Observational ISM and Star Formation

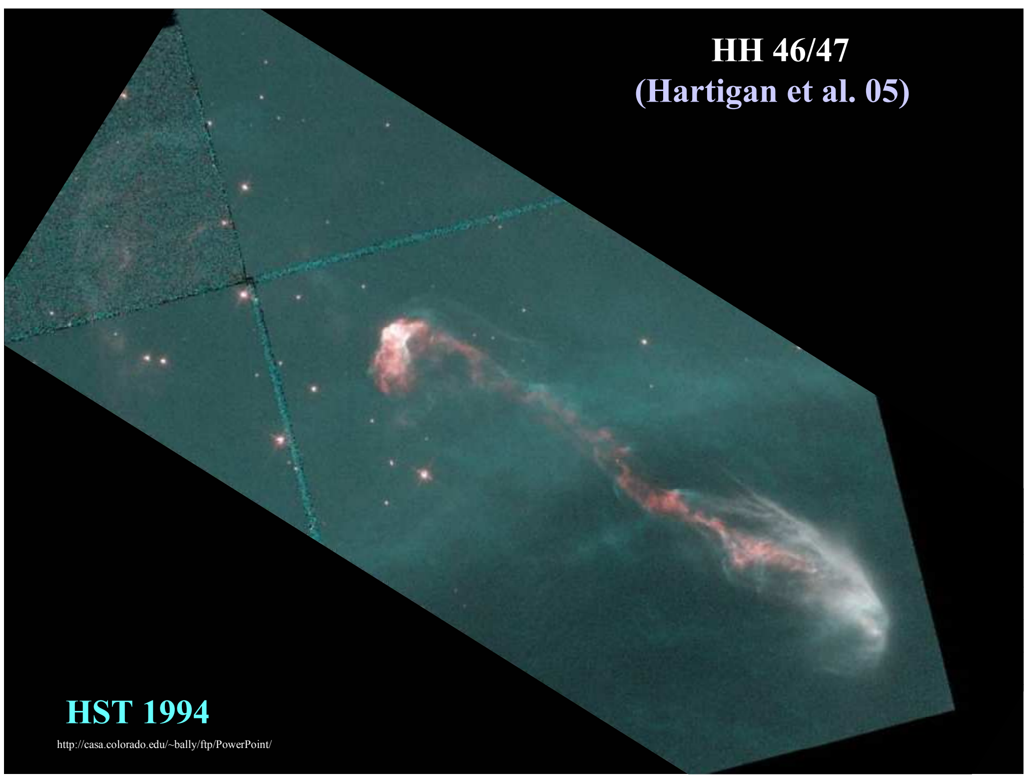
<u>This Class (Lecture 13):</u>
William Kormos /Jana Bilikova

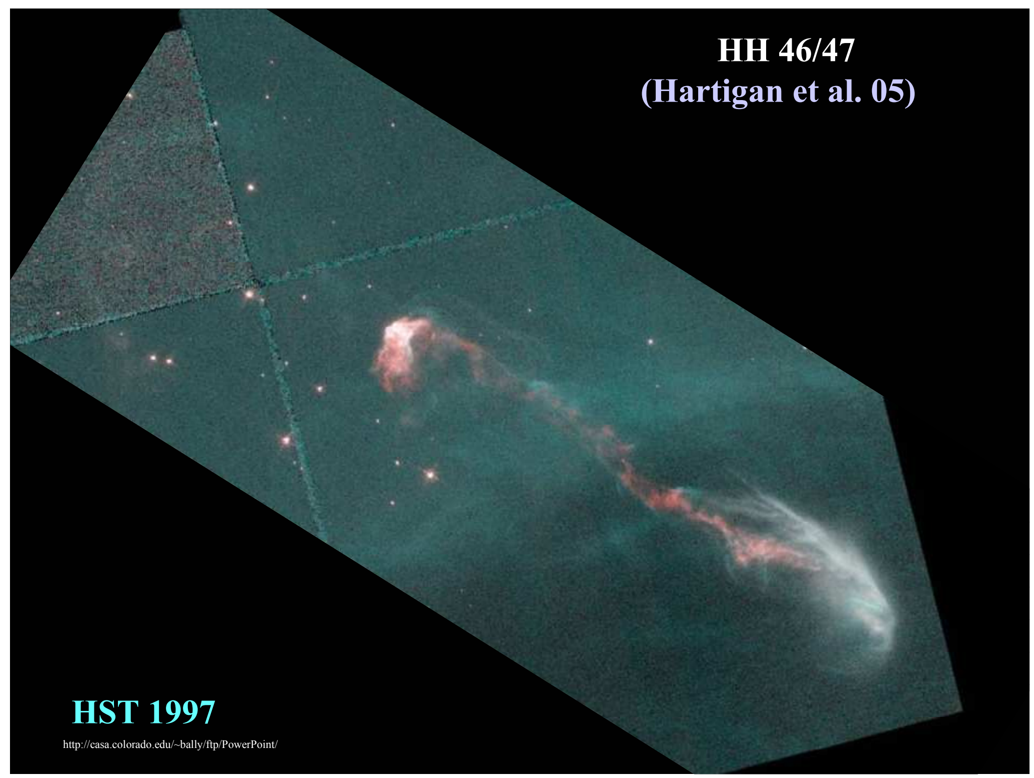
<u>Next Class:</u>
Kristen Samuels/Britt Lundgren

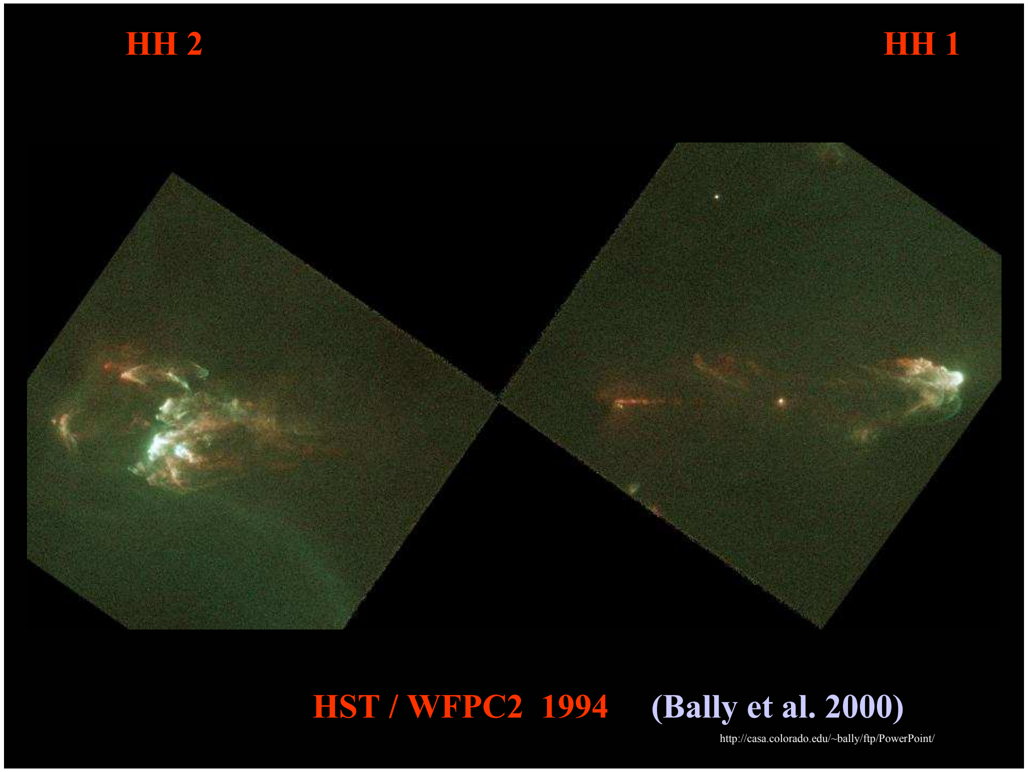
Music: *Under the Milky Way* – The Church

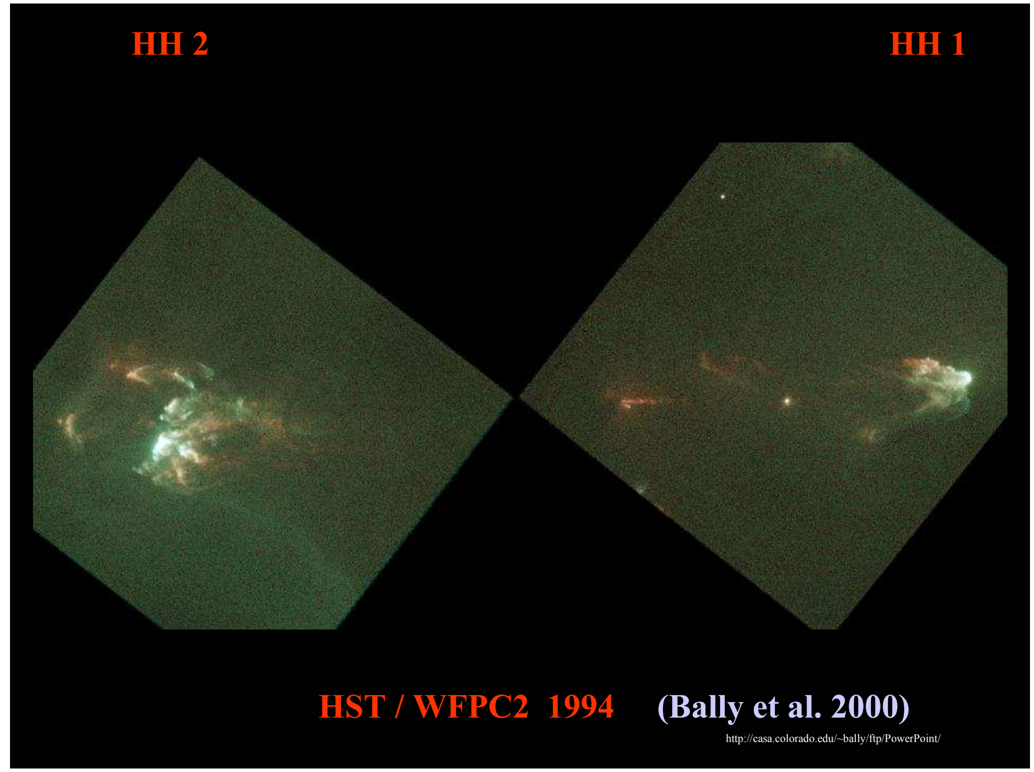
Outline

- Outflows, outflows, outflows
- Models of creating outflows






HH 2
HH 1
HST / WFPC2 1994
(Bally et al. 2000)
http://casa.colorado.edu/~bally/ftp/PowerPoint/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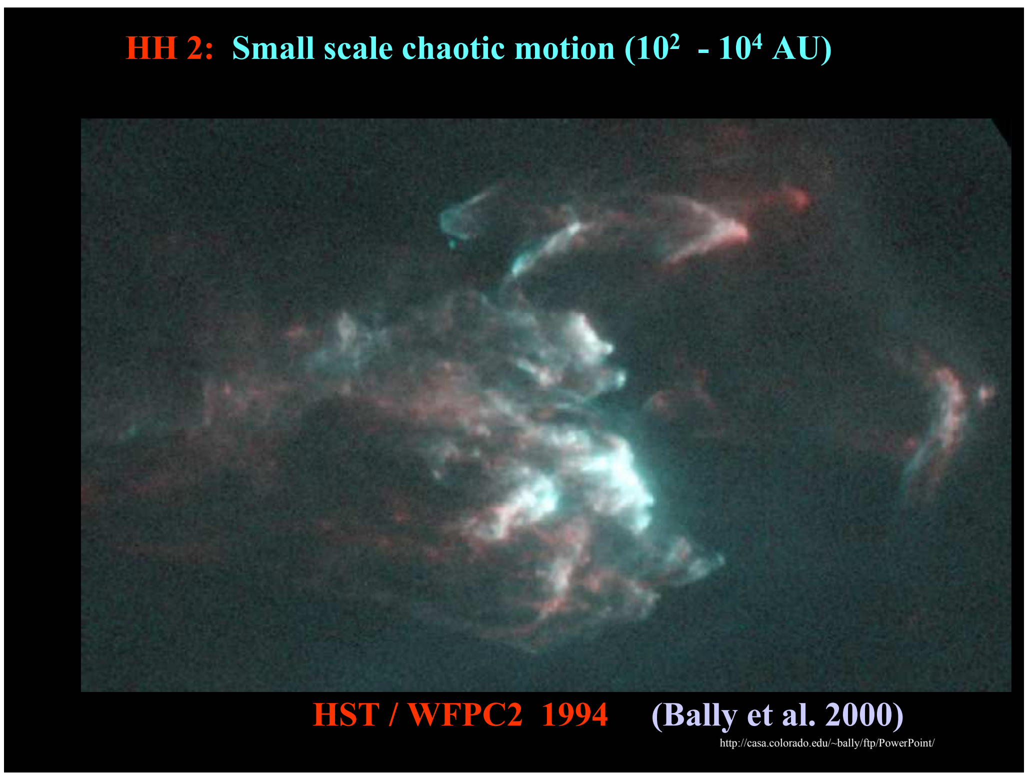
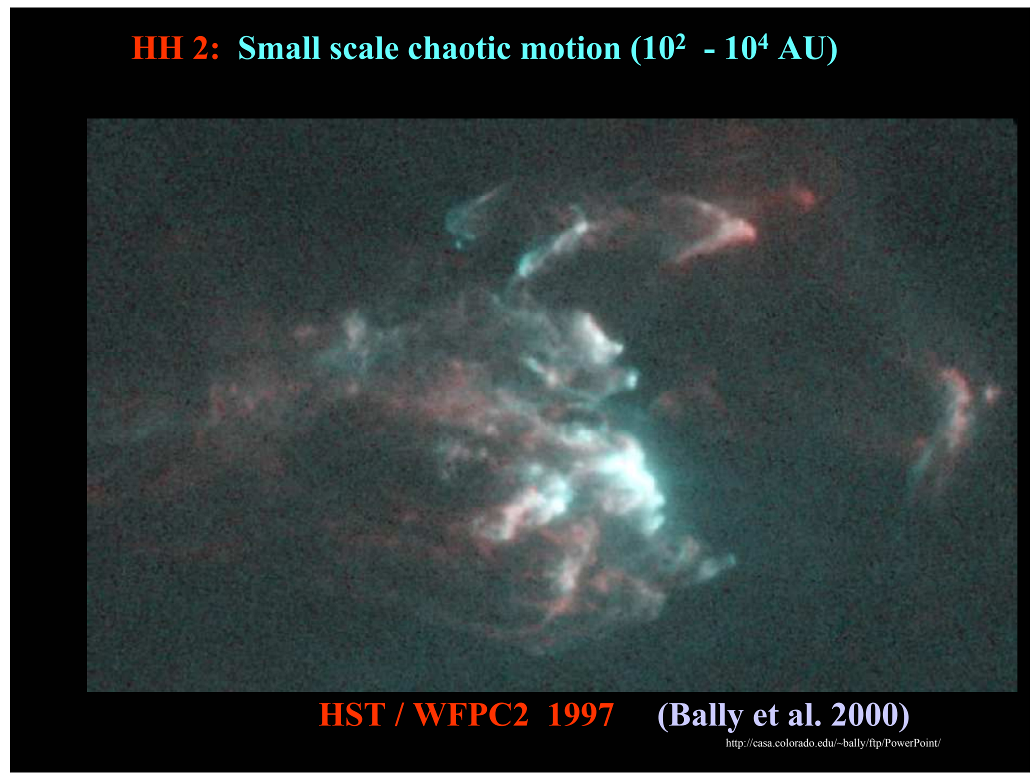

HH 2: Small scale chaotic motion (10^2 - 10^4 AU)
HST / WFPC2 1994
(Bally et al. 2000)
http://casa.colorado.edu/~bally/ftp/PowerPoint/


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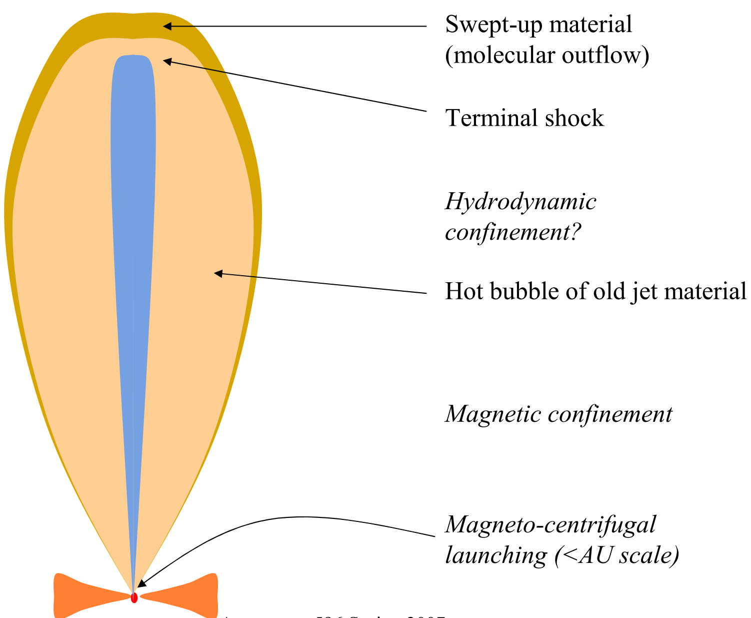
Bipolar outflows

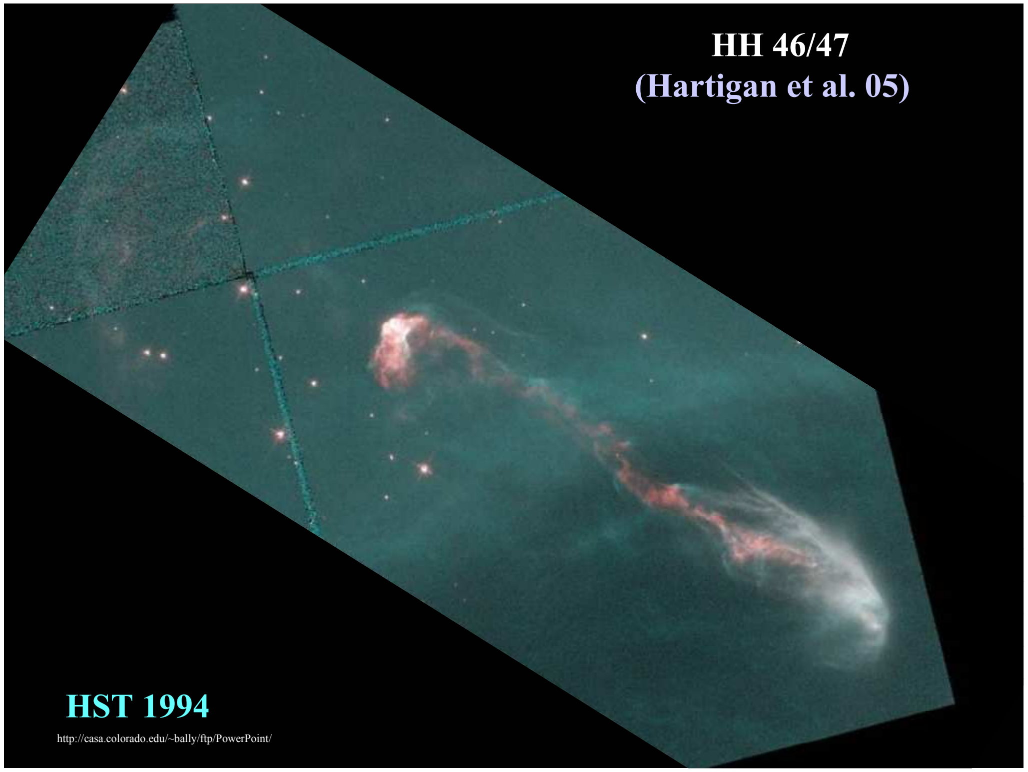
- Optically detected jets:
  - Very collimated streams of gas, moving at supersonic speed (~100 km/s)
  - Mostly bipolar, mostly perpendicular to disk
  - Jet outflow rate typically 10^{-9}... 10^{-7} $M_{\odot}$.
- Molecular outflows:
  - Detected in CO lines
  - Often associated with optical jets (i.e. 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

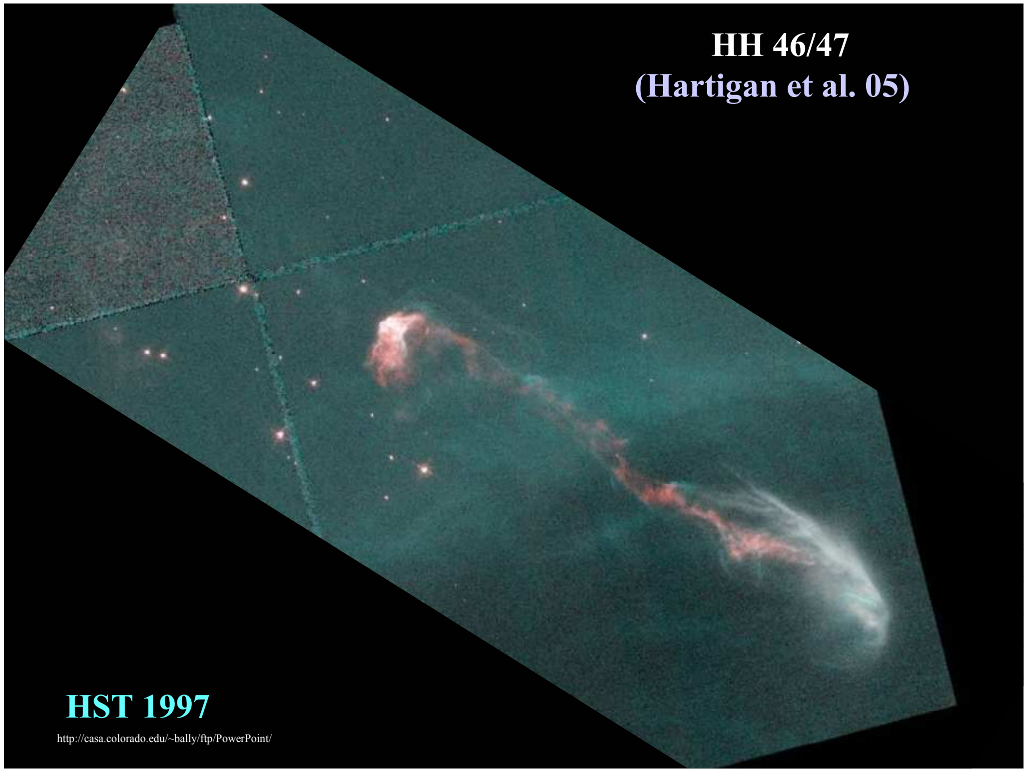
Recent Observations

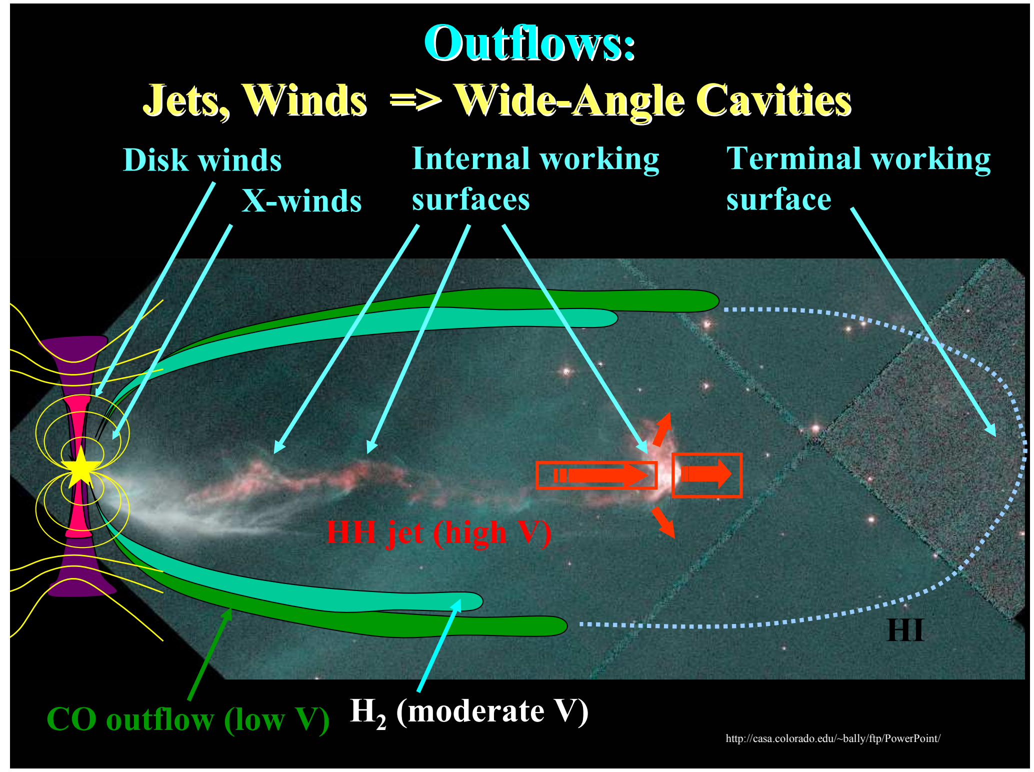
- Irradiated jets
  - Follow jets outside molecular clouds
- Wandering/rotating jets
  - Outflows can indeed carry off significant amount of angular momentum
- Deeply embedded jets and outflows seen in mid-IR
  - Outflows inject sufficient energy and momentum to drive turbulence motions in cloud cores (but not in entire GMCs)

Bipolar outflows

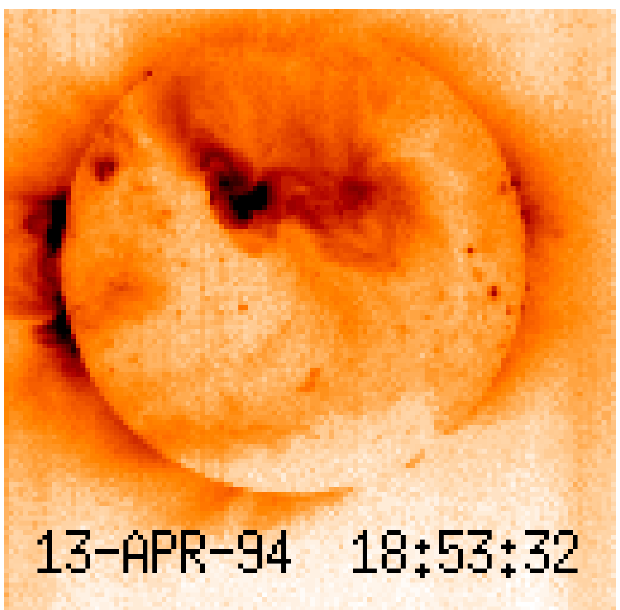






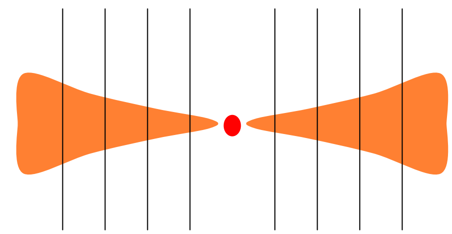


Models Tied to Magnetic Fields, Star/Disk Interactions

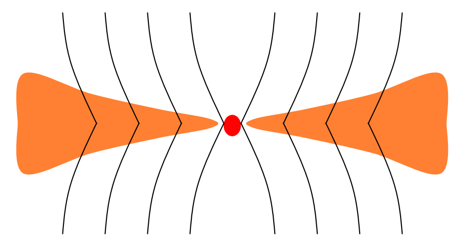


Magnetically Threaded Disks

Suppose disk is treaded by magnetic field:



Inward motion of gas in disk drags field inward:

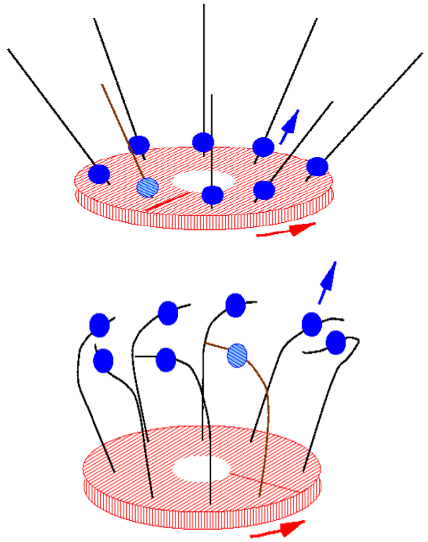


B-field acquires angle with disk

Outflow Mechanism

Magneto-centrifugal acceleration (Blandford & Payne 1982)

- Magnetic field lines co-rotate with disk
- Matter moves along the field (beads on a wire)
  - If field line inclination < 60°
  - Unstable equilibrium
  - Acceleration outwards (slingshot effect)

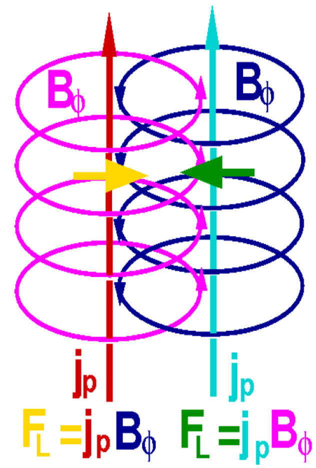


http://www.mpia-hd.mpg.de/homes/fendt/Lehre/Lecture_OUT/lect_jets3.pdf

Collimation Mechanism

- Imagine "two-wire" experiment
- Moving charged particles creates B-field
- Parallel current attracts
- Self-collimation by tension of toroidal field

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



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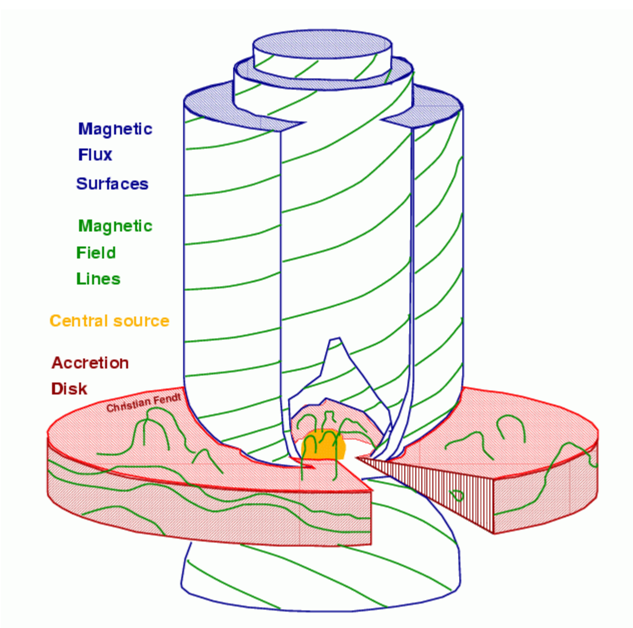
Collimation Mechanism



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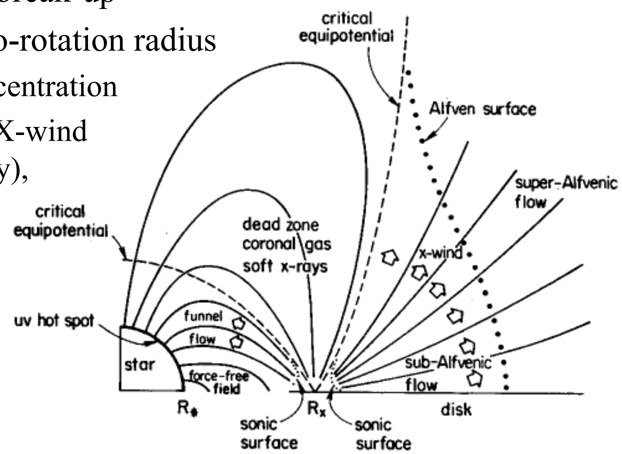
The Models

- 3 models
  - Disk wind: Pudritz & Norman (1983)
  - Star-disk magnetosphere: Camenzind (1990)
  - X-wind: Shu et al. (1994)
- Common properties:
  - All take into account MHD
  - Main jet component is launched from disk
- Differences in model geometry:
  - Impact of stellar / disk component / magnetic field

Recent literature:
see reviews of the Protostar & Planets V:
Bouvier et al.; Shang et al.; & Pudritz et al.

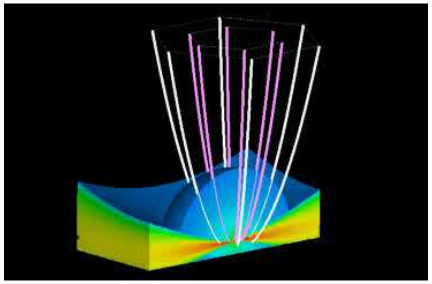
X-Windy

- From model of rapidly rotating protostar at equatorial break-up
- X-point: X- radius = co-rotation radius
  - magnetic energy concentration
  - energy released into X-wind (magnetocentrifugally), becomes collimated into jets



Shu 1994

Example: Disk



Hydromagnetic launch of jet from disk

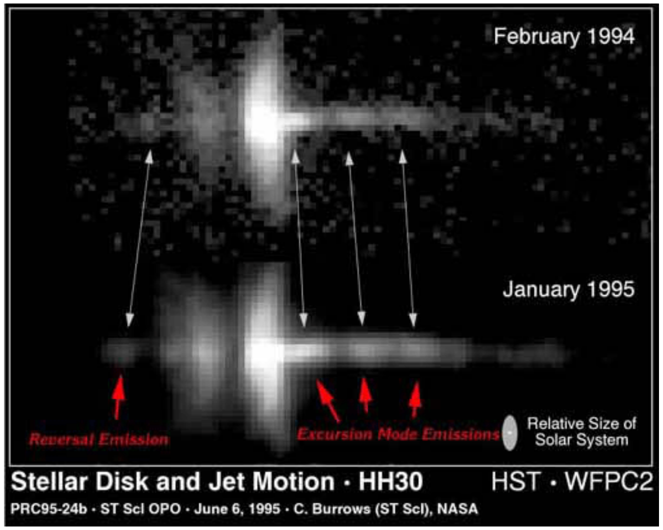
Kudoh, Matsumoto & Shibata (2003)
http://th.nao.ac.jp/~kudoh/movies_e.html

Example

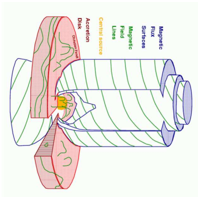
- Jets are surrounded by cocoon of pressurized gas
  - Cocoon partly made of old jet material, partly by swept up material from the environment
  - Jet material moves *supersonically*
- Head of jet ('hot spot') drills through ISM: shock
- Often knots seen (Herbig-Haro objects)

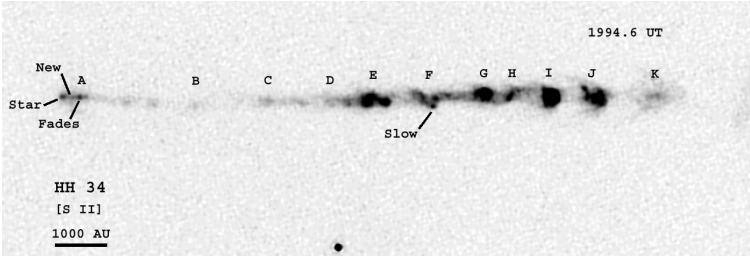
Stone & Norman 1993 http://www.astro.princeton.edu/~jstone/pjets.html

Knots Landing



Jet Powered Science



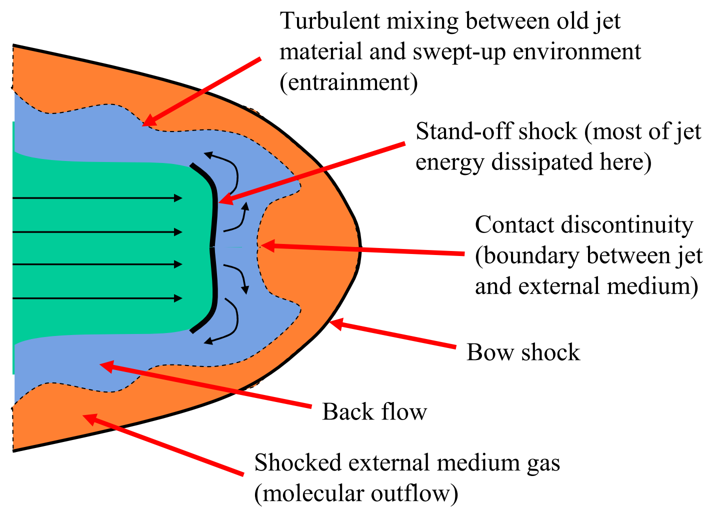


Hardigan et al.: http://sparky.rice.edu/~hartigan/movies.html

http://www.mpia-hd.mpg.de/homes/fendt/Lehre/Lecture_OUT/lect_jets3.pdf

(jet pictures from airliners.net)

Head of the Jet



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