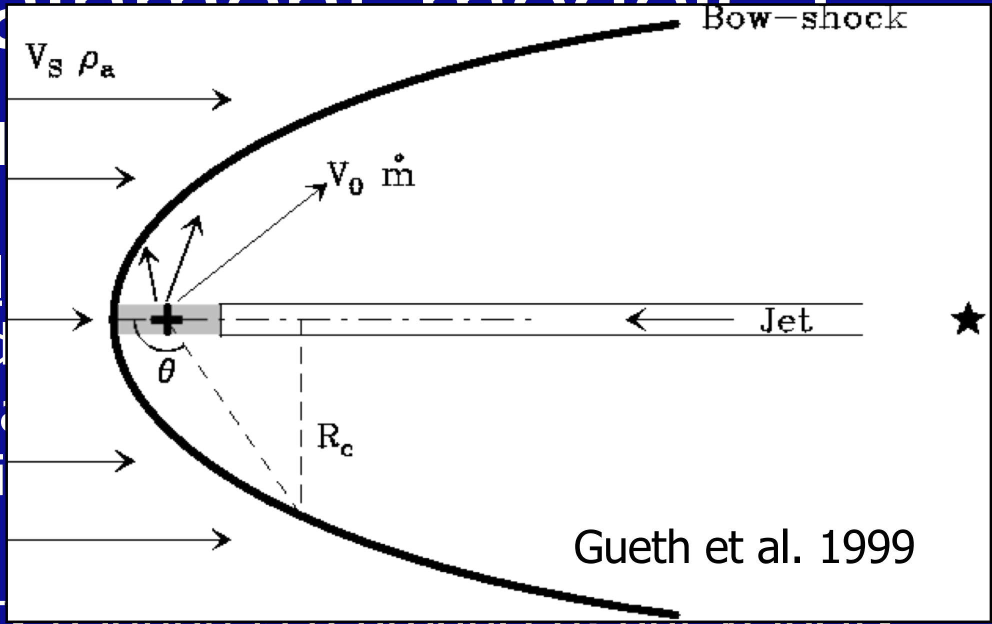

Gueth et al. 1999

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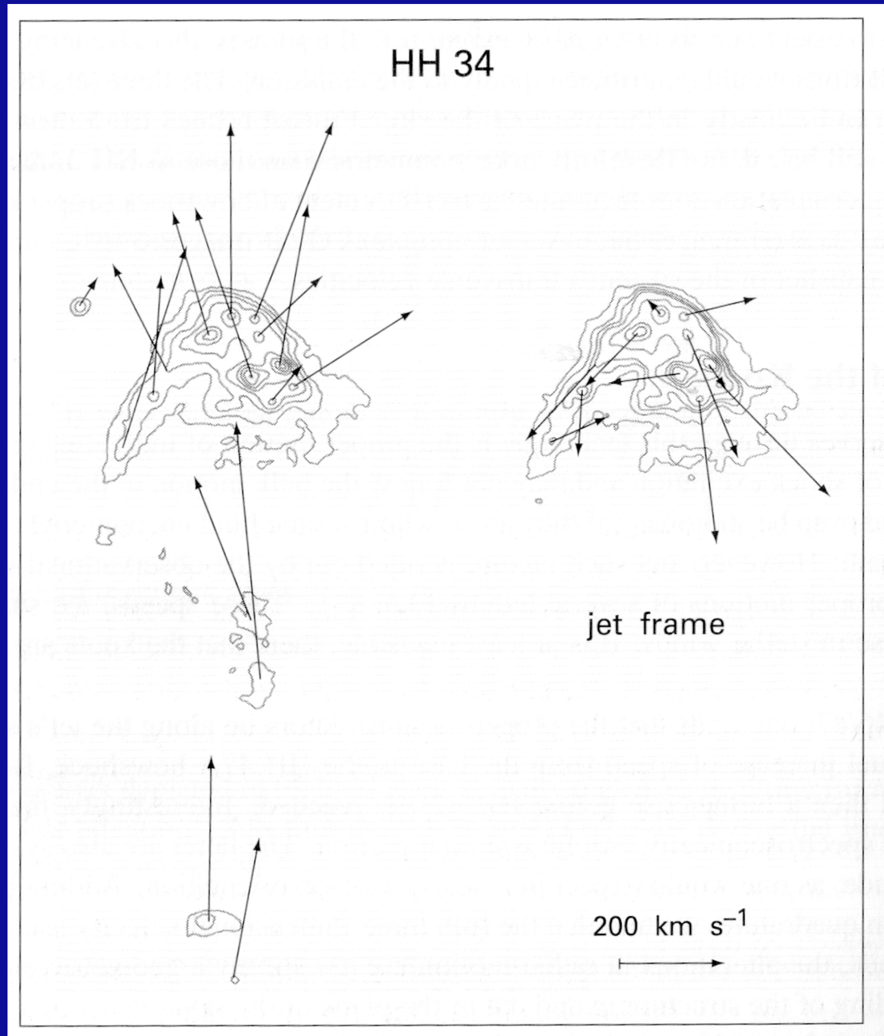
The case of the HH34 bow shock



In the jet-frame, after subtracting the velocity of the mean axial flow, the knots are following the sides of the bow shock.

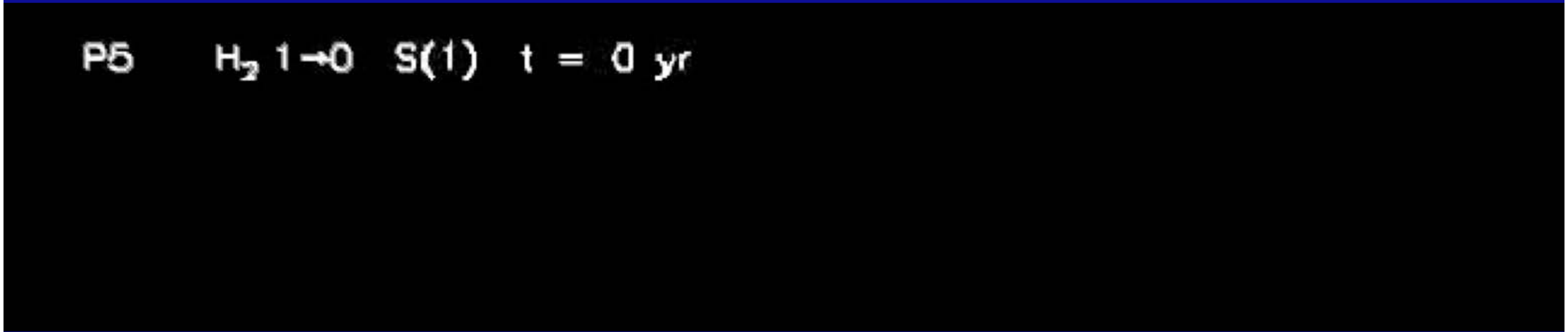
Reipurth et al. 2002

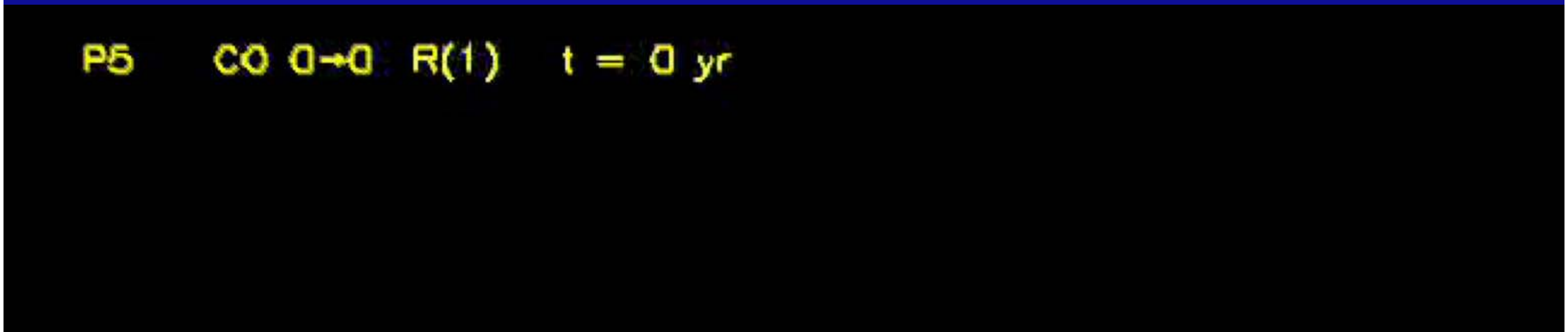
Jet simulations I

3-dimensional hydrodynamic simulations, including H, C and O chemistry and cooling of the gas, this is a pulsed jet.

Rosen & Smith 2004

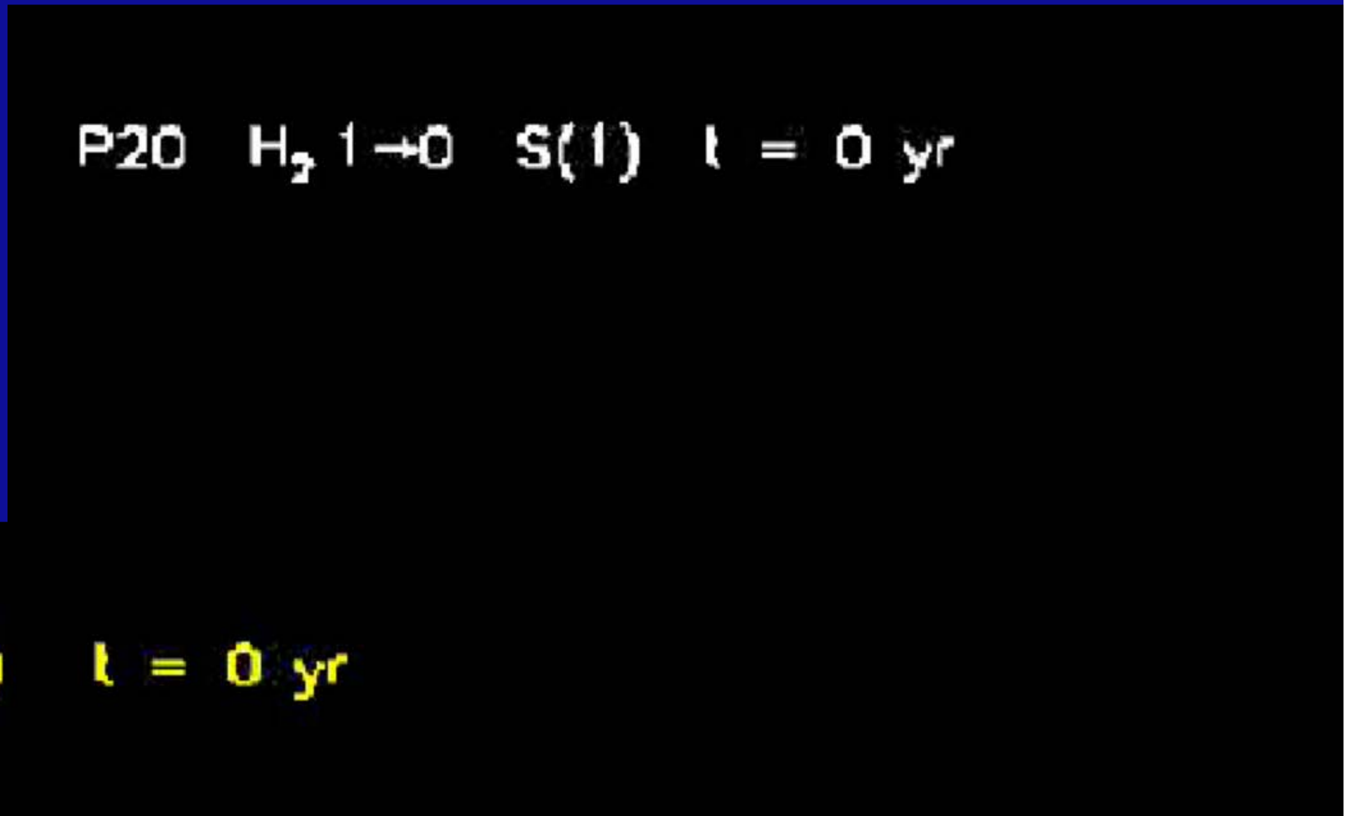
Jet simulations II: small precession

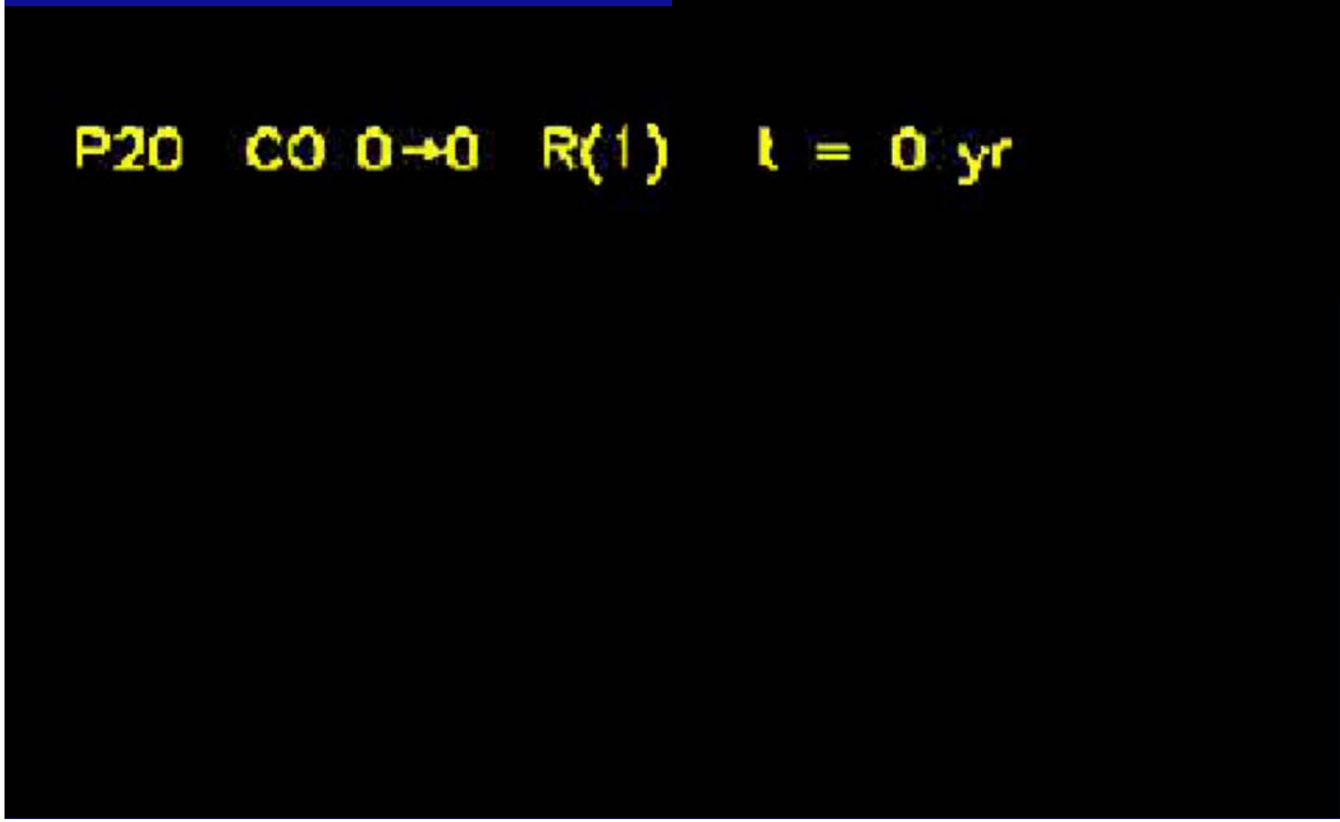




Rosen &
Smith 2004

Jet simulations III, large precession





Rosen & Smith 2004

Outflow entrainment models II

Wide-angle wind model

- Wide-angle wind blows into ambient gas forming a thin swept-up shell.
- Different degrees of collimation can be explained by different density structures of the ambient gas.
- Attractive models for older and low collimated outflows.

Circulation model

- Molecular gas is not entrained by underlying jet or wind, but it is rather infalling gas that was deflected from the central protostar in a region of high MHD pressure.
- This model was proposed to explain also massive outflows because it was originally considered difficult to entrain that large amounts of gas. Maybe not necessary today anymore …

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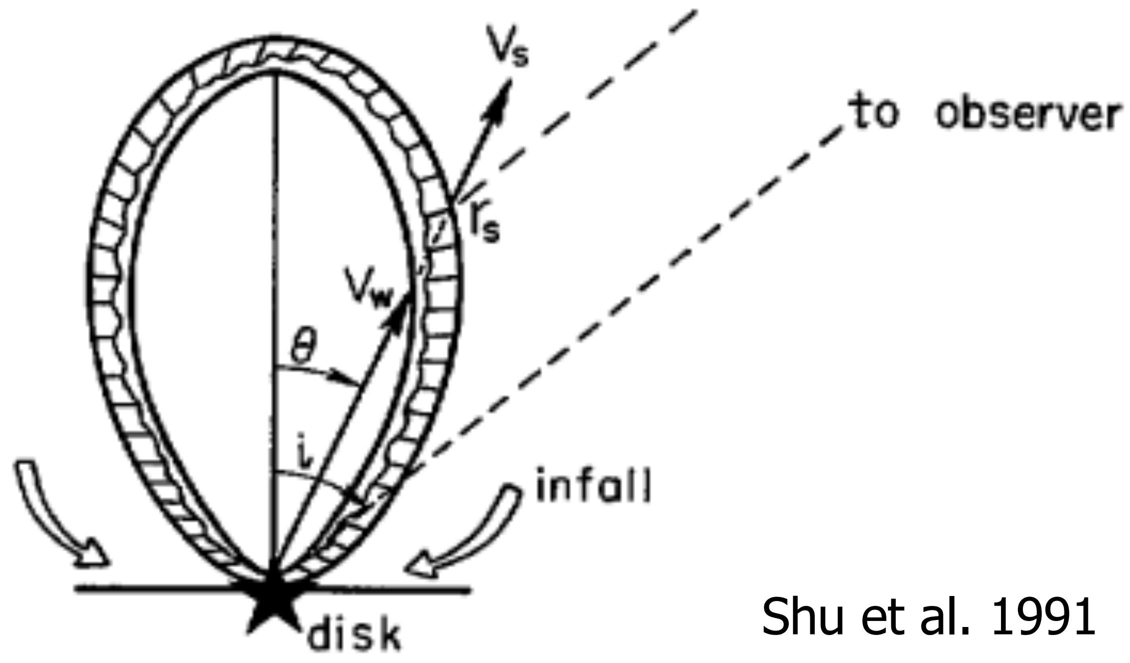
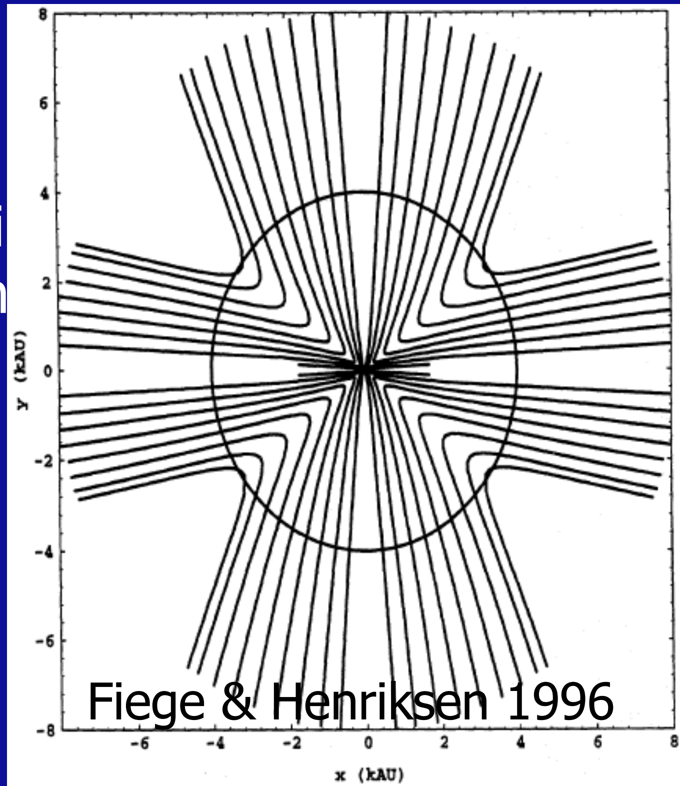


Shu et al. 1991

Outflow entrainment models II



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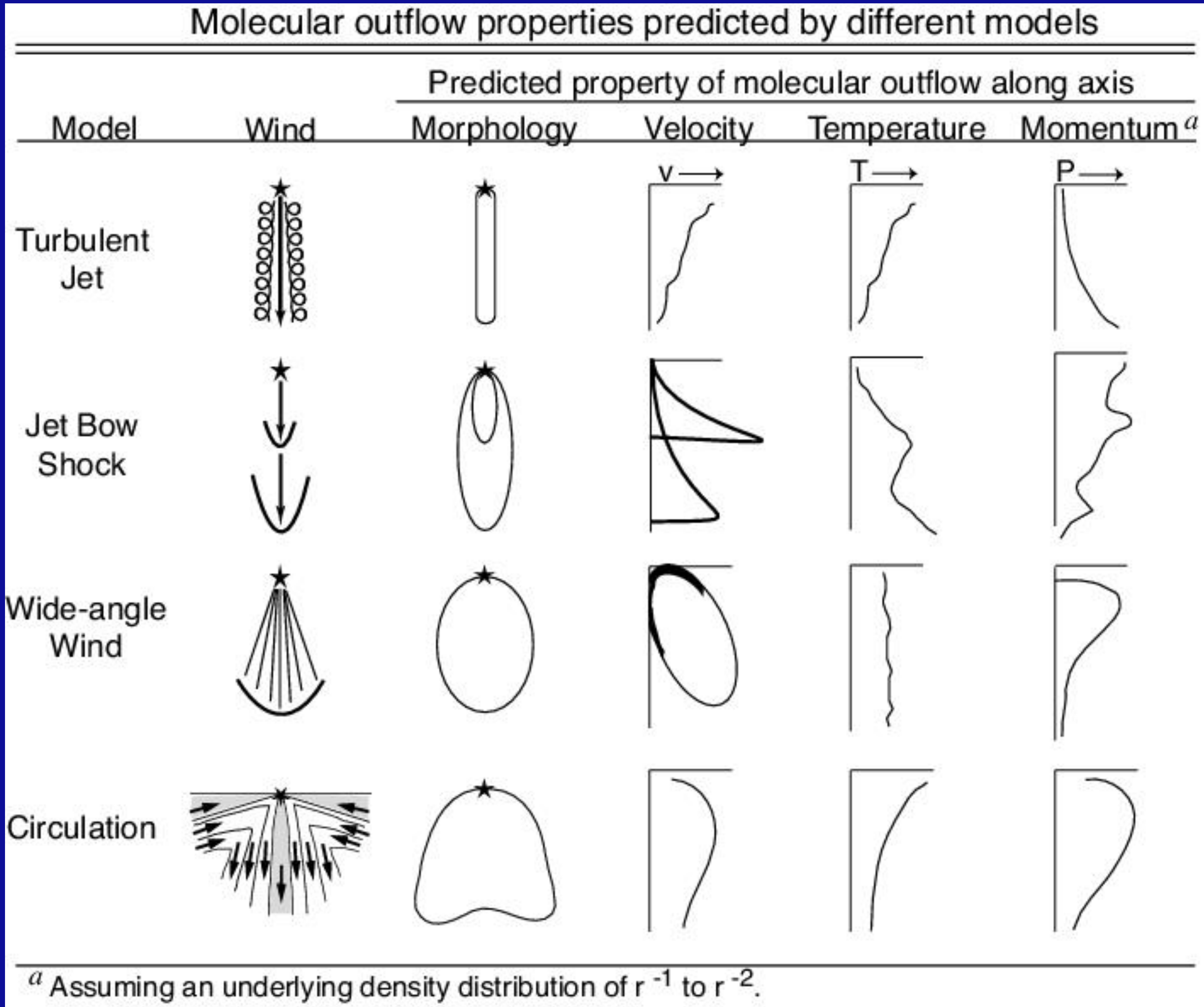
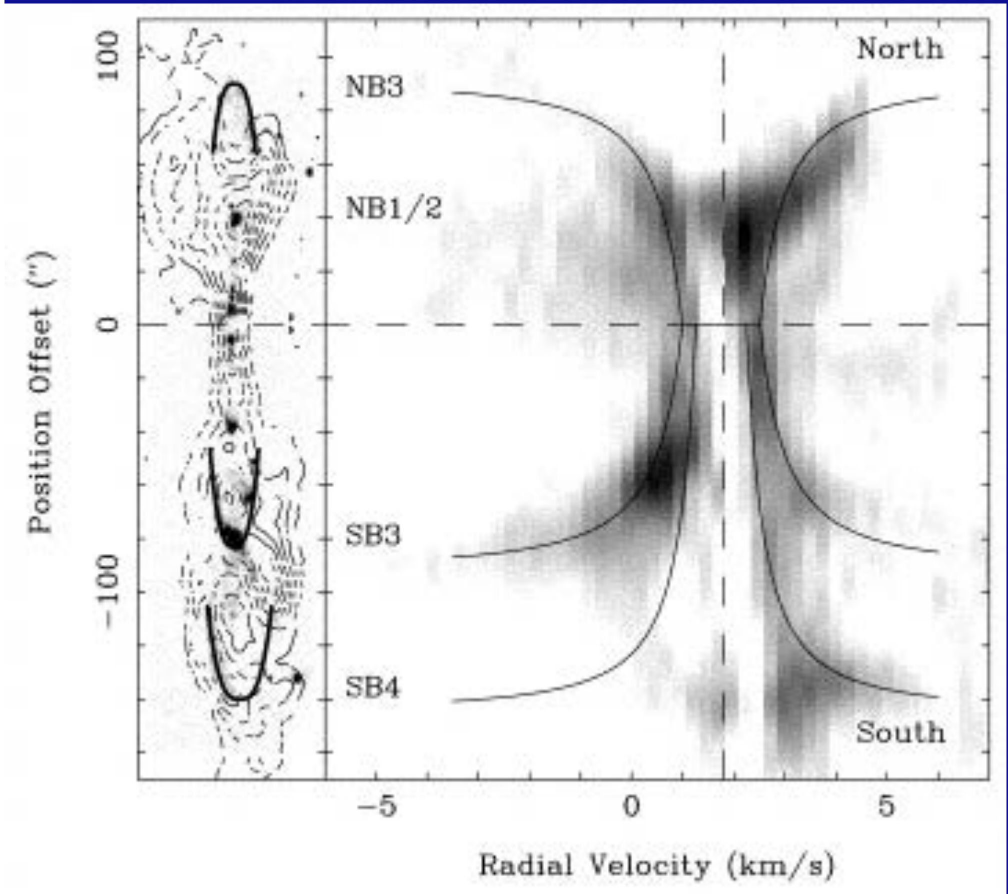
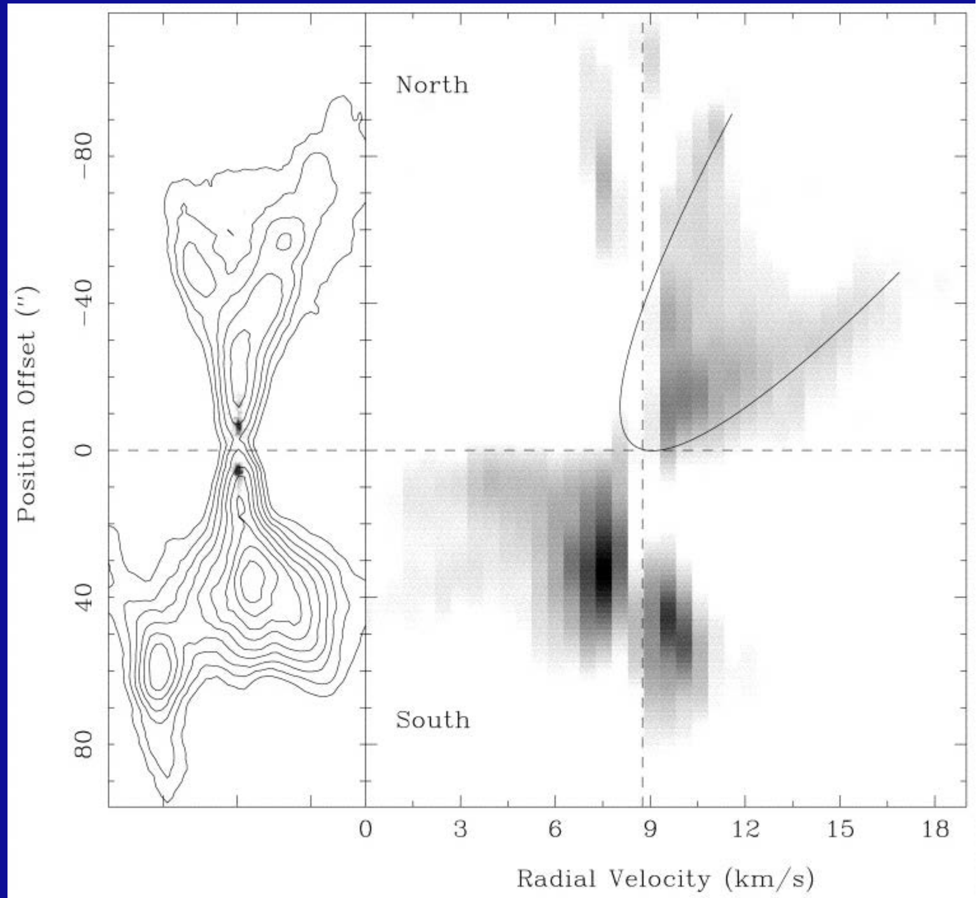


Arce et al. 2007

Collimation and pv-structure





HH212: consistent with jet-driving

VLA0548: consistent with wind-driving

- pv-structure of jet- and wind-driven models very different
- Often Hubble-law observed → increasing velocity with increasing distance from the protostar

Lee et al. 2001

Summary

- End of protostellar/beginning or pre-main sequence evolution → birthline.

- Pre-main sequence evolution in the Hertzsprung-Russel (HR) diagram.

- Connection of HR diagram with protostellar and pre-main sequence classes.

- Outflows and jets are ubiquitous and necessary phenomena in star formation.

- Transport angular momentum away from protostar.

- They are formed by magneto-centrifugal disk-winds.

- Collimation is caused by Lorentz forces.

- Gas entrainment can be due to various processes: turbulent entrainment, bow-shocks, wide-angle winds, circulation ...

- They inject significant amounts of energy in the ISM, may be important to maintain turbulence and disrupt their maternal clouds.

Sternentstehung - Star Formation

Winter term 2020/2021

Henrik Beuther, Thomas Henning & Sümeyye Suri

03.11 Today: Introduction & Overview (Beuther)
10.11 Physical processes I (Beuther)
17.11 Physcial processes II (Beuther)
24.11 Molecular clouds as birth places of stars (Suri)
01.12 Molecular clouds (cont.), Jeans Analysis (Suri)
08.12 Collapse models I (Henning)
15.12 Collapse models II (Henning)
------------ Christmas break -------------
12.01 Protostellar evolution (Beuther)
19.01 Pre-main sequence evolution & outflows/jets (Beuther)
26.01 Accretion disks I (Henning)
02.02 Accretion disks II (Henning)
09.02 High-mass star formation, clusters and the IMF (Suri)
16.02 Extragalactic star formation (Henning)
23.02 Examination week, no star formation lecture

Book: Stahler & Palla: The Formation of Stars, Wileys

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2021.html

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