Observational ISM and Star Formation

This Class (Lecture 12):
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Stacey Alberts

Next Class:

William Kormos /Jana Bilikova

Music: *The Space Race is Over* – Billy Bragg

Talks

Astro Colloquium:

Control of Star Formation by Gravitational Instability in Disk Galaxies

Mordecai Mac-Low,
American Museum of Natural History

Tuesday 1600: Astro Classroom

Outline

- Collapsing with other features
- The role of rotation
- Outflows, outflows, outflows

Other Collapse Models

- Other solution: Larson (1969) and Penston (1969), furthered by Hunter (1977)
  - Starts with a uniform density that evolves toward a SIS
  - Solution details also gives r^{-2} outside and $r^{-3/2}$ inside, but NOT inside-out collapse
  - Mass accretion is not constant, velocity is not free-fall, and density structure evolves differently
- Numerical solutions show that there is a continuum of solutions that are bracketed by LP and Shu solutions (Whitmore & Summers 1985; Hunter 1986).
- However, most solutions are more similar to LP than Shu.

Other Collapse Models

- Foster & Chevalier (1993) used numerical models starting with a critical Bonner-Ebert Sphere
  – Higher infall rate than in SIS model, but it decays substantially with time.
  – More resembles LP solution
  – Overall collapse occurs more quickly

Still Missing?

- Non-isothermality
- Magnetic fields
  – e.g. "Protostar Formation in Magnetic Molecular Clouds beyond Ion Detachment" Tassis & Mouschovias (2007) + many other Mouschovias et al.
  – e.g. "Collapse of Magnetized Molecular Cloud Cores" Galli & Shu (1993/2006)
- Rotation
  – e.g. "The collapse of the cores of slowly rotating isothermal clouds" Terebey, Shu, & Cassen (1984)

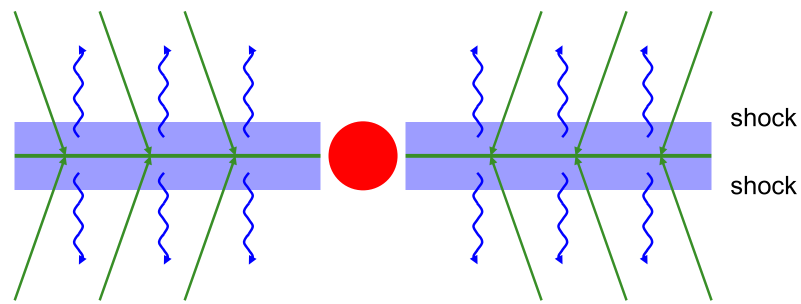
Rotation

- Infalling gas-parcel falls *almost* radially inward, but close to the star, its angular momentum starts to affect the motion.
- For given shell (i.e. given r_0), all the matter falls within the centrifugal radius r_c onto the midplane.

$$r_c = \frac{\Omega^2 r_0^4}{GM}$$

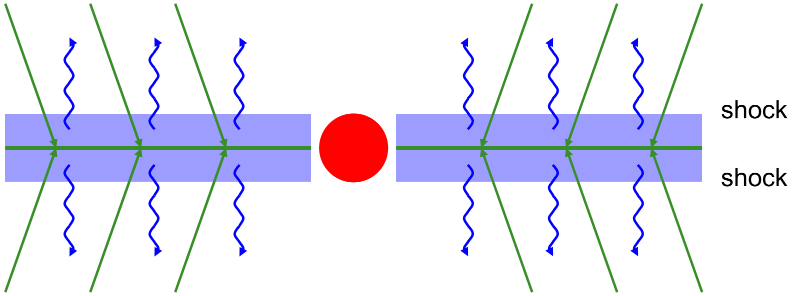
  – If $r_c < r_*$, then mass is loaded directly onto the star
  – If $r_c > r_*$, then a disk is formed
- In Shu model $r_o \sim t$ so $r_c \sim t^4$
- In TSC model, $r_c \sim t^3$

Disk Formation



- Symmetric argument suggests that flows above and below the plane collide
- Infalling gas passes through a shock at the equator
- Kinetic energy ⊥ to equator dissipates

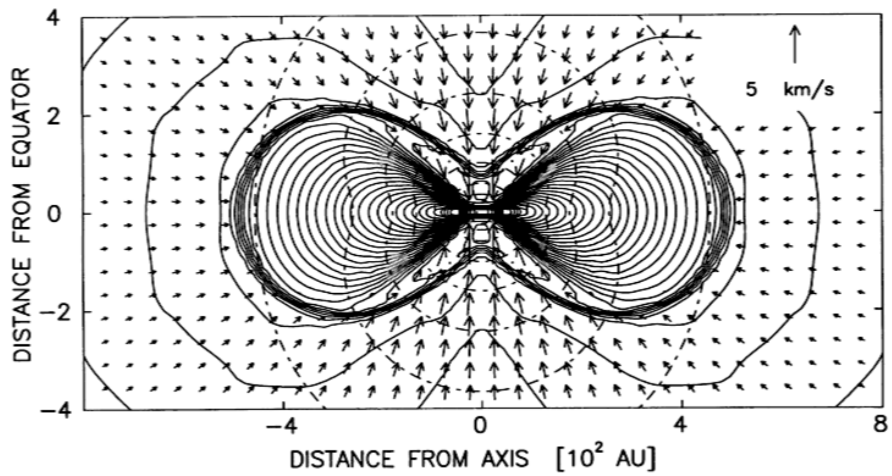
Disk Formation



- If cools rapidly, then material accumulates in a thin structure
- In general, the left over velocity in that plane is not circular, so material mixes
- Further dissipation of energy and angular momentum transport must occur before circular motions

3-D Radiation-Hydro Simulations

3-D Radiation-Hydro simulations of disk formation



Yorke, Bodenheimer & Laughlin 1993

Angular Momentum Problem

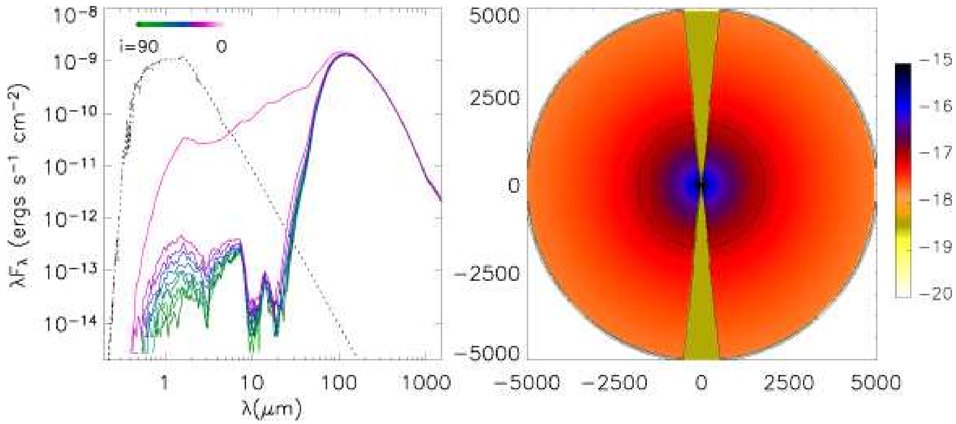
- Angular momentum of 1 $M_\odot$ in 10 AU disk:
  $3x10^{53}$ cm^2/s
- Angular momentum of 1 $M_\odot$ in 1 $R_\odot$ star:
  $\ll 6x10^{51}$ cm^2/s (= breakup-rotation-speed)
- Original angular momentum of disk = 50 × higher than maximum allowed for a star
- Two possible solutions:
  - Torque against external medium (via magnetic fields?)
  - Very outer disk absorbs all angular momentum by moving outward, while rest moves inward.

Need *friction through viscosity*!

Ongoing Collapse/Accretion

- Friction within the disk causes matter to accrete onto the star
- Jets are often launched from the inner regions of these disks
- A jet penetrates through the infalling cloud and opens a cavity

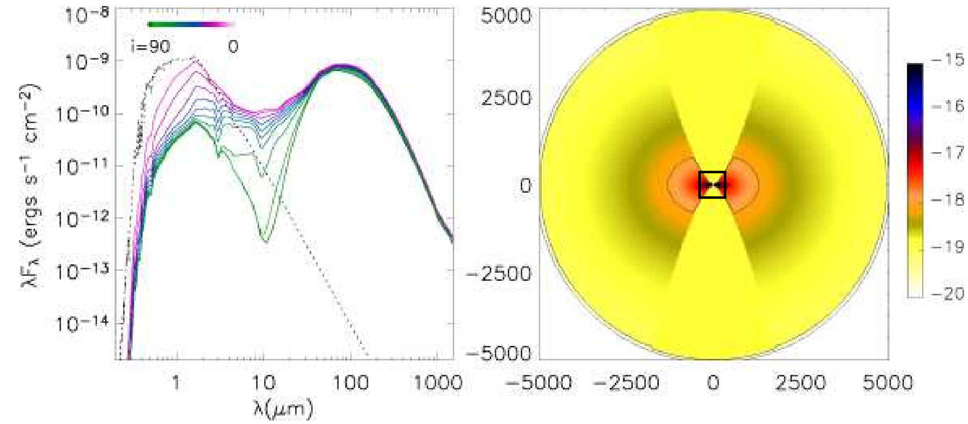
Collapsing Cloud + Star + Disk



Class 0

Whitney et al. 2003

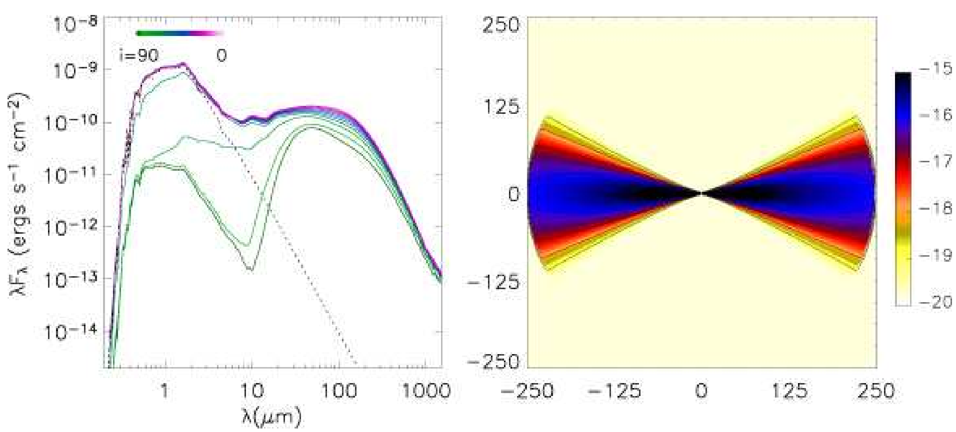
Collapsing Cloud + Star + Disk



Class I

Whitney et al. 2003

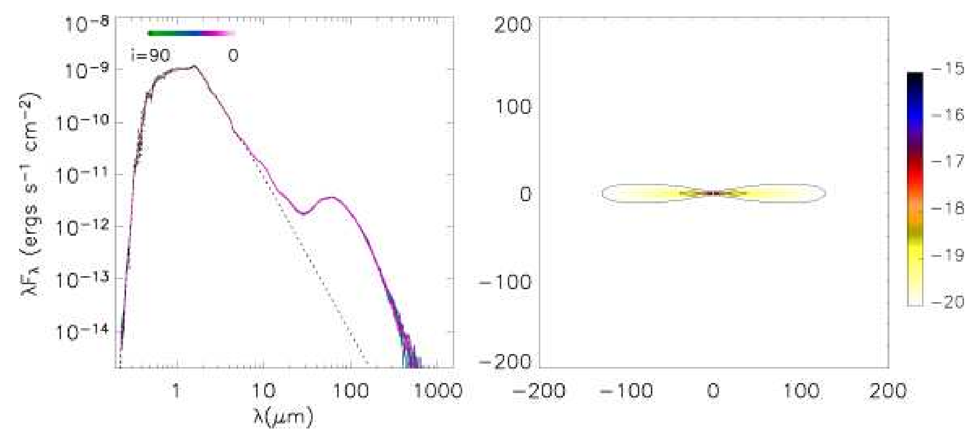
Collapsing Cloud + Star + Disk



Class II

Whitney et al. 2003

Star + Disk

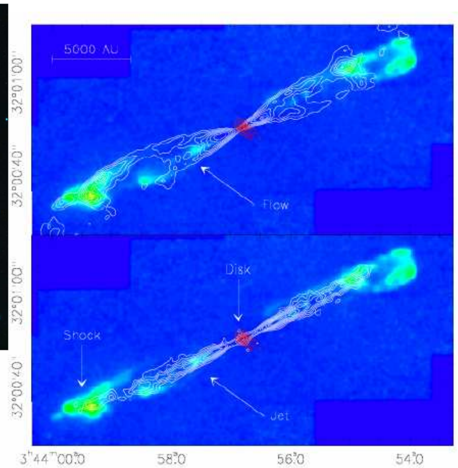


Class III

Whitney et al. 2003

Outflows

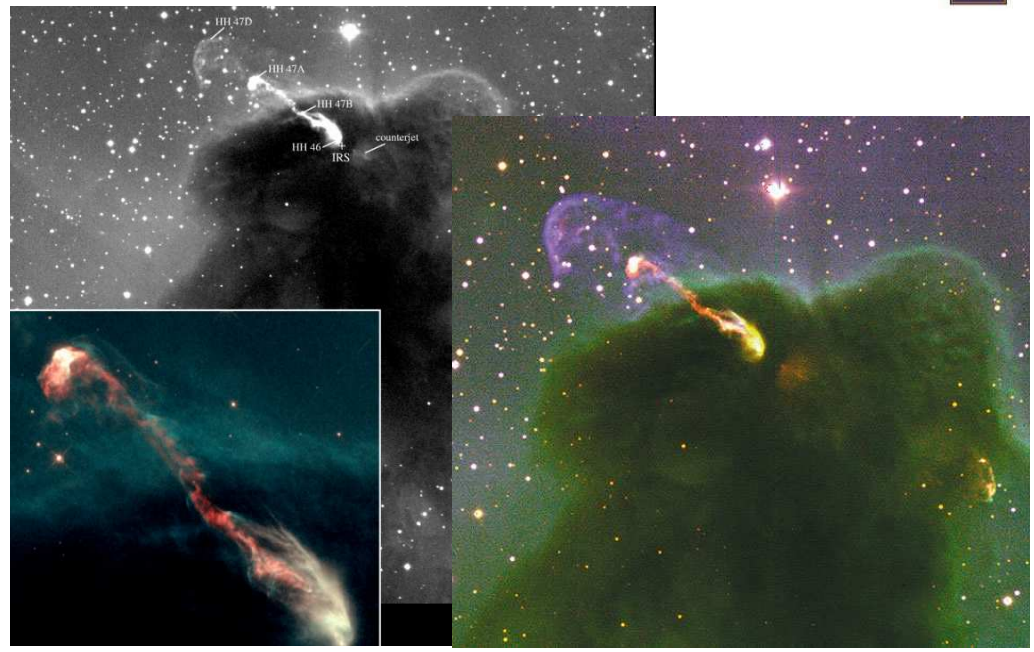
NGC 1333 in IRAC Band 3 (H_2)

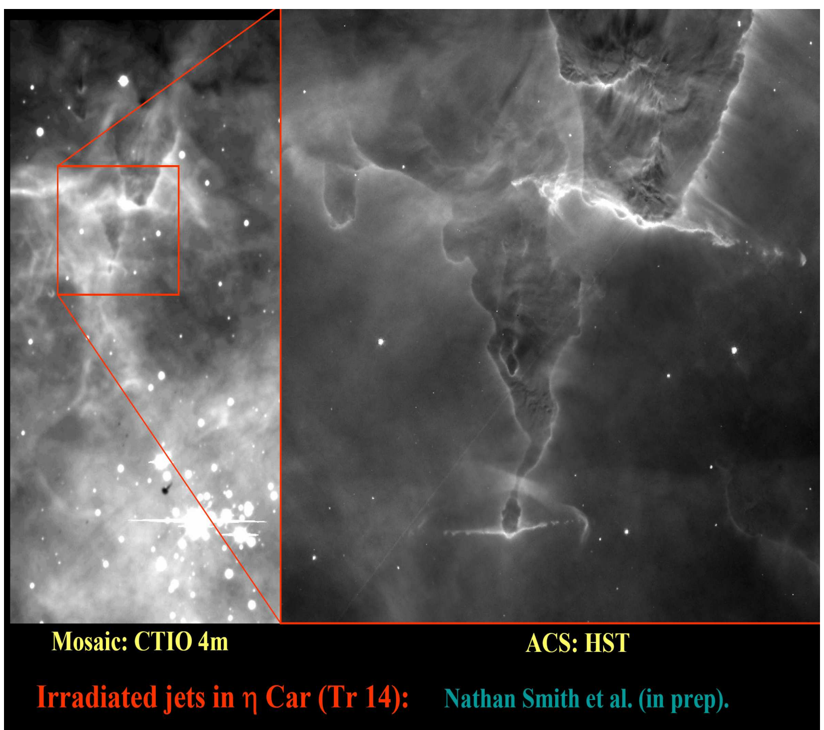


HH211: CO in contours, H_2 in color scale.

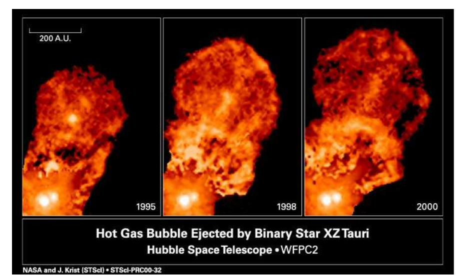
Outflow momentum is *substantial*, can alter clouds

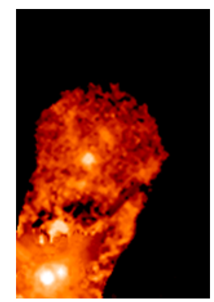
From the Holes in Heaven

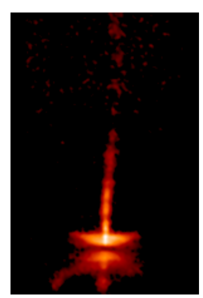


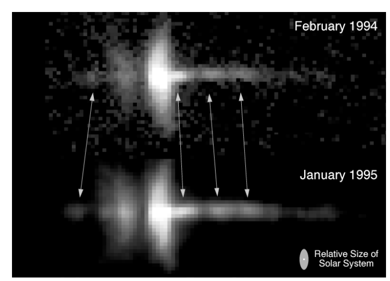


Outflowing Gas Is Variable

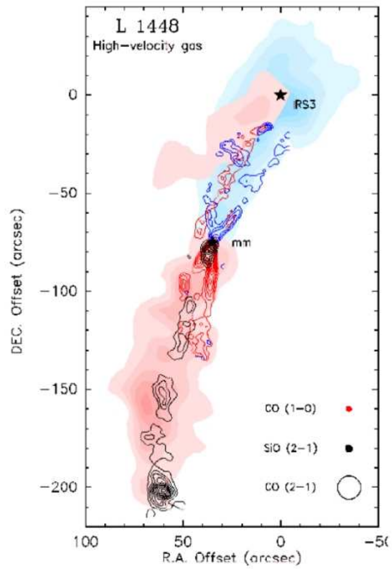








Molecular Gas

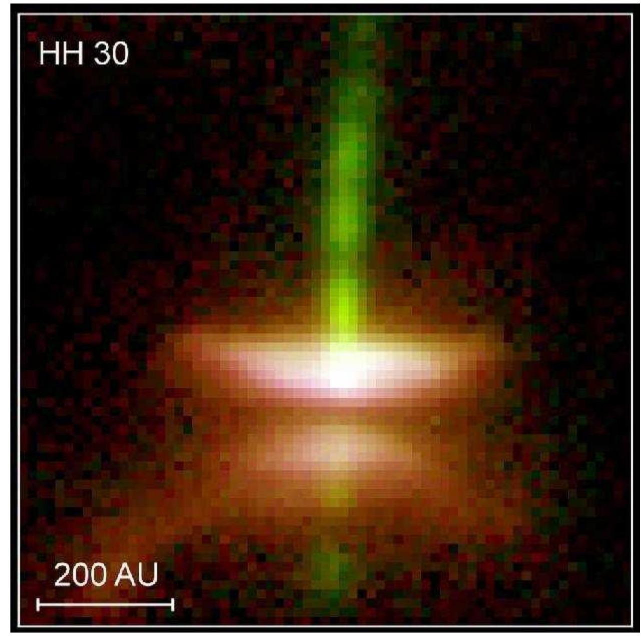


Outflows often seen in molecular lines.

Molecular outflows

Bachiller et al.

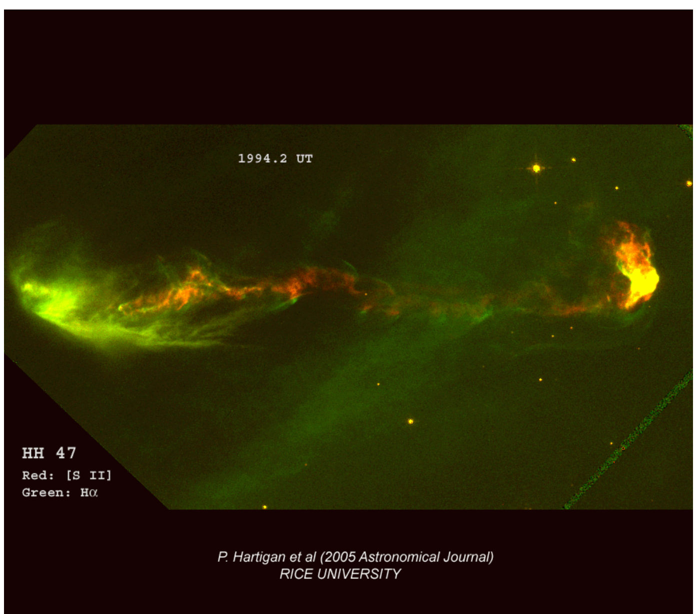
Bipolar outflows

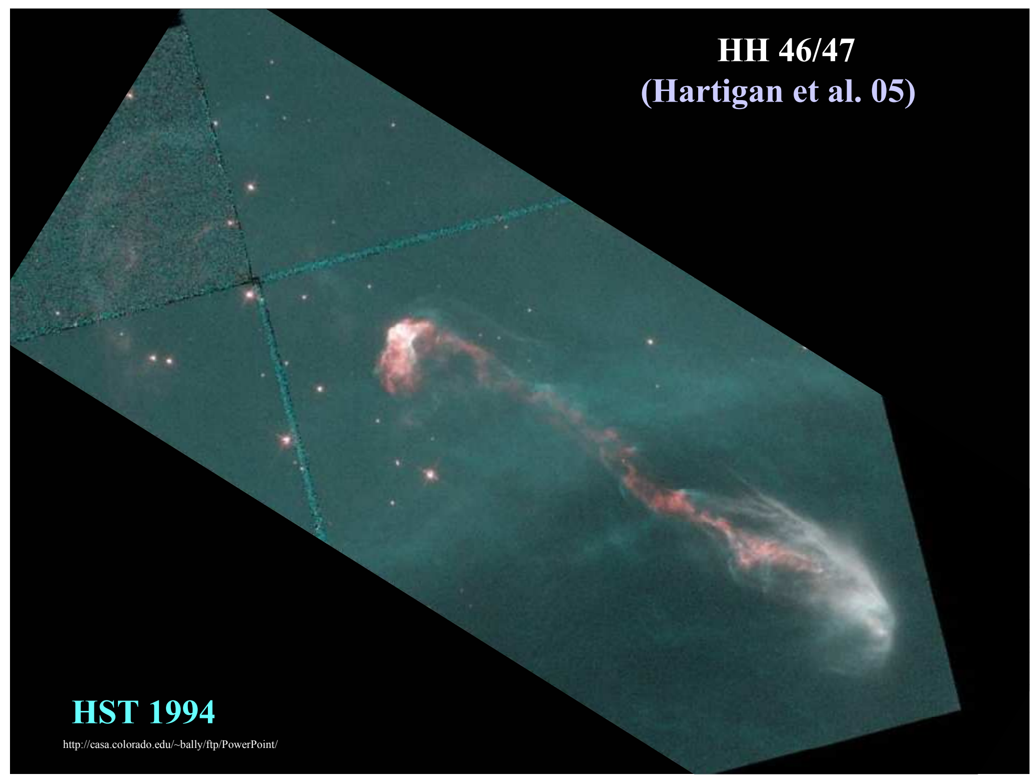


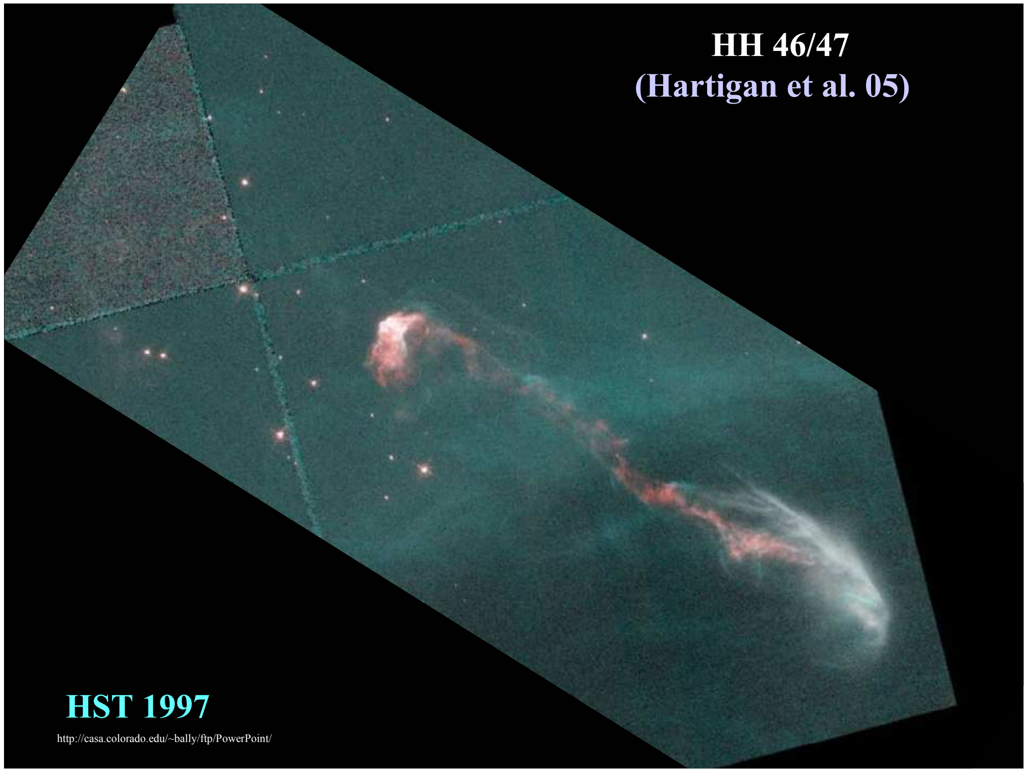
But, jets originate from inner regions of protoplanetary disks

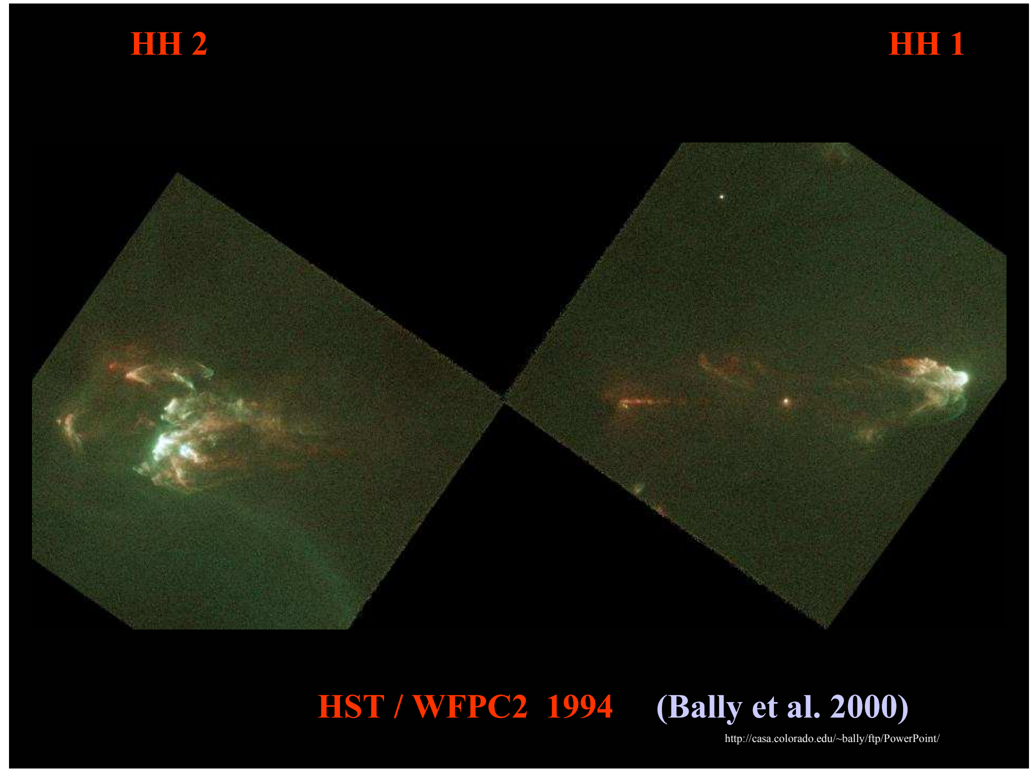
Hubble Space Telescope image

Watching Them Move






HH 46/47
(Hartigan et al. 05)
HST 1997
http://casa.colorado.edu/~bally/ftp/PowerPoint/


HH 2
HH 1
HST / WFPC2 1994
(Bally et al. 2000)
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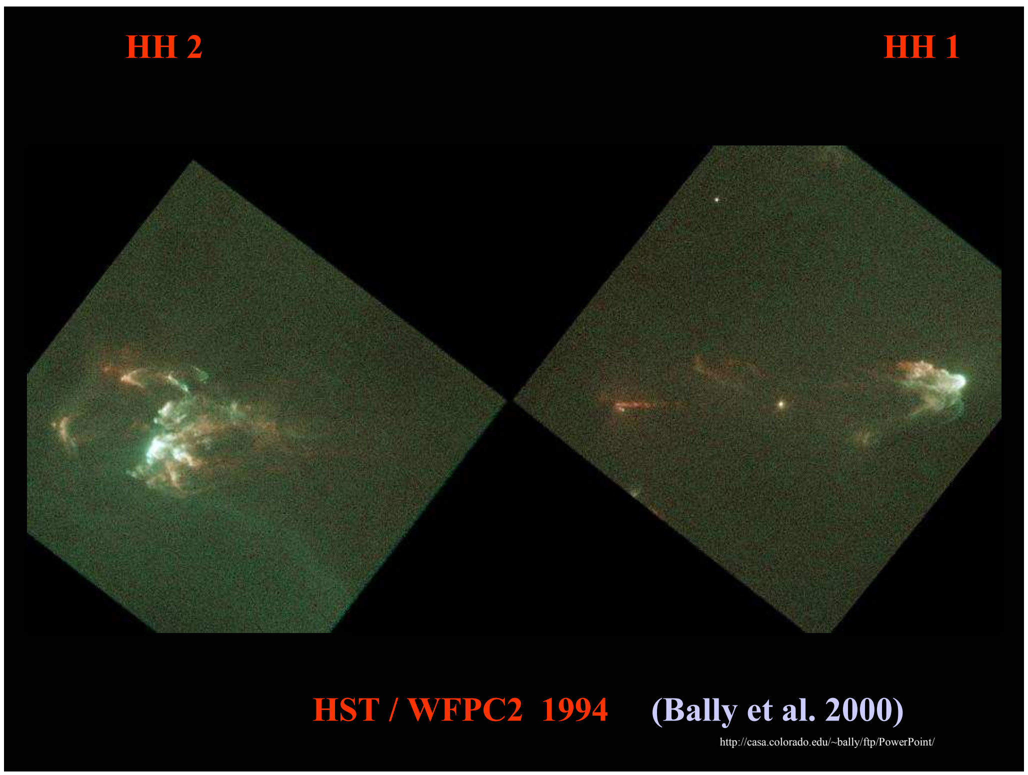
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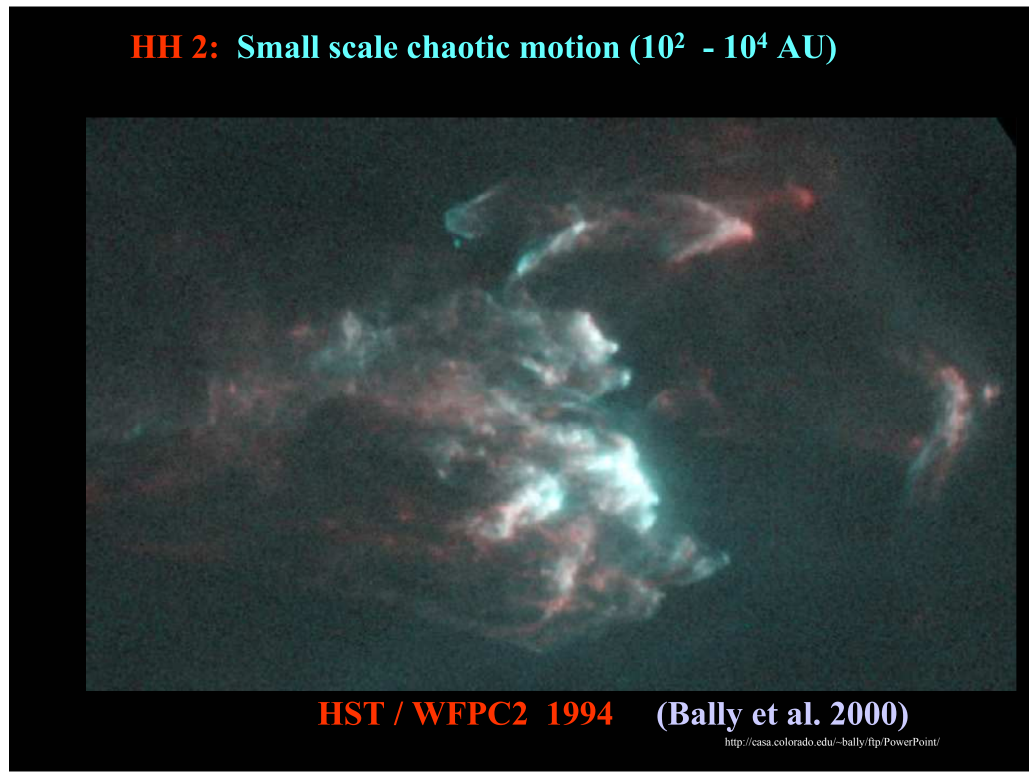
HH 2: Small scale chaotic motion (10^2 - 10^4 AU)
HST / WFPC2 1994
(Bally et al. 2000)
http://casa.colorado.edu/~bally/ftp/PowerPoint/

HH 2: Small scale chaotic motion (10^2 - 10^4 AU)

HST / WFPC2 1997 (Bally et al. 2000)

http://casa.colorado.edu/~bally/ftp/PowerPoint/

Bipolar outflows

- Optically detected jets:
  - Very collimated streams of gas,
    moving at supersonic speed (~~100 km/s)
  - Mostly bipolar, mostly perpendicular to disk
  - Jet outflow rate typically 10^{-9}... 10^{-7} $M_{\odot}$.
- Molecular outflows:
  - Detected in CO lines
  - Often associated with optical jets (i.e. same origin)
  - Derived mass: 0.1...170 $M_{\odot}$ (freaky large!)
    - Most of accelerated mass must have been swept up from the cloud core, rather than originating in mass ejected from the star