Outflows and Jets: Theory and Observations

Summer term 2011

Henrik Beuther & Christian Fendt

15.04 Today: Introduction & Overview (H.B. & C.F.)
29.04 Definitions, parameters, basic observations (H.B.)
06.05 Basic theoretical concepts & models (C.F.)
13.05 Basic MHD and plasma physics; applications (C.F.)
20.05 Radiation processes (H.B.)
27.05 Observational properties of accretion disks (H.B.)
03.06 Accretion disk theory and jet launching (C.F.)
10.06 Outflow interactions: Entrainment, instabilities, shocks (C.F.)
17.06 Outflow-disk connection, outflow entrainment (H.B.)
24.06 Outflow-ISM interaction, outflow chemistry (H.B.)
01.07 Outflows from massive star-forming regions (H.B.)
08.07 Observations of extragalactic jets (C.F.)
15.07 Theory of relativistic jets (C.F.)

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ss11.html

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Topics today

- Jet launching processes, magnetic field morphology and jet launching observations

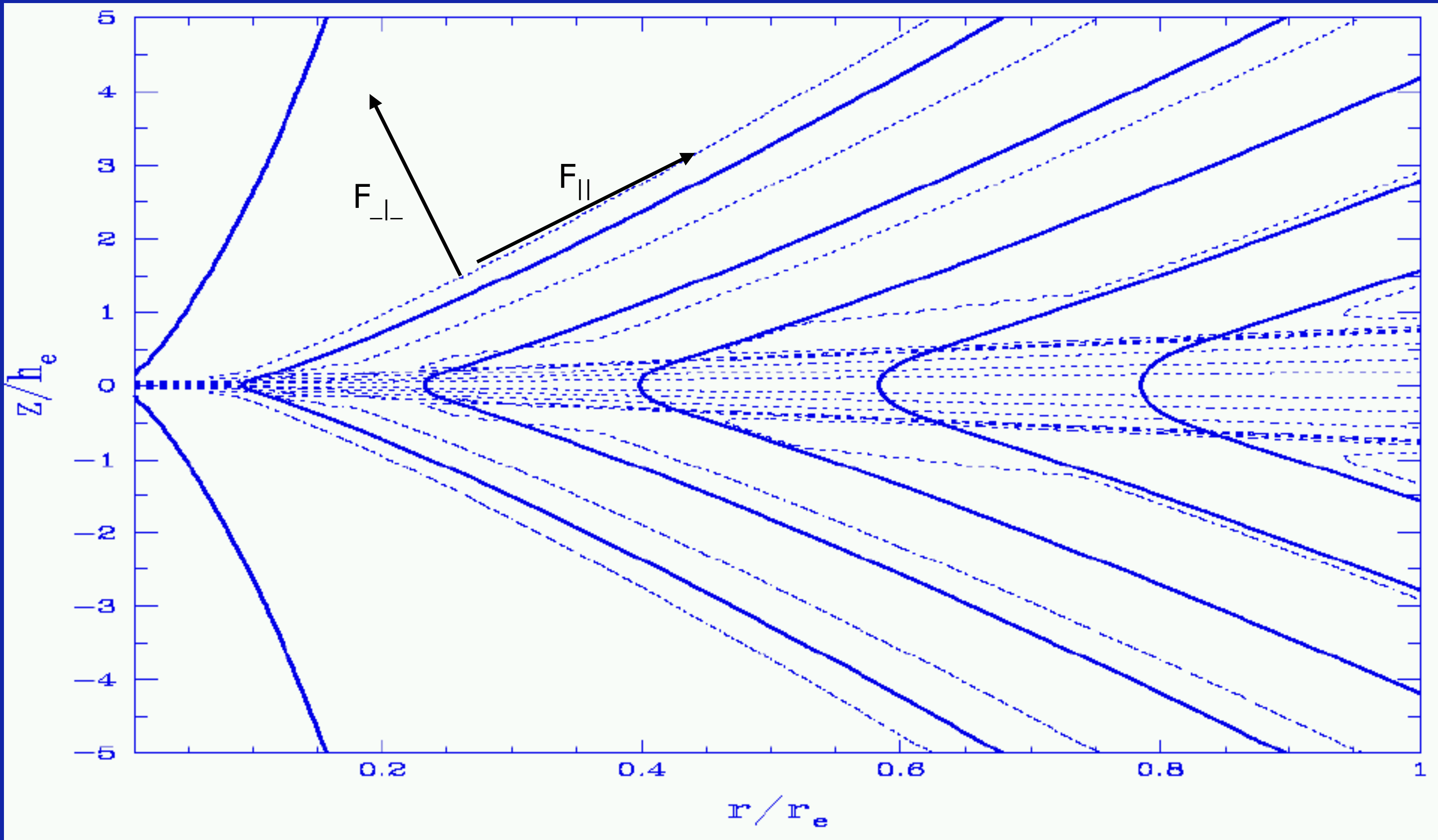
- Outflow entrainment models

- Additional observables to constrain outflow/jet properties

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)

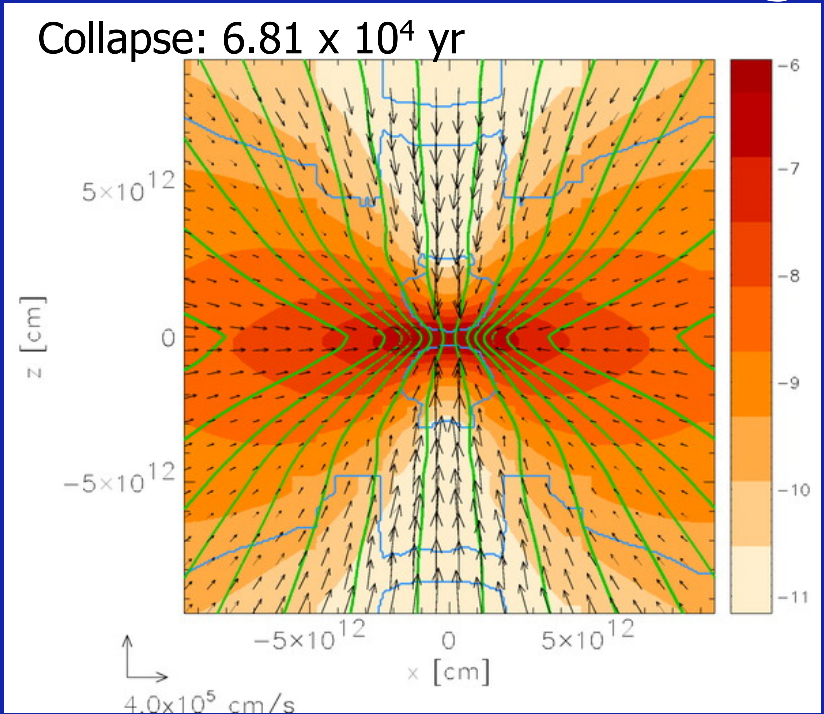
Jet launching

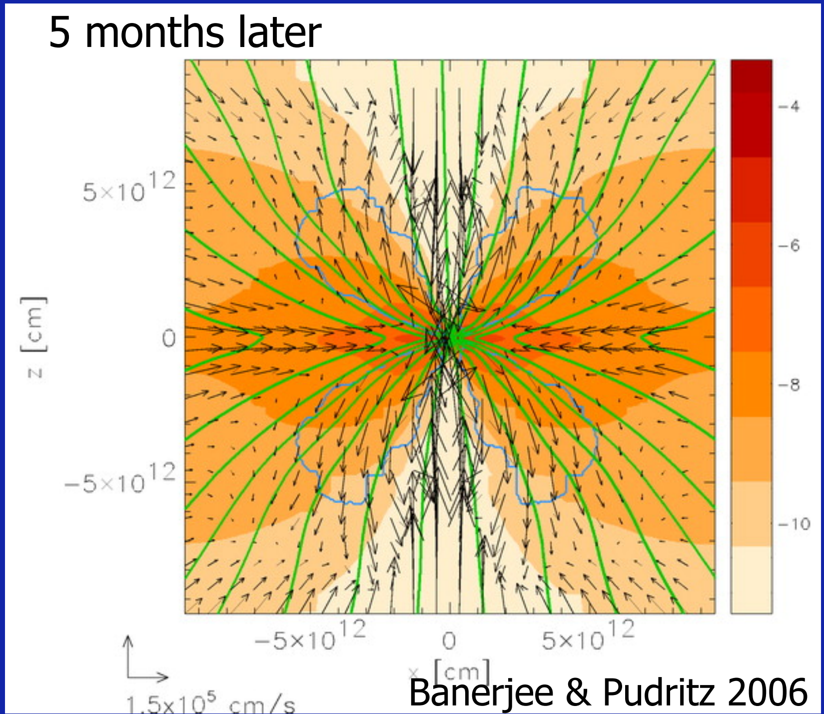
- Large consensus that outflows are likely driven by magneto-centrifugal winds from open magnetic field lines anchored on rotating circumstellar accretion disks.

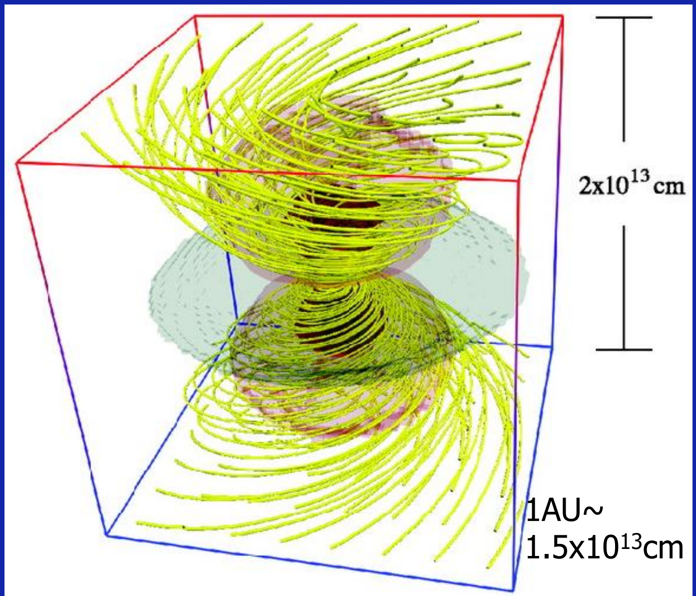
- Two main competing theories: disk winds <==> X-winds

- Are they launched from a very small area of the disk close to the truncation radius (X-wind), or over larger areas of the disk (disk wind)?

Jet-launching: Disk winds I



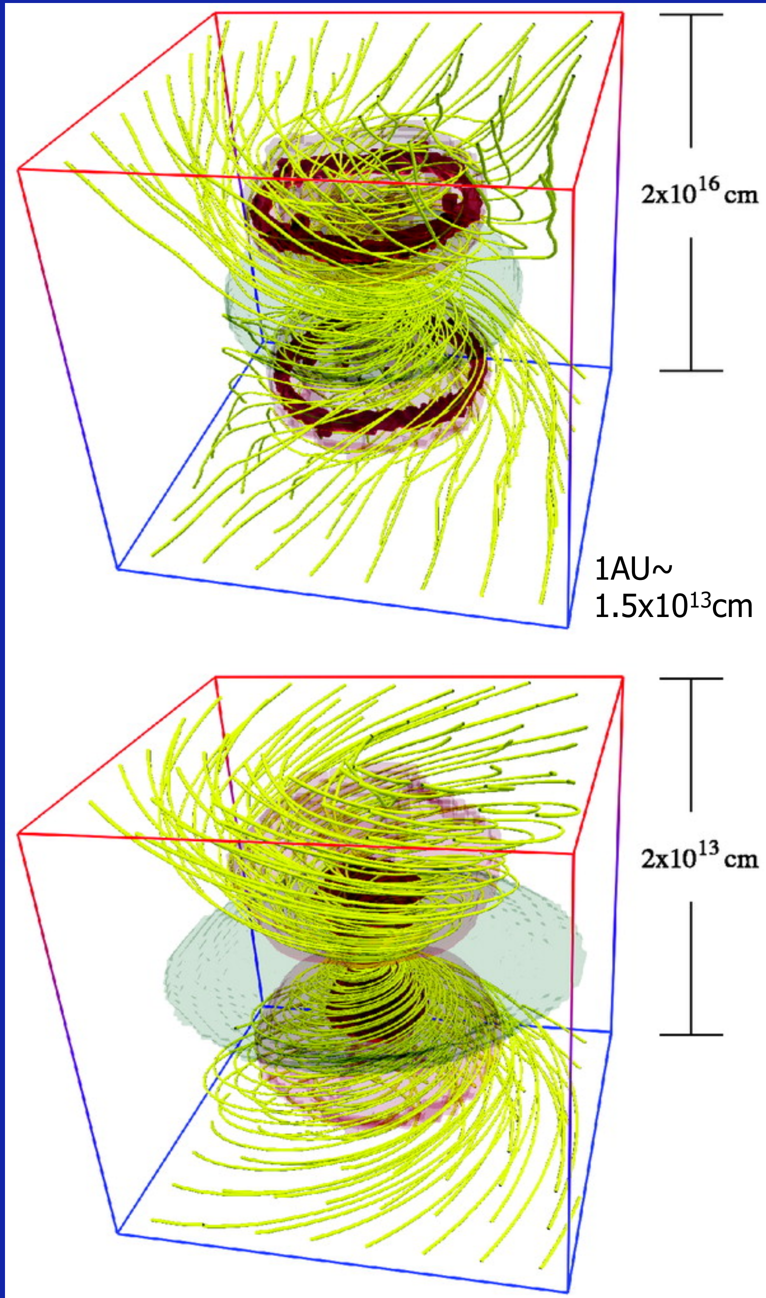


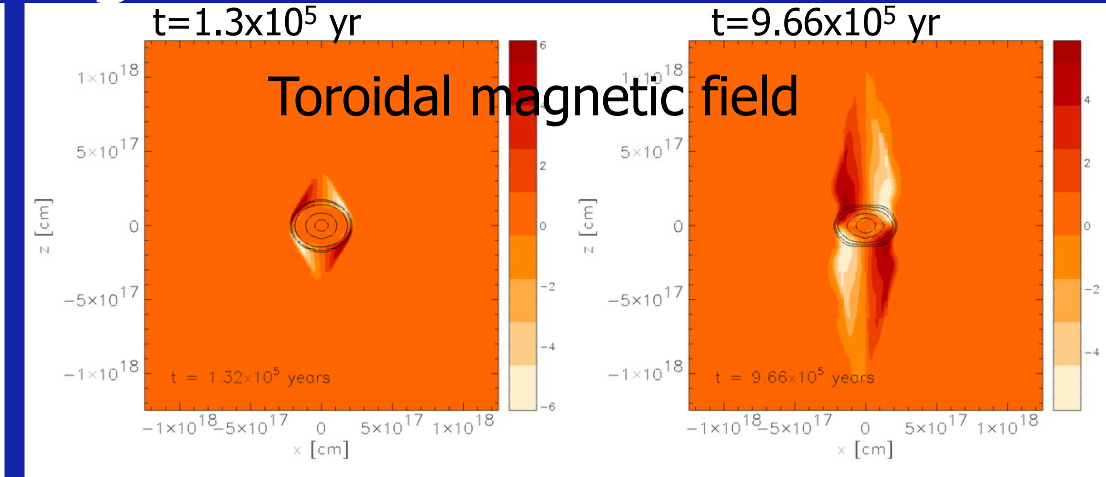


- Infalling core pinches magnetic field.
- If poloidal magnetic field component has angle larger 30° from vertical, centrifugal forces can launch matter-loaded wind along field lines from disk surface.
- Wind transports away from 60 to 100% of disk angular momentum.

Review: Pudritz et al. 2006

Jet-launching: Disk winds II



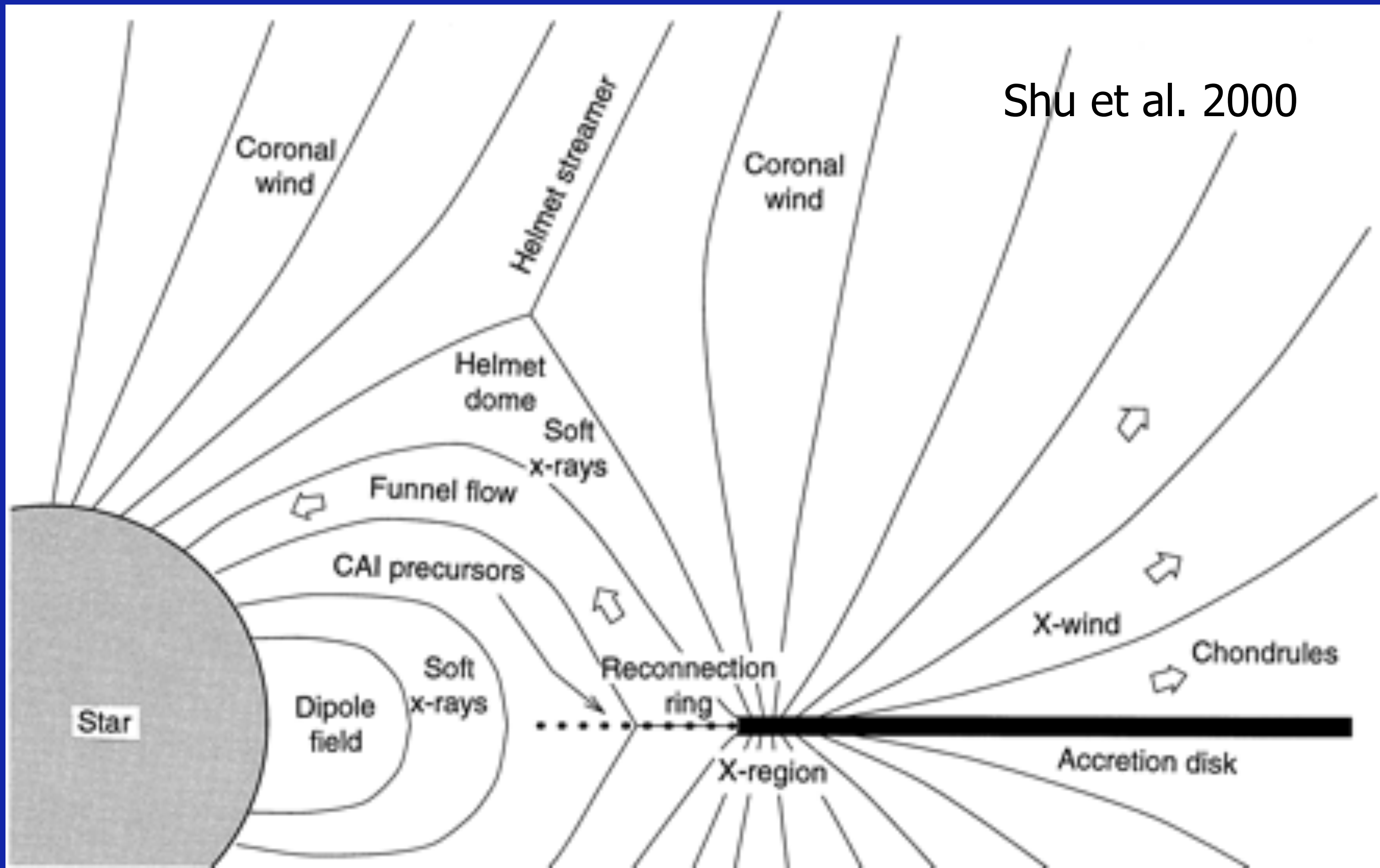


- On larger scales, a strong toroidal magnetic field builds up during collapse.

- 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

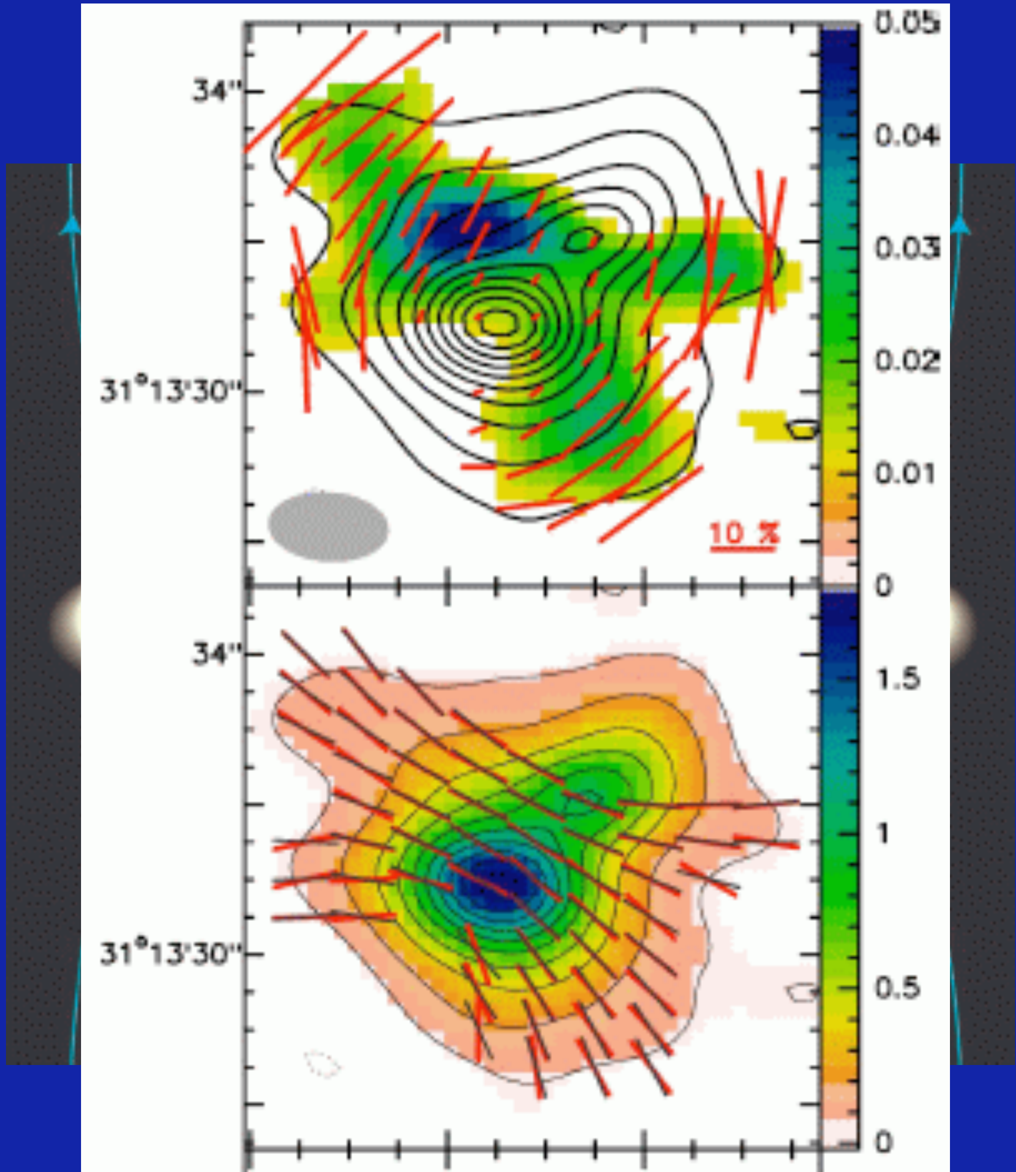
X-winds



Shu et al. 2000

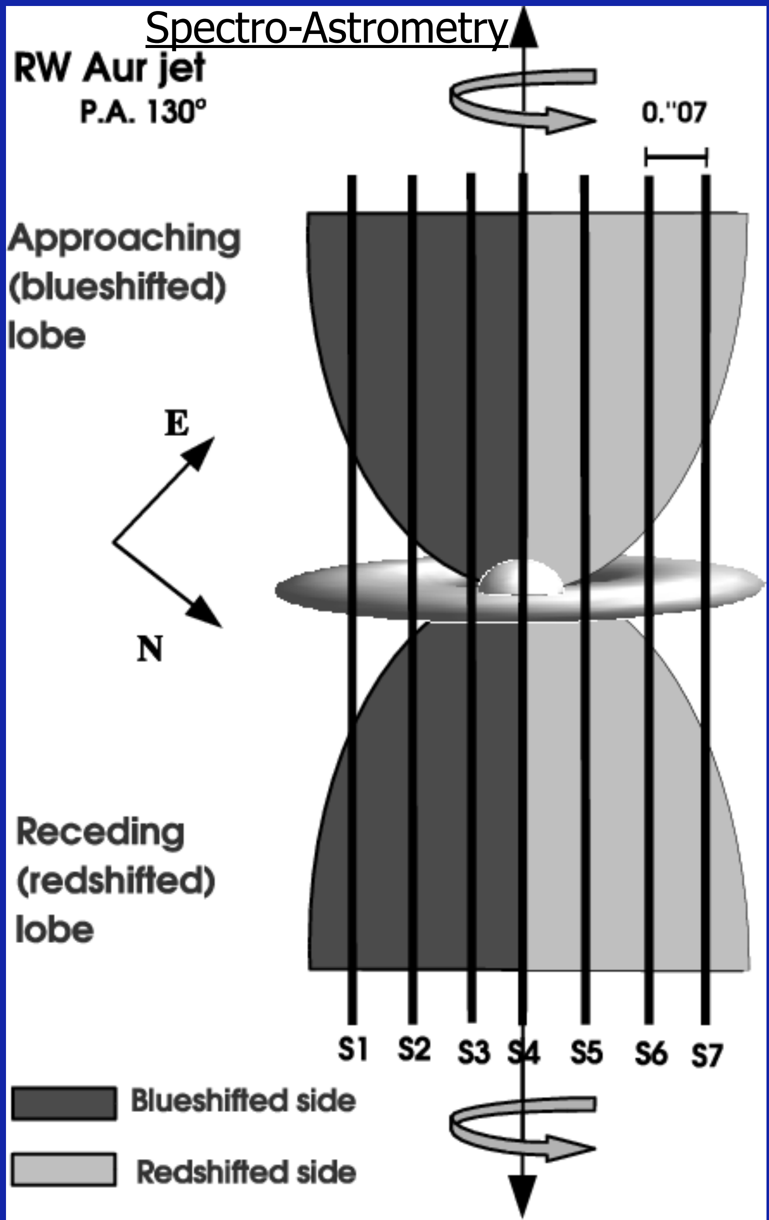
- The wind is launched magneto-centrifugally from the inner co-rotation radius of the accretion disk (~0.03AU)

Ambipolar diffusion

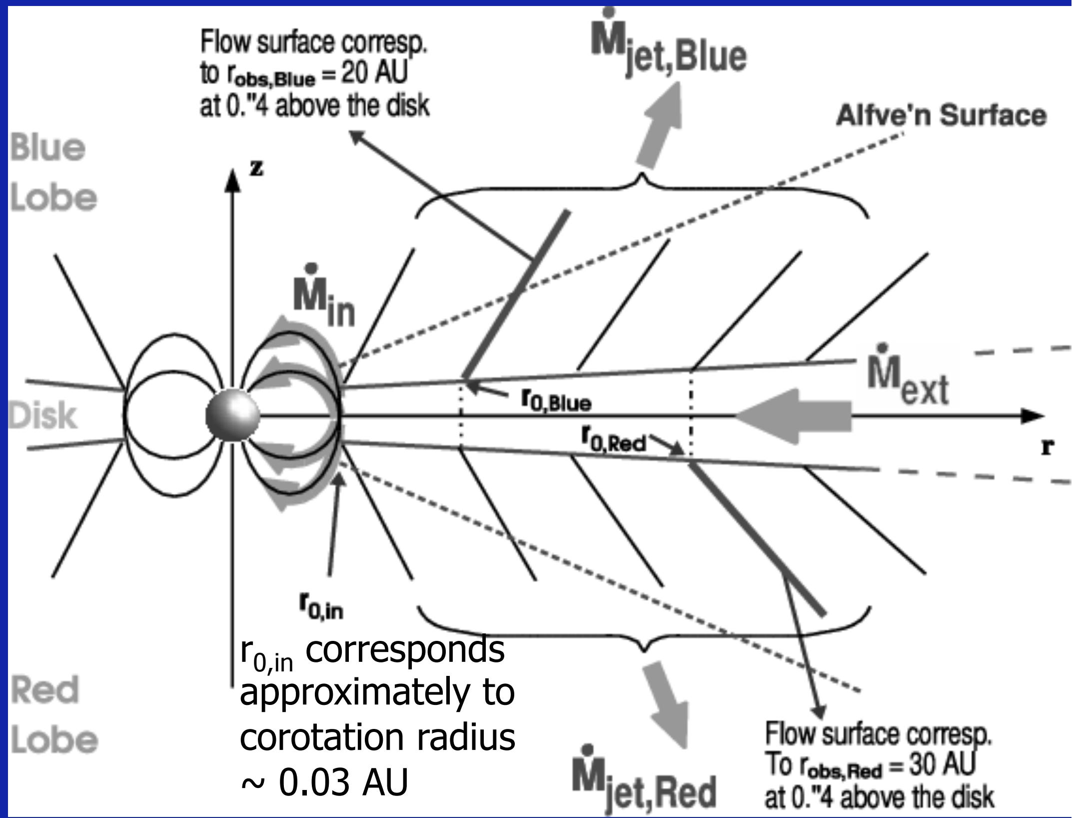


Girart et al. 2006

Jet-launching points and angular momenta



Woitas et al. 2005



- From toroidal and poloidal velocities, one infers 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.

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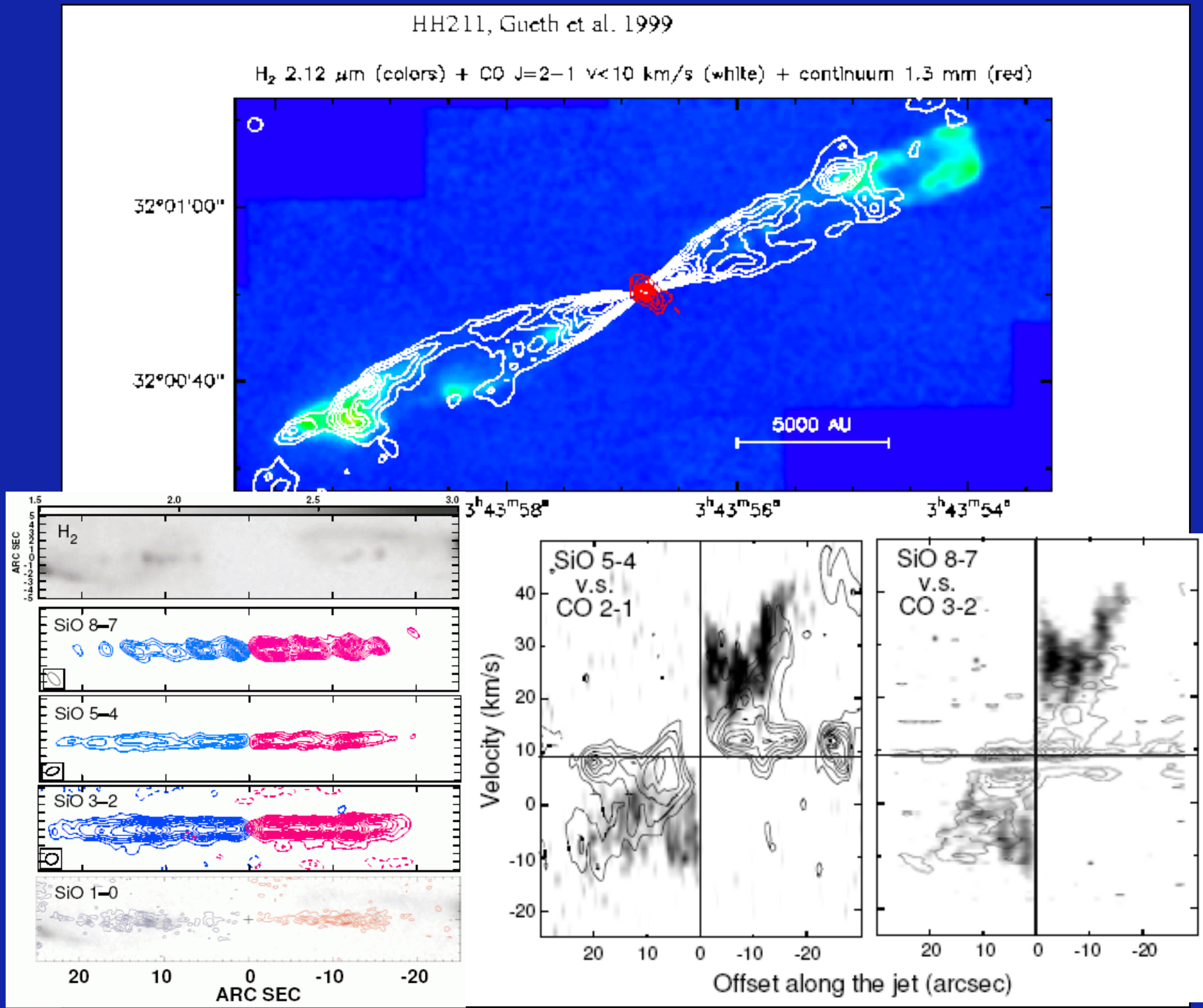
- Outflow entrainment models

- Additional observables to constrain outflow/jet properties

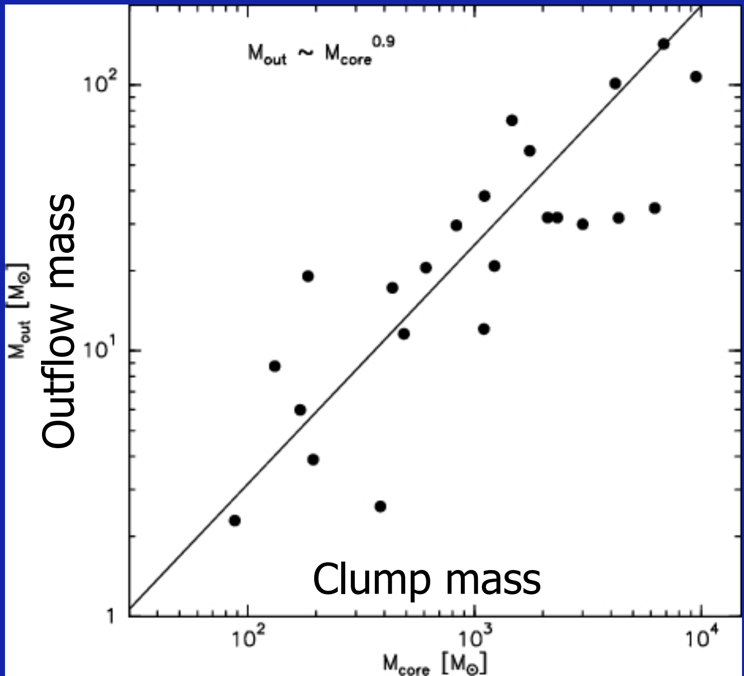
Driving jet and entrained molecular outflow

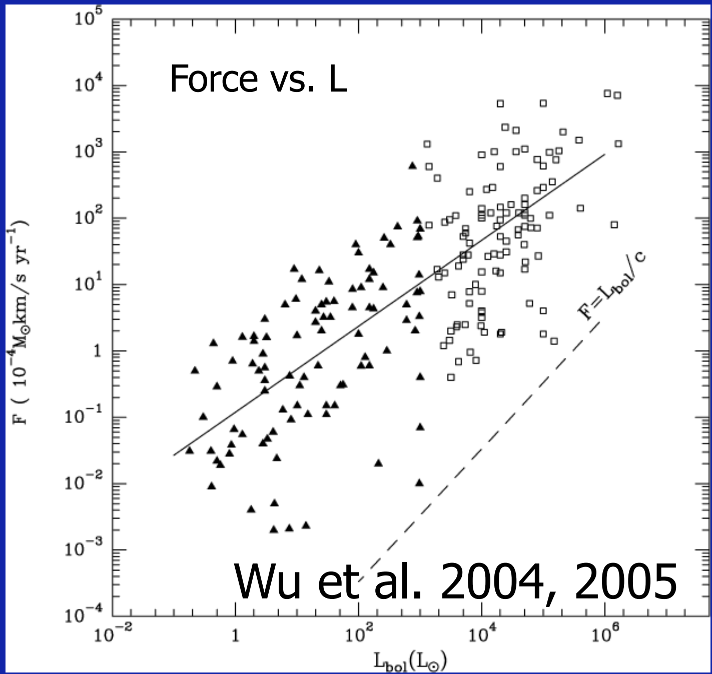


HH211, Gueth et al. 1999, Hirano et al. 2006, Palau et al. 2006

Outflow driving I

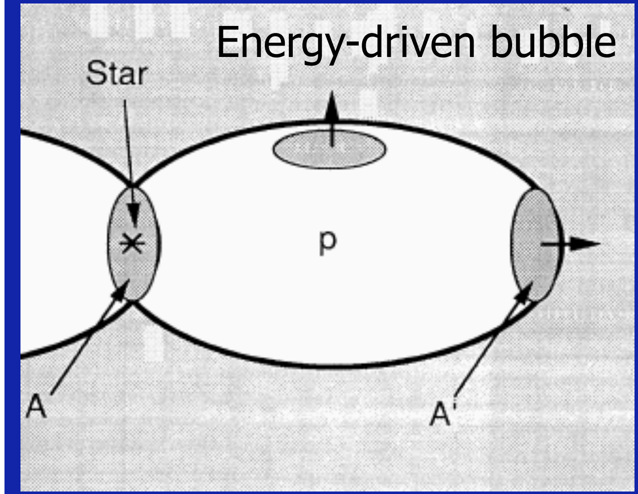
- Molecular outflow masses usually much larger than stellar masses
  → unlikely that outflow-mass directly from star-disk, rather swept-up entrained gas.
- Clump mass correlates with outflow mass.
- Force observed in outflow cannot be explained just by force excerted from central object → other outflow driving and entrainment processes required.





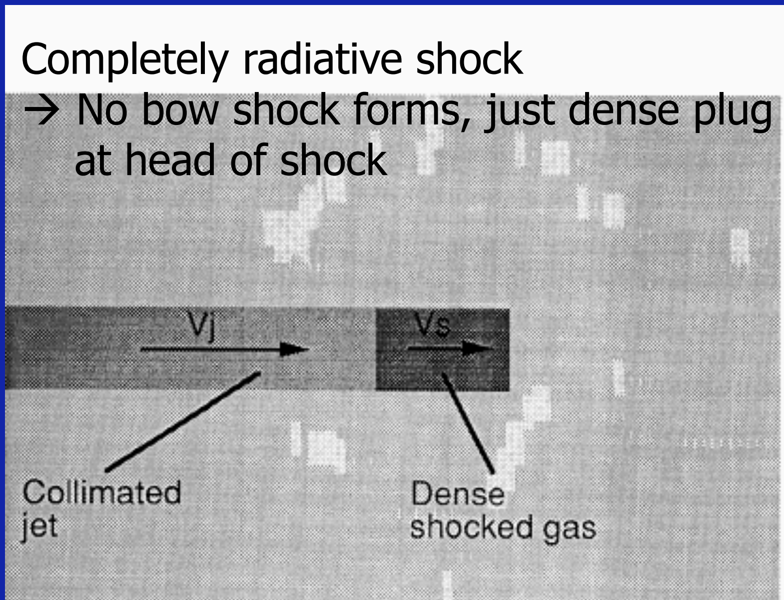
Outflow driving II

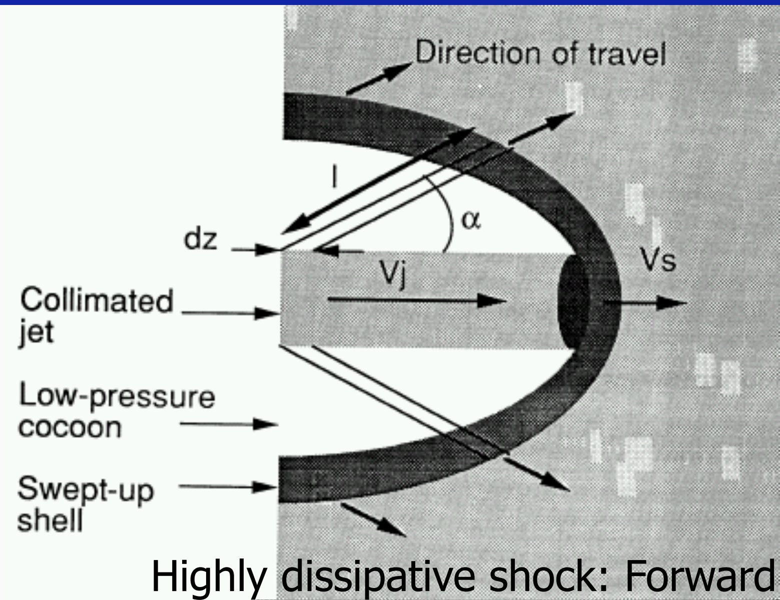
Momentum-driven vs. energy-driven molecular outflows



- In the energy-driven scenario, the jet-energy is conserved in a pressurized bubble that gets released adiabatically as the bubble expands. This would result in 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 shocks required → forward motion and bow shock!
→ This can accelerate the ambient gas!





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

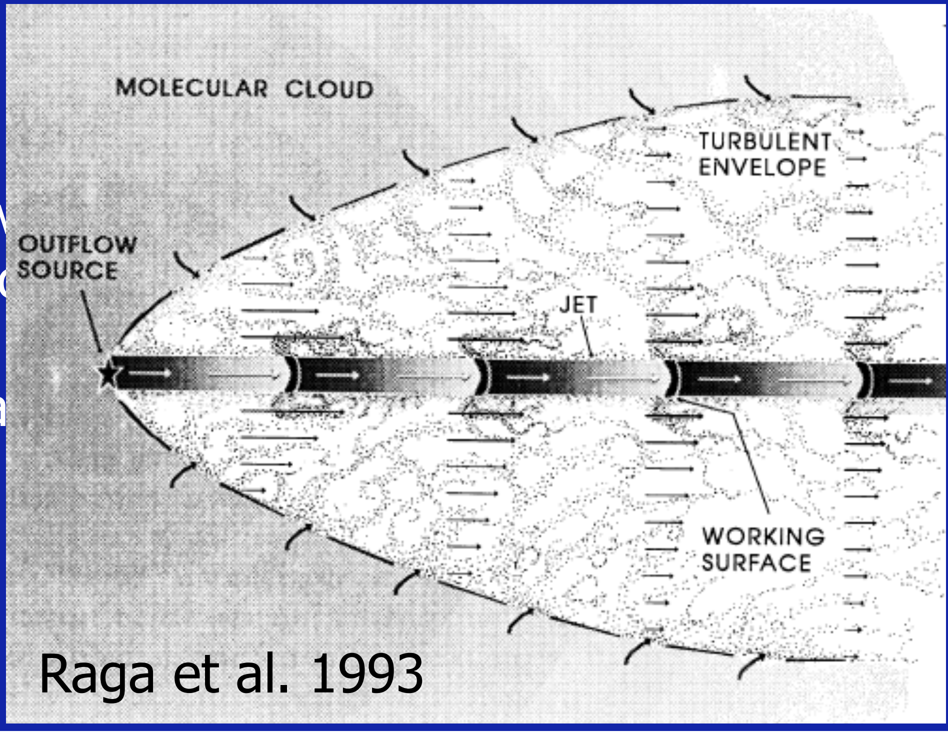
Masson et al. 1993

Outflow entrainment models I

Basically 4 outflow entrainment models are discussed in the literature:

Turbulent jet entrainment model
- 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

Jet-bow shock model
- As jet impact on ambient gas, bow
  pressure gas is ejected sideways,
  the ambient gas. Episodic ejection
- Numerical modeling reproduce ma



Raga et al. 1993

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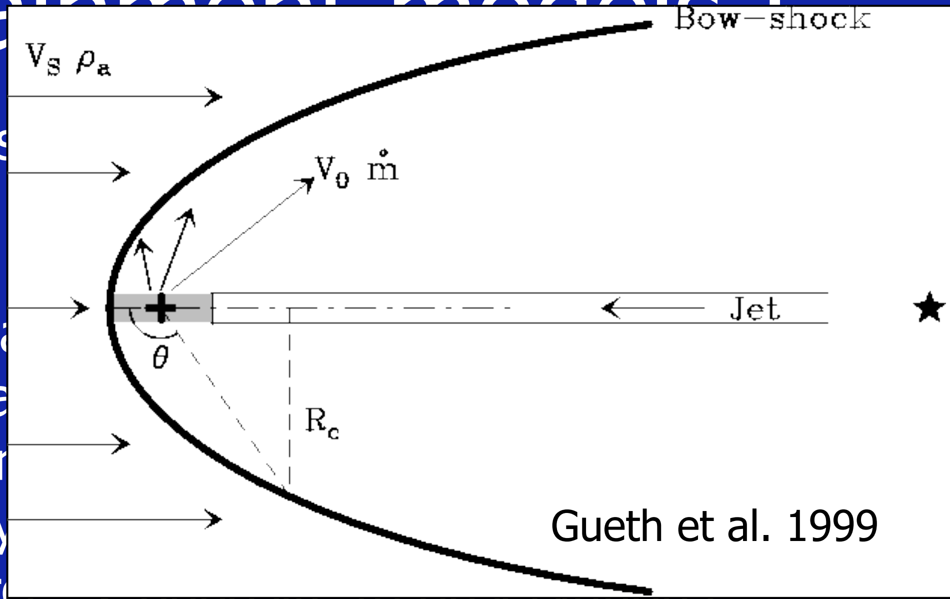
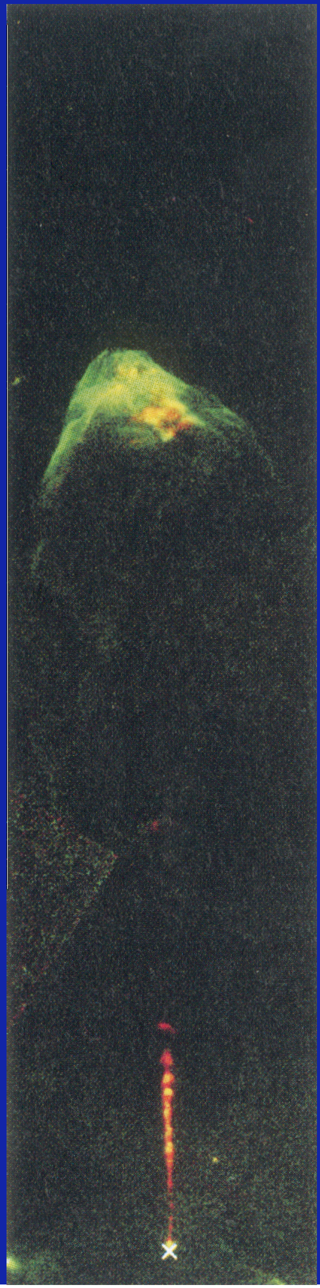


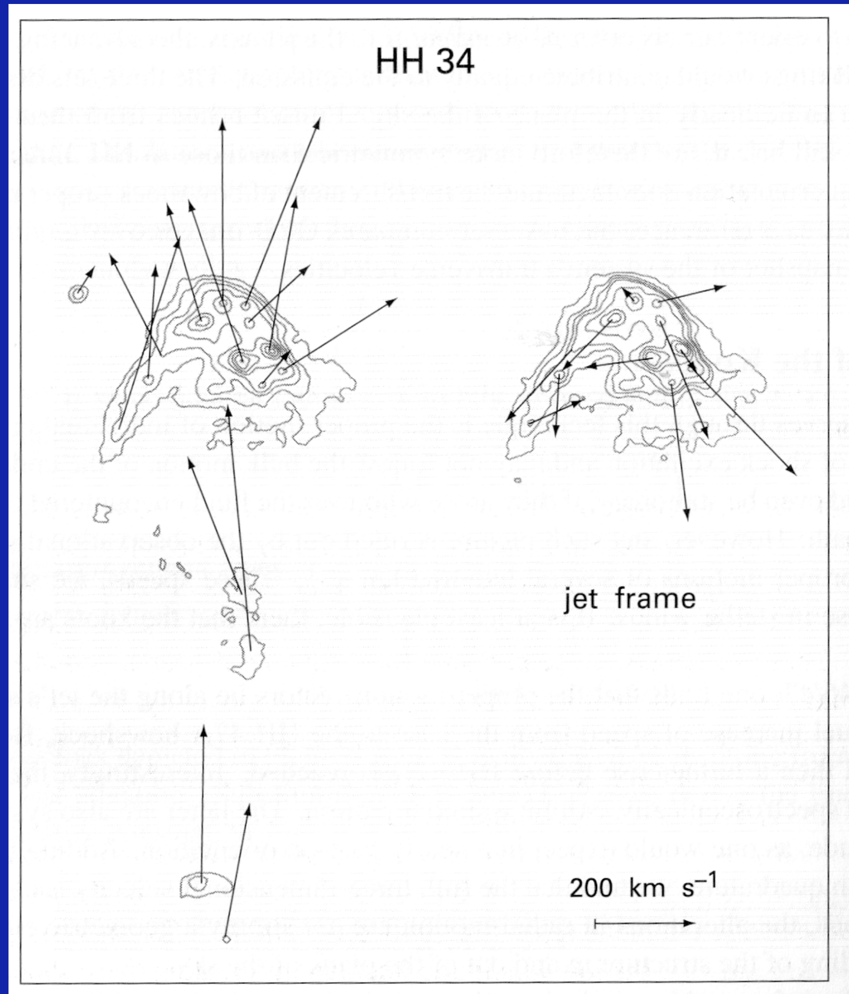
Gueth et al. 1999

Jet-bow shock model

- As jet impact on ambient gas, bow shocks are formed at head of jet. High pressure gas is ejected sideways, creating a broader bow shock entraining the ambient gas. Episodic ejection produces chains of knots and shocks.
- Numerical modeling reproduce many observables, e.g. Hubble-law.

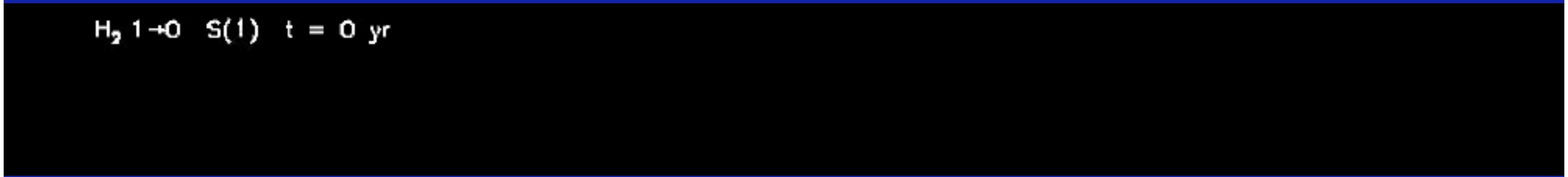
The case of the HH34 bow shock



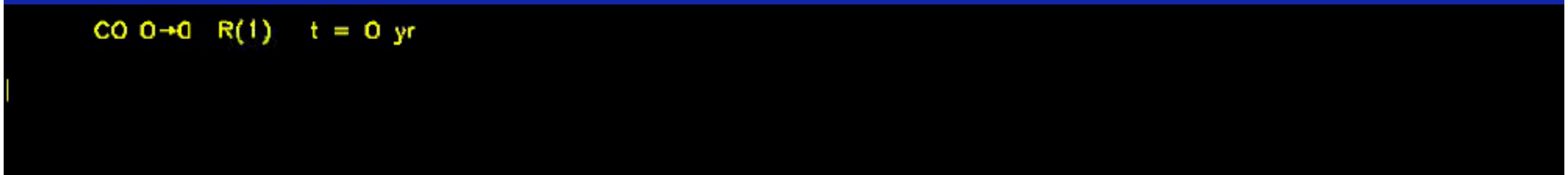


In the jet-frame, after subtracting the velocity of the mean axial flow, the knots are following the sides of the bow shock.

Jet simulations I

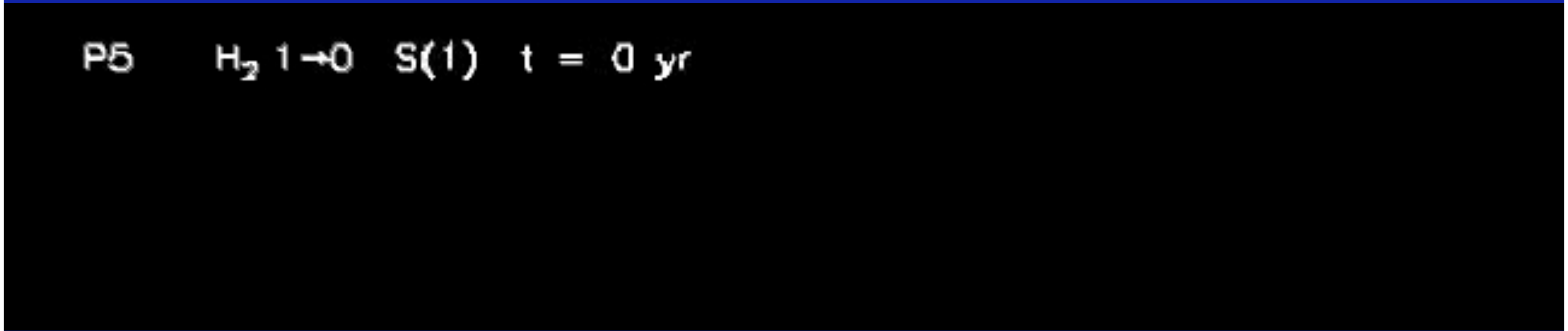


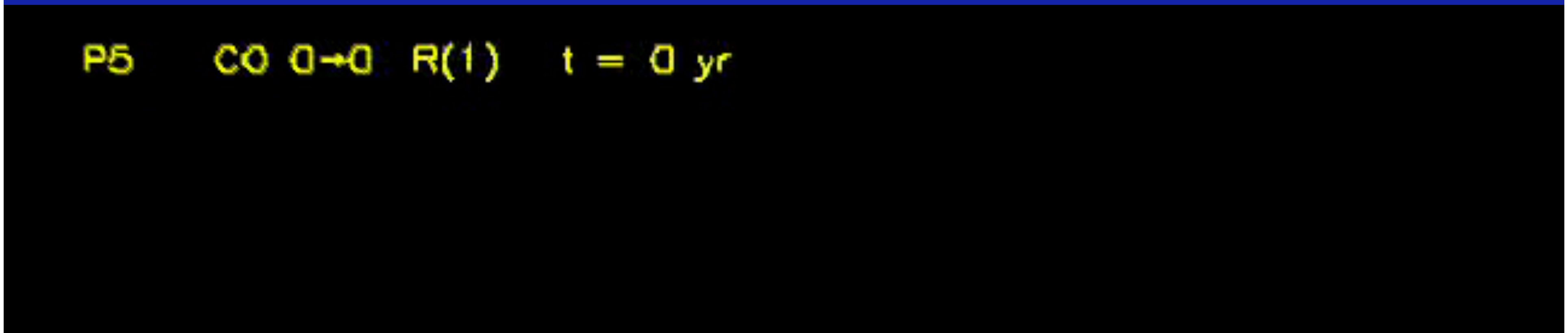
3-dimensional hydrodynamic simulations, including H, C and O chemistry and cooling of the gas, this is a pulsed jet.



Rosen & Smith 2004

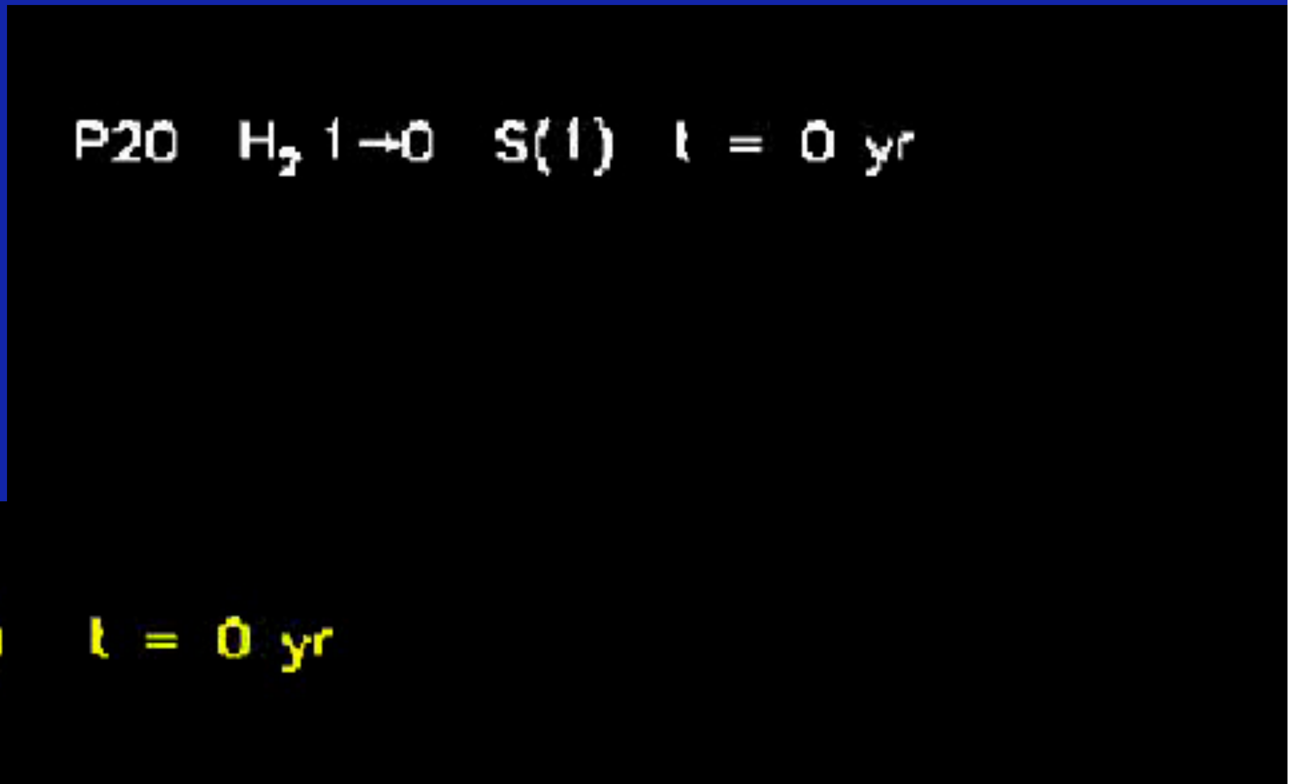
Jet simulations II: small precession

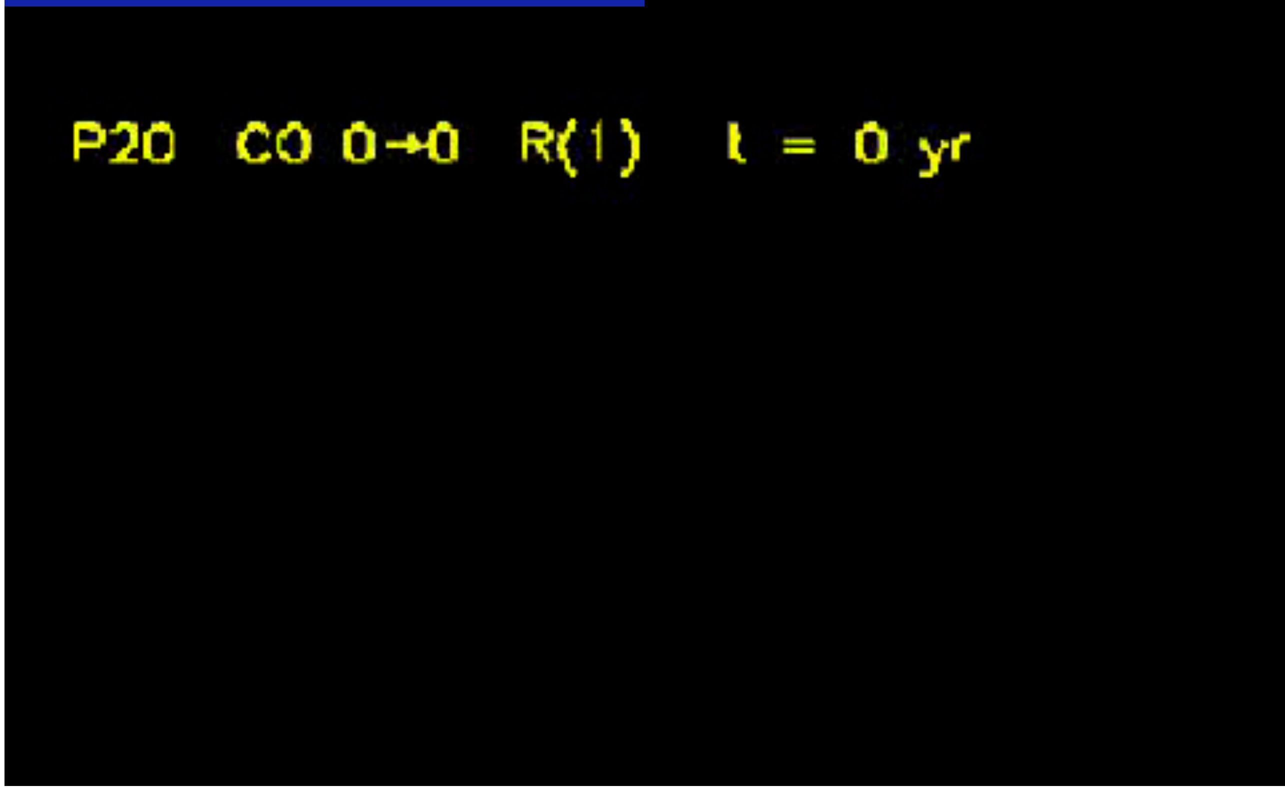




Rosen & Smith 2004

Jet simulations III, large precession





Rosen &
Smith 2004

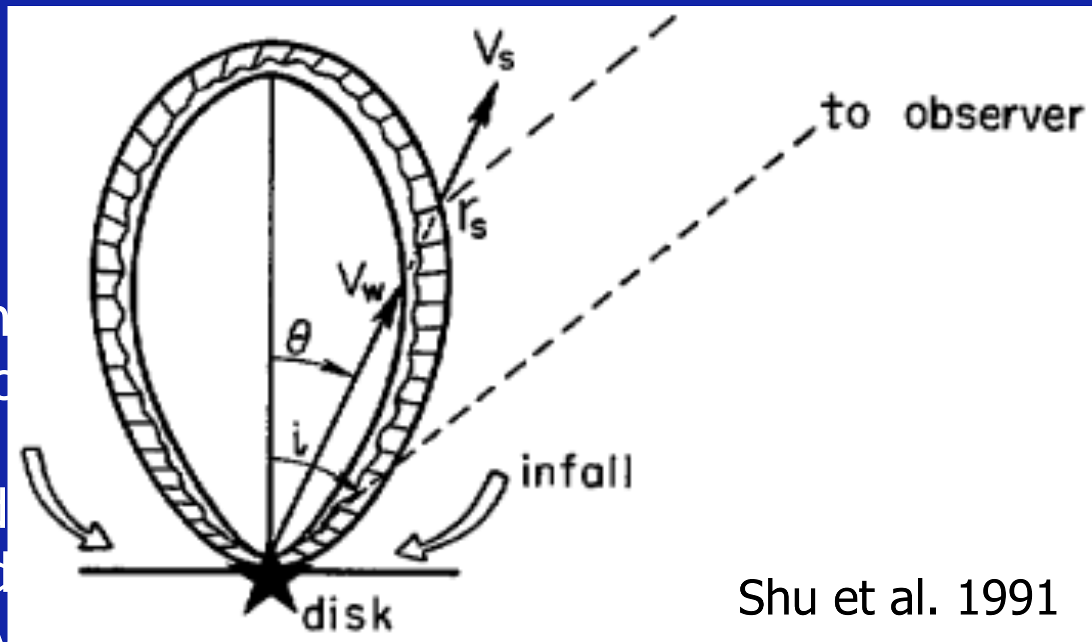
Outflow entrainment models II

Wide-angle wind model

- A wide-angle wind (a disk-wind from larger disk-radii resulting naturally in lower velocities and lower collimations degree) blows into ambient gas forming a 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.

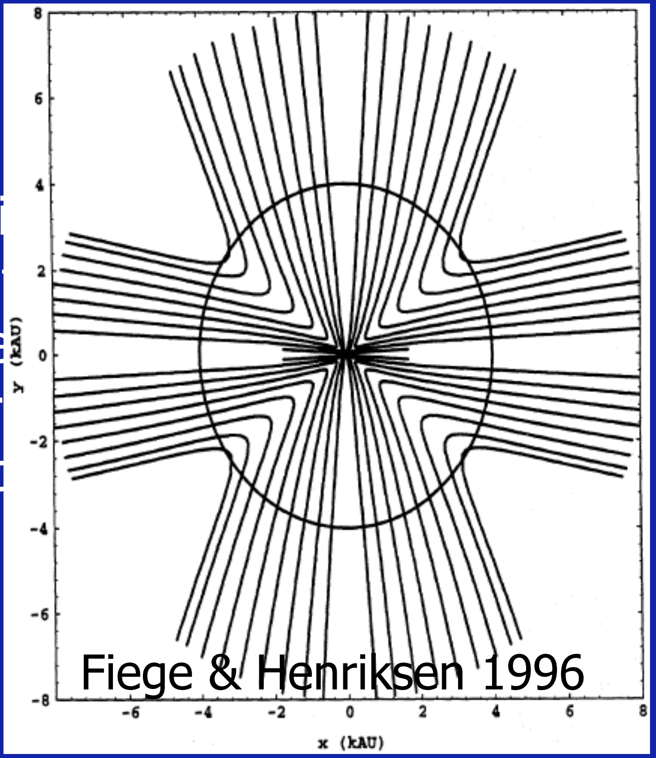
Circulation model

- Molecular gas is not entrain
  infalling gas that was deflec
  of high MHD pressure.
- This models were proposed
  it was originally considered
  Maybe not necessary today anymore ...



Shu et al. 1991

Outflow entrainment models II



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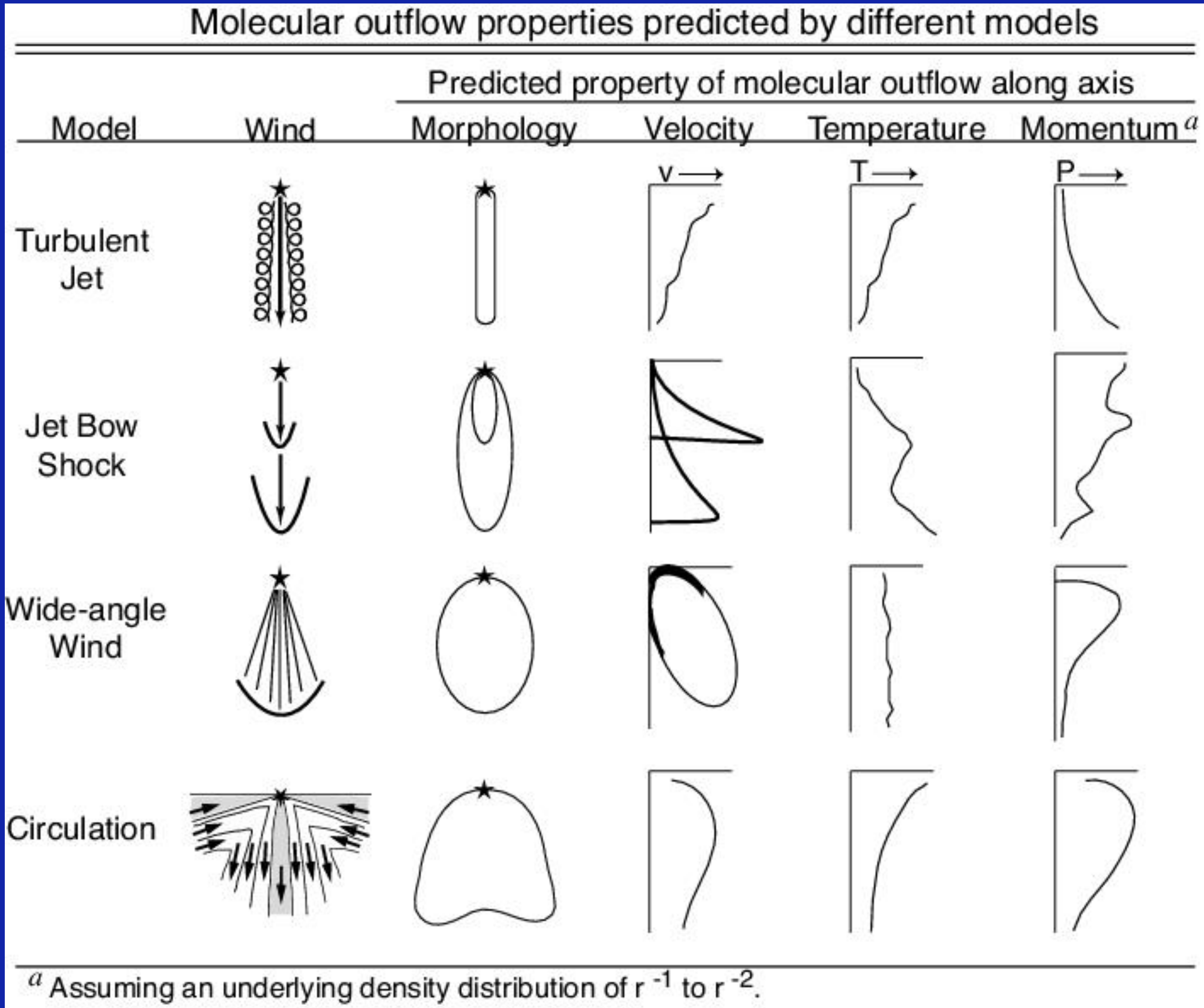
- Attractive models for older and low collimated

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 models were proposed to explain also massive outflows because it was originally considered difficult to entrain that large amounts of gas. Maybe not necessary today anymore …

Outflow entrainment models III



Arce et al. 2002

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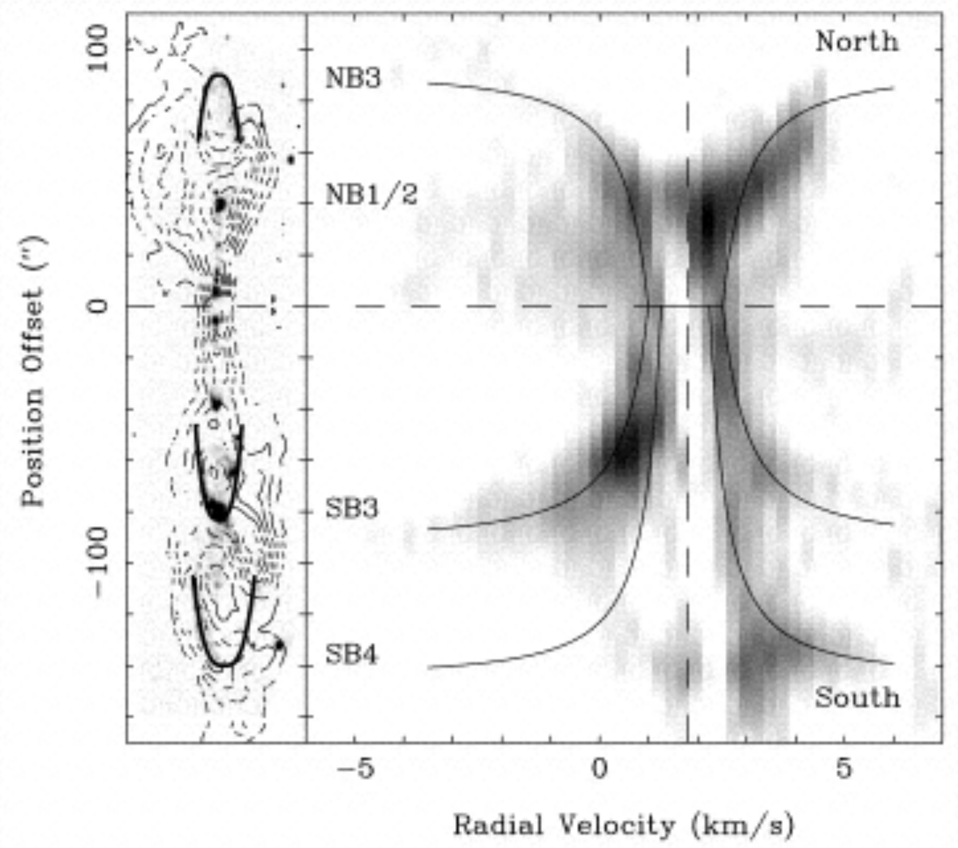
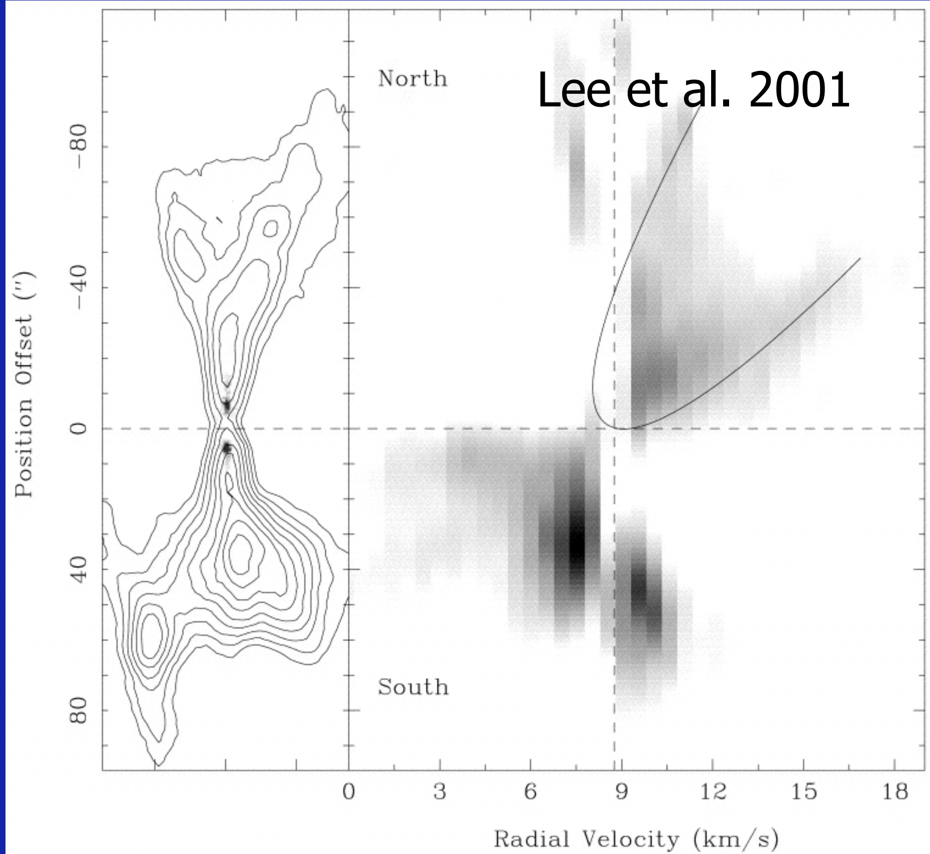
Collimation and pv-structure

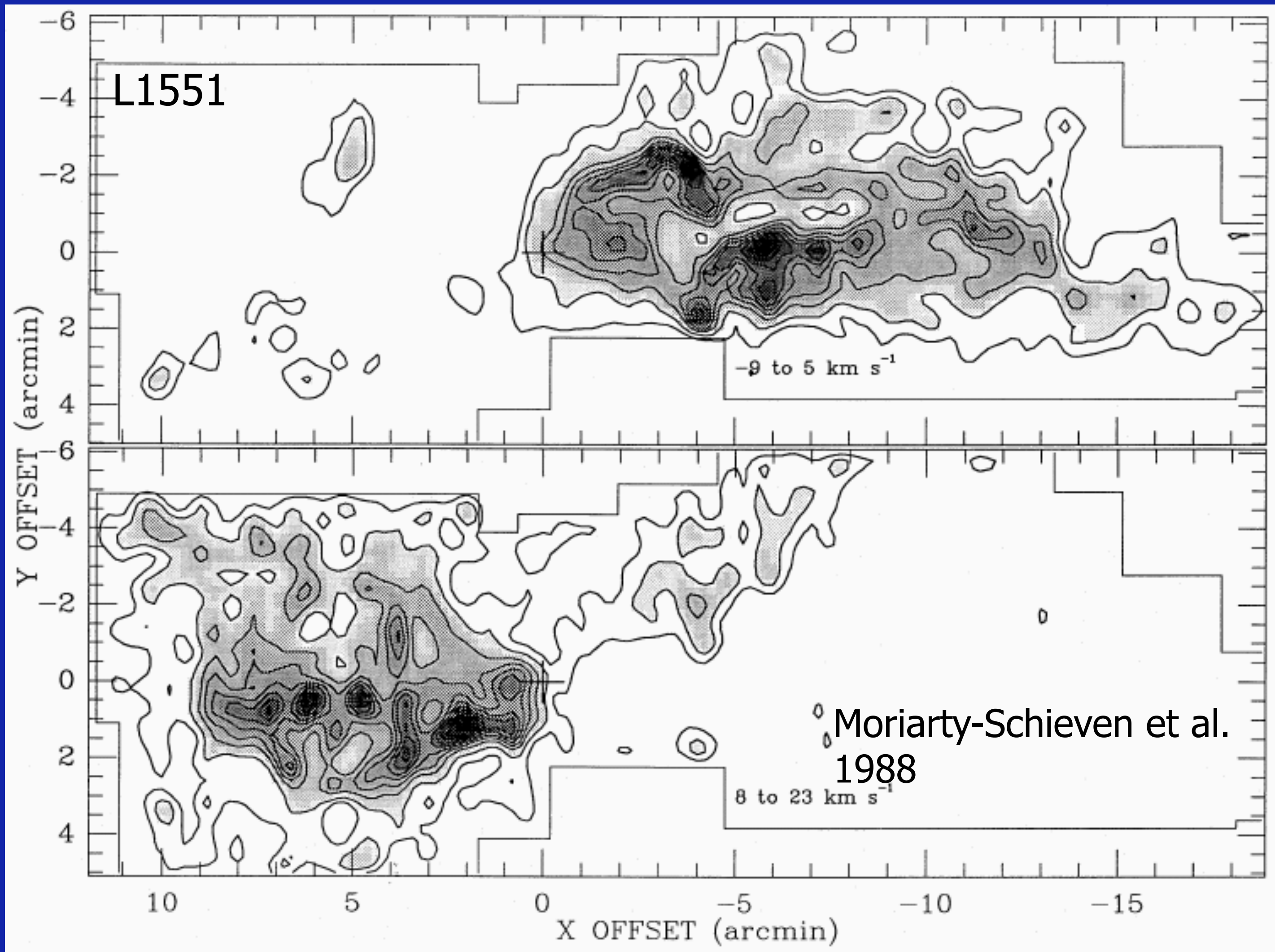




HH212: consistent with jet-driving VLA0548: consistent with wind-driving

- pv-structure of jet- and wind-driven models very different.
- Often Hubble-law observed → increasing velocity with increasing dist. from protostar
- Hubble-law maybe explained by: (a) decreasing grav. potential with distance to star (for central jet), (b) decreasing density gradient and hence pressure with distance from star (for larger-scale outflow), (c) continuous (or episodic) driving of the jet in a non-ballistic fashion that energy constantly gets induced in jet.

Episodic ejection events and bullets



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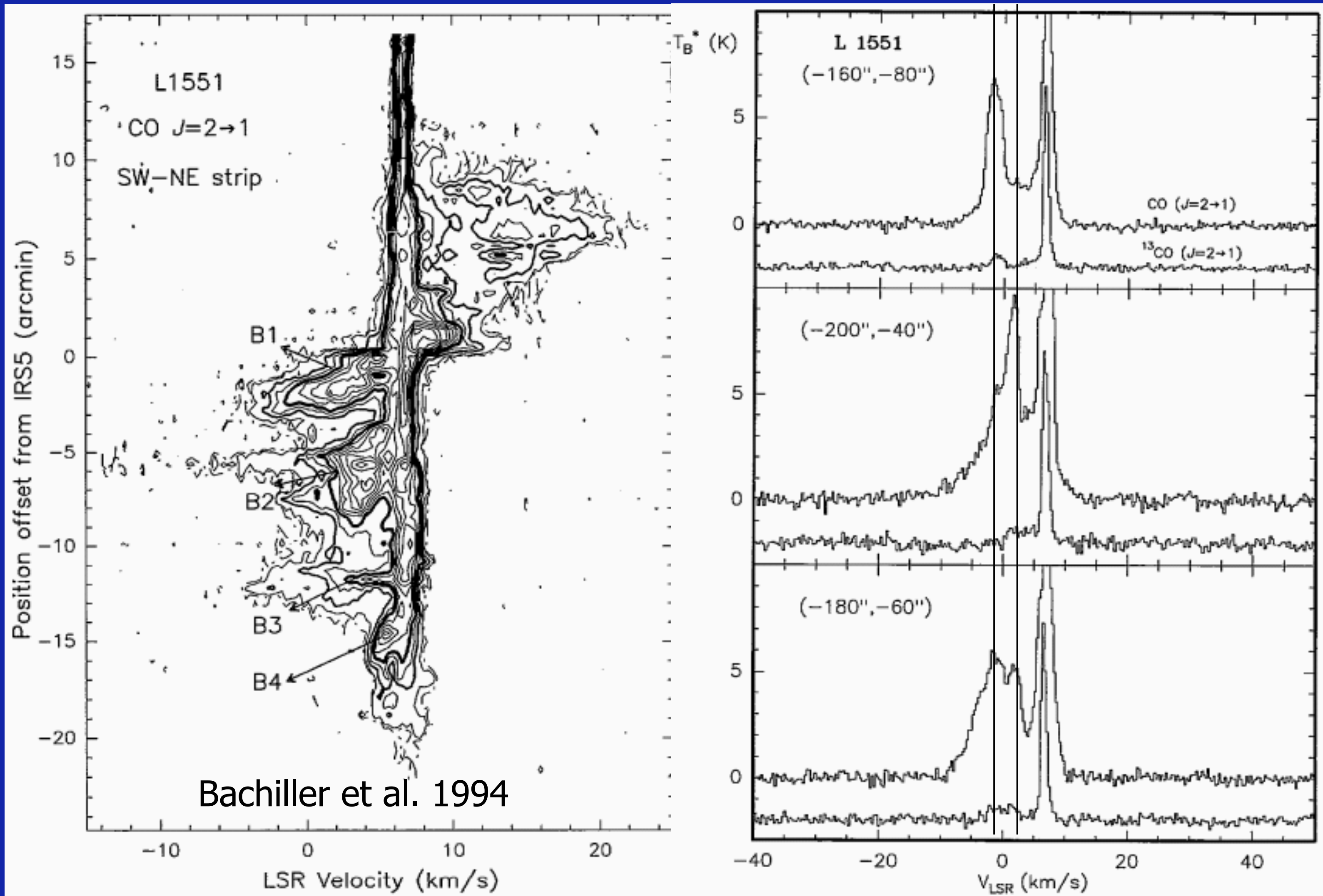
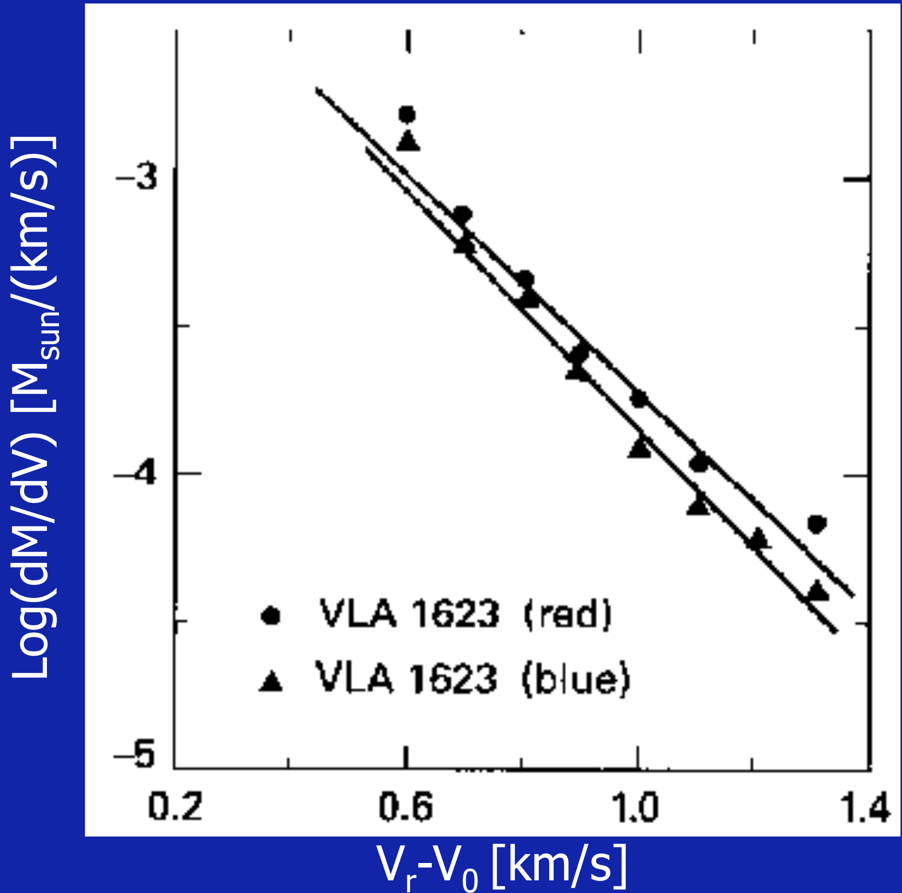
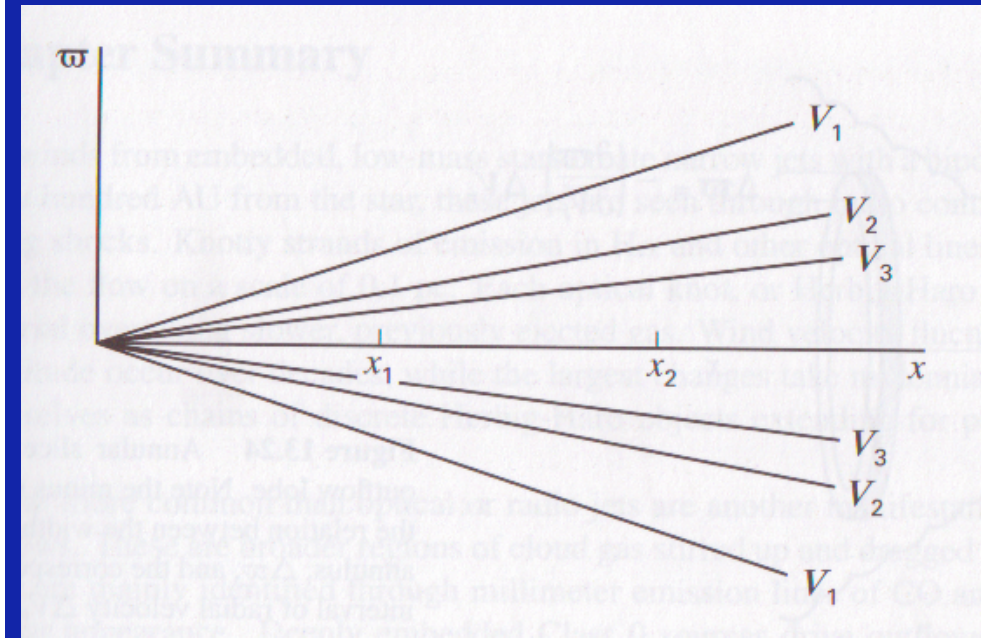


Cut along the jet-axis

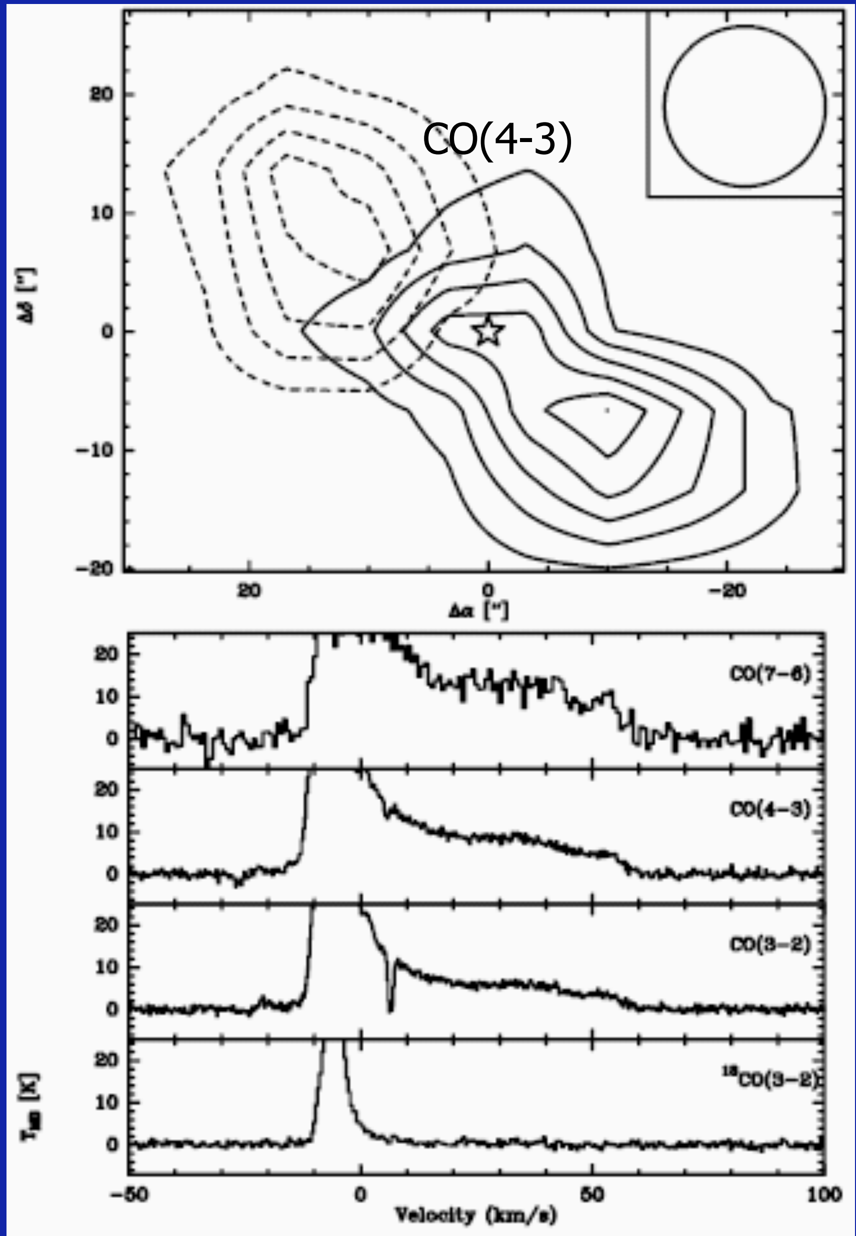
Mass-velocity relation



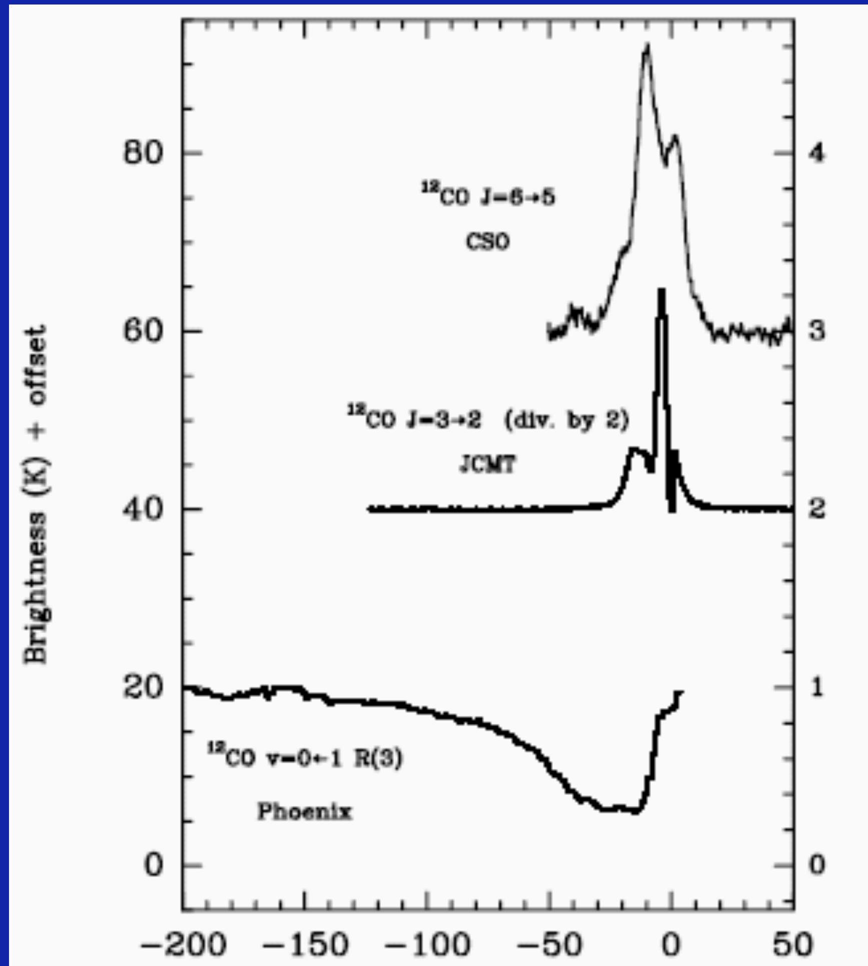


- The mass-velocity relation usually displays a power-law.
- In the jet-entrainment model this can be explained by the successively larger annulli of the lower-velocity, entrained outer gas layers.
- Different power-laws and power-law breaks have been observed. This can be attributed to varying inclination angles and also periodicity.

Highest velocity molecular gas



NGC6334I, Leuirni et al. 2006, T>50K



AFGL2591, van der Tak et al. 1999

Summary

- Protostellar jets are launched magnetohydrodynamically from the disk and then accelerated magneto-centrifugally.

- Outside the Alfven radius r_A (kin. energy equals magn. energy) B_ϕ dominates and collimation happens via Lorentz-force.

- Jet-launching discussed as disk-wind or X-wind. Observations support disk-wind scenario (although X-wind can be considered as special case of disk-wind at the inner disk-truncation radius).

- Various outflow-entrainment models, jet-entrainment and wide-angle wind are likely the two most reasonable mechanisms.

- Outflows/jets are likely episodic.

- Observational tools like pv-diagrams, mv-diagrams and various different jet/outflow tracers allow us to constrain the models.

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