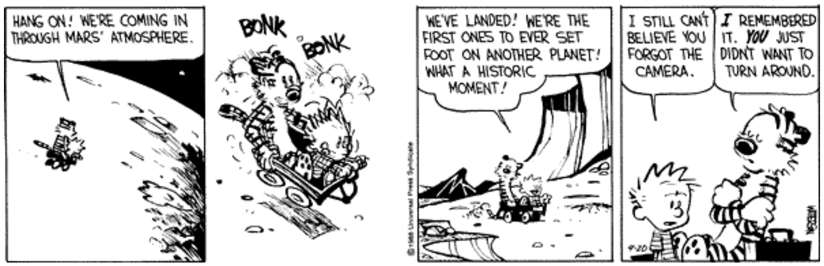
Observational ISM and Star Formation



<u>This Class (Lecture 19):</u>

Jake O'Keefe & Woojin Kwon
(Meyer et al.)

<u>Next Class:</u>

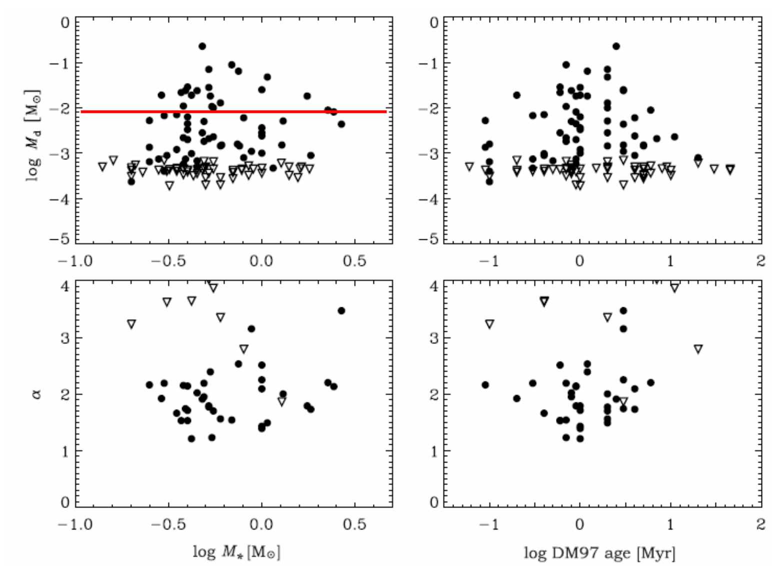
Britt Lundgren & Kijeong Yim
(Najita et al.)

Music: *Spaceboy* – Smashing Pumpkins

Outline

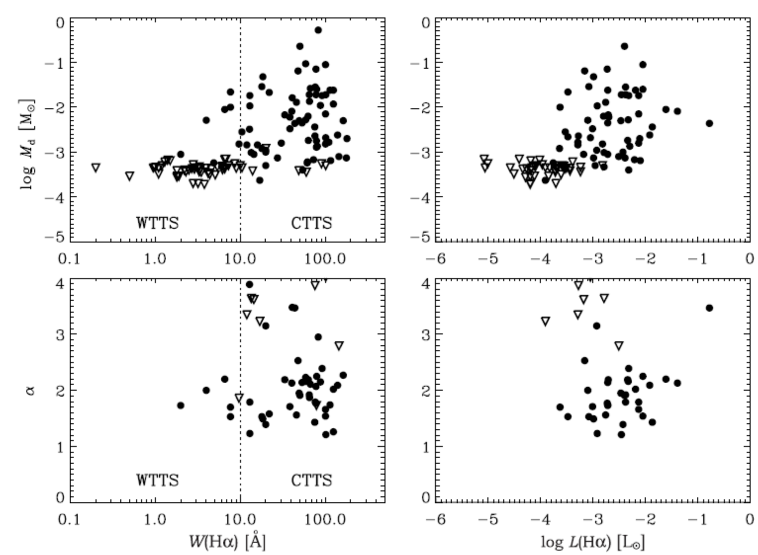
- SED surveys
- Imaging CO in the disk
- What's been happening to the protostar during all this disk evolution?

Use Resolved Data to Guide Continuum Surveys

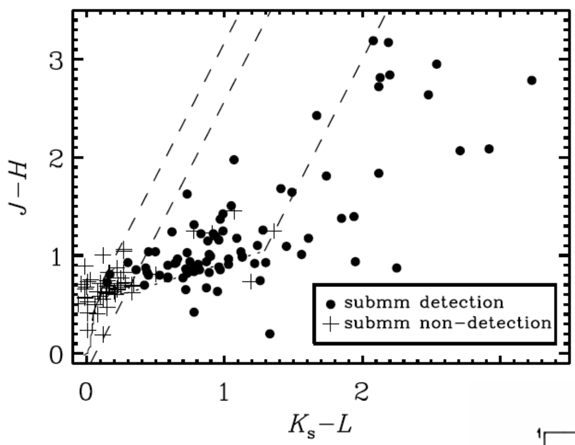


Andrews & Williams 2005

Only substantial correlation is with overall SED and/or accretion rate indicators, otherwise LARGE scatter!



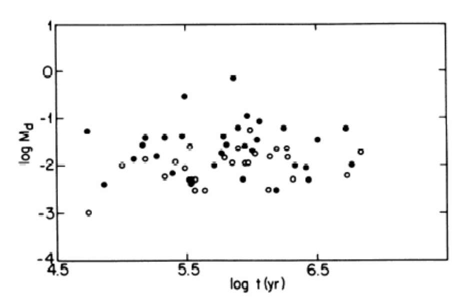
Andrews & Williams 2005



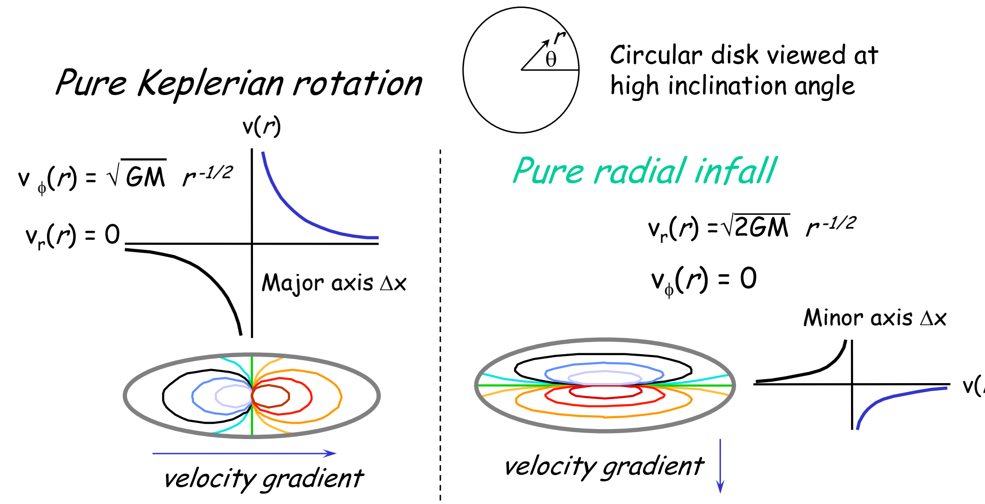
Other "factoids":

Submm flux highly correlated with the presence or absence of IR excess. Almost no disks w/weak IR but strong submm.

Very little dependence of MAXIMUM disk mass on age (that is, some fairly OLD stars have >MMSN disks).



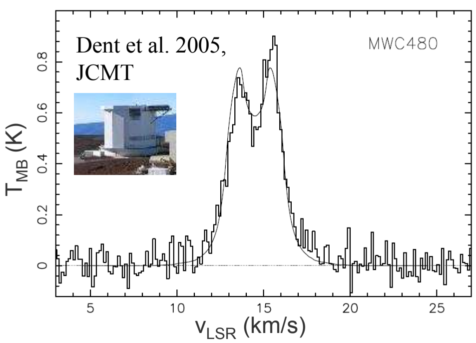
Velocity gradients & gravity

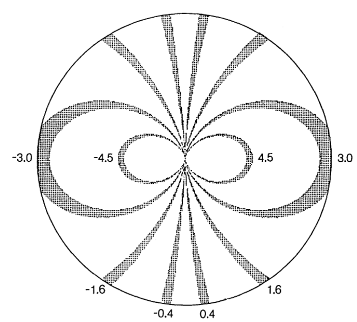


Dutrey *et al.* (1994)
Saito *et al.* (1995)

Hayashi *et al.* (1993)

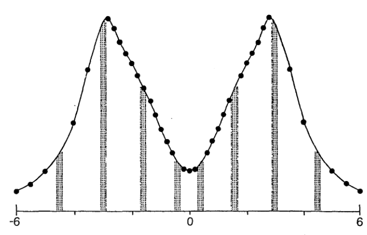
Gas? ➡ CO/Good Dynamical, T Tracer



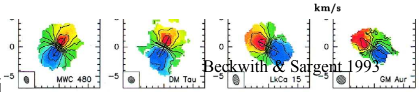


The CO line shape is Sensitive to:
R_{disk}, M_{star}, Inc.

These can be *measured* w/resolved images:

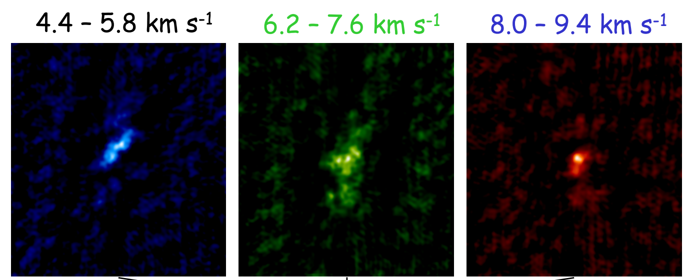


M. Simon et al. 2001, PdBI



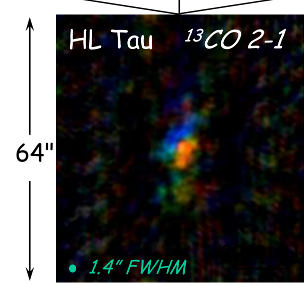
Beckwith & Sargent 1993

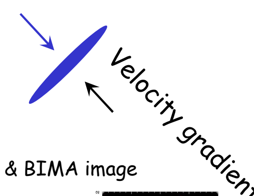
Gas Dynamics in HL Tau: mostly infall



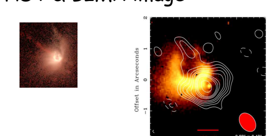
HL Tau shows an *infalling* disk.

Hayashi *et al.* (1993)
Koerner & Sargent (1995)
Looney et al. (2000)



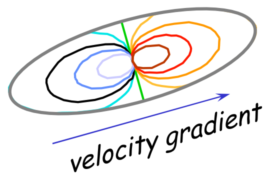


HST & BIMA image

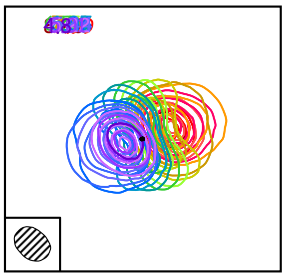


GG Tau system: a rotating disk

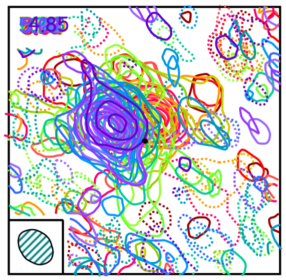
Dutrey *et al.* 1994, *A&A*, **286**, 149



^{13}CO *J*=1-0



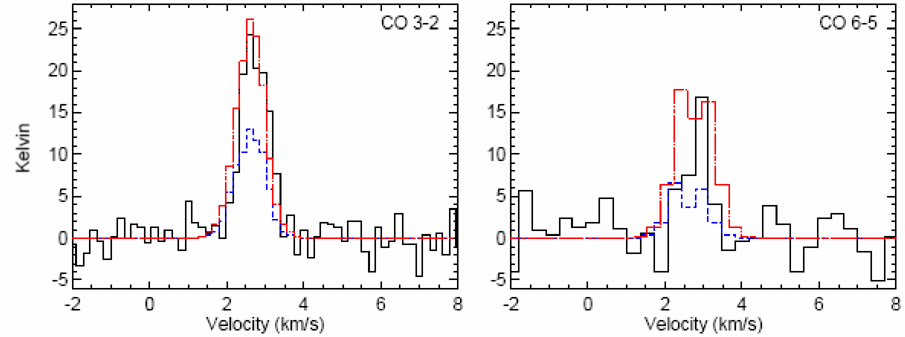
Model calculation

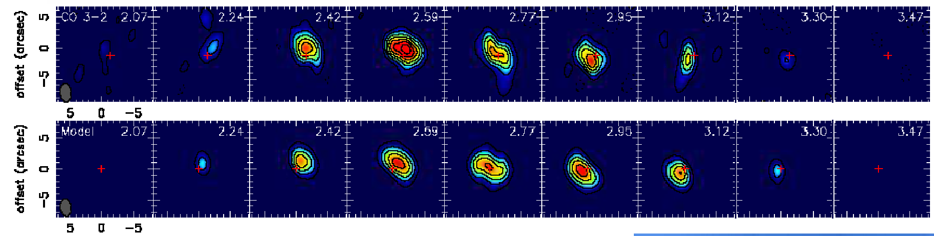


Observed velocity map

http://feps.as.arizona.edu/pub_presentations/kobe_2005/Kobe_nbsp_05Jul13.ppt (Steve Beckwith)

With multiple CO lines ➡ T gradients:



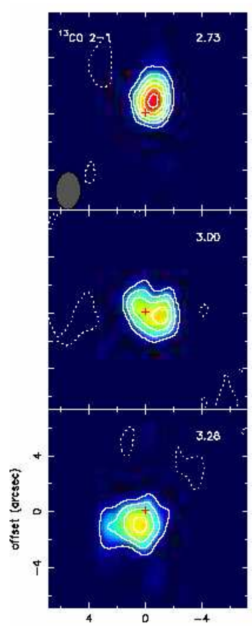


TW Hya w/SMA

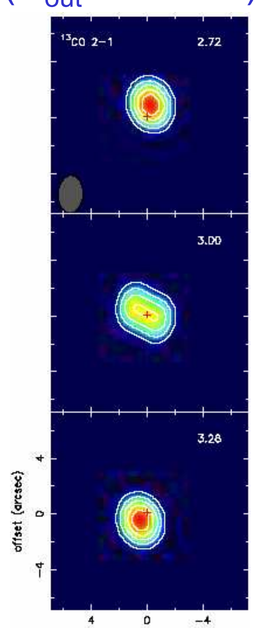
Qi et al. 2004

^{13}CO 2-1/TW Hya

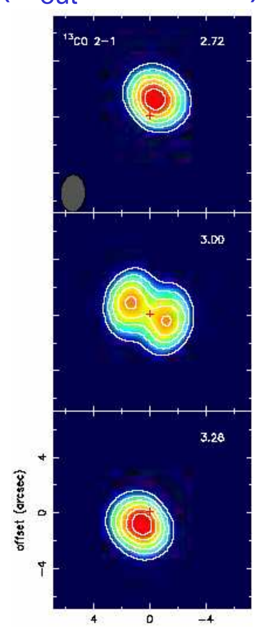
Data



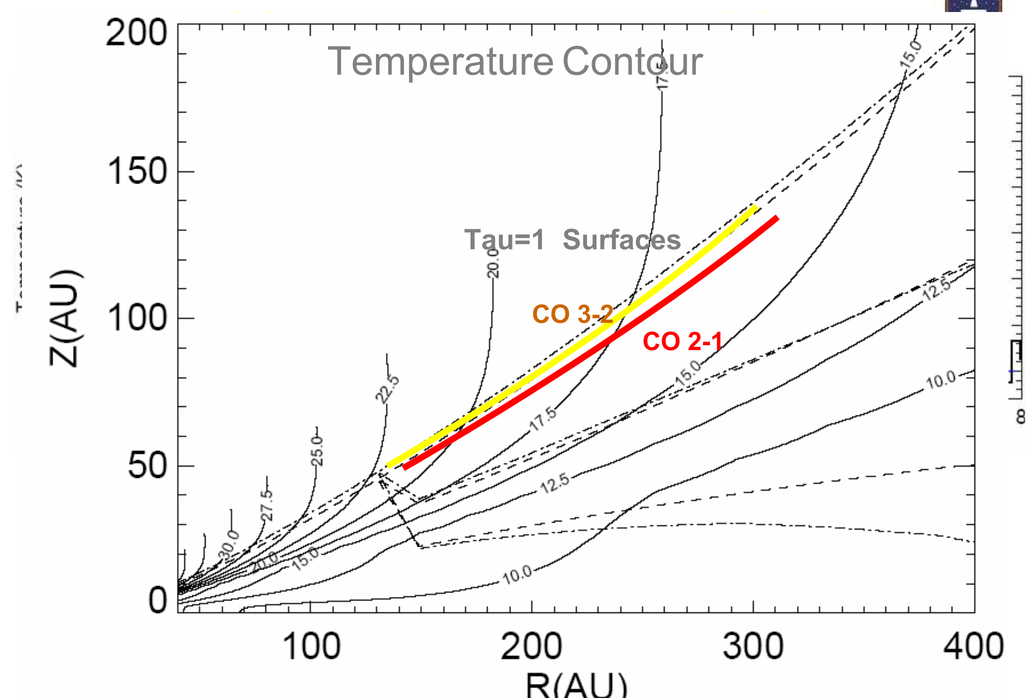
Model (R_{out} =110 AU)



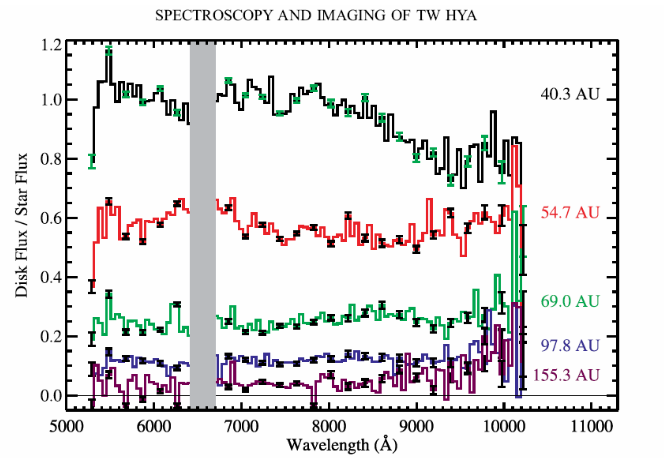
Model (R_{out} = 172 AU)



Only sensitive to disk surface layers, hard to get mass.



Spatially Resolved Spectra: TW Hydra



The scattered light from the disk is essentially gray from ~50 AU to ~150 AU.

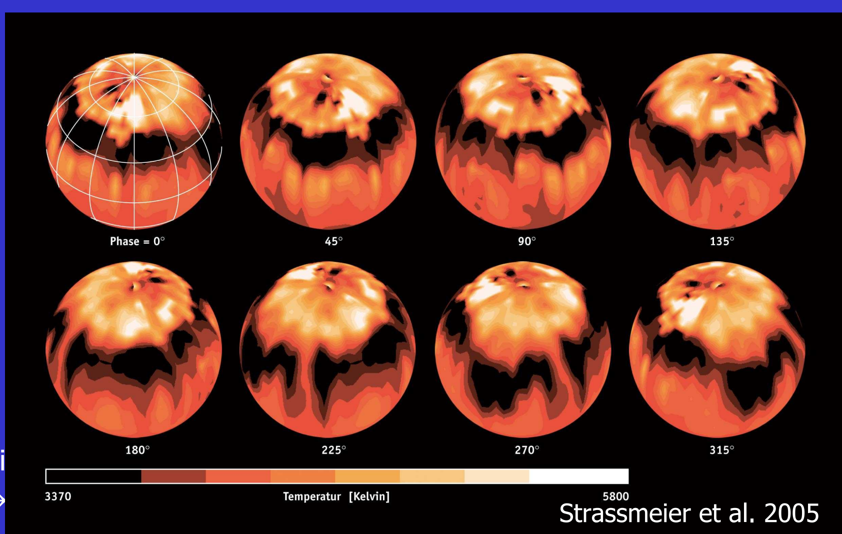
This result argues for relatively large (>1 μm) scattering particles

Roberge *et al.* (2005)

During all this time, what is happening at the protostar?

- The protostar is accreting and accreting.
- Many observations suggest that the accretion is periodic– e.g., FU Ori objects.
- Theory is beginning to suggest that this type of accretion is expected (e.g. Tassis et al. 2007).
- The end of this accretion stage is thought to occur for the classical T Tauri stars.

Accretion and Mass Transport



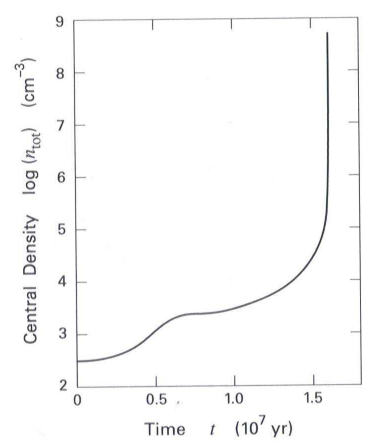
Equili

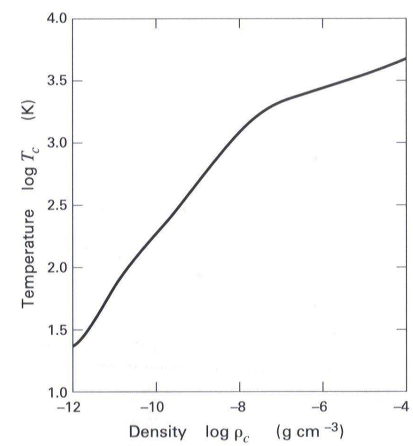
→

→ mass transport inward, angular momentum transport outward, heating

The inner disk is warm enough for large ionization: matter and magnetic field are coupled well → accretion columns transport gas from disk to protostar

Remember the First Core



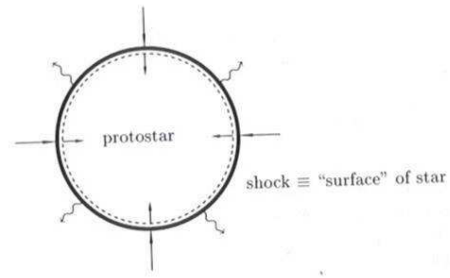


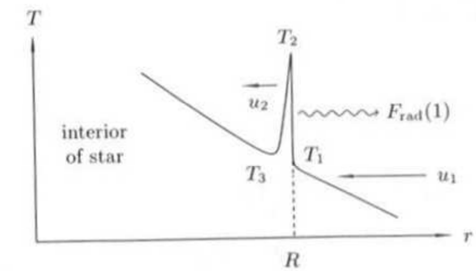
- Contraction of core via ambipolar diffusion initially a slow process.
- When flux ratio reaches critical threshold, contraction speeds up
  - Core becomes opaque → cooling less efficient → T & P rise.
- Interior still mainly molecular hydrogen (core is low-mass 0.05 Msun but big, 5 AU, at this stage)
  - Important for final collapse

And The Second Core

- With the addition of mass and further shrinking, first core reaches 2000K, so collisional dissociation of H_2 occurs.
- But, a modest increase of dissociated H_2 absorbs most of the gravitational energy from the collapse
  - Marginal increase in temperature and pressure
  - A region of atomic H spreads outward from center
- Without significant T & P increase, the first core cannot keep equilibrium.
- The entire core becomes unstable, collapses and forms protostar.
  - Significant temperature and density increase, sufficient to collisionally ionize most hydrogen
  - Emerging protostar is now dynamically stable.
- A protostar of 0.1 Msun has radius of several R_*, $T \sim 10^5$K and $\rho \sim 10^{-2}$g cm-3

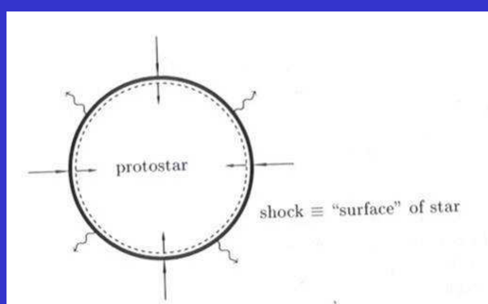
Protostar





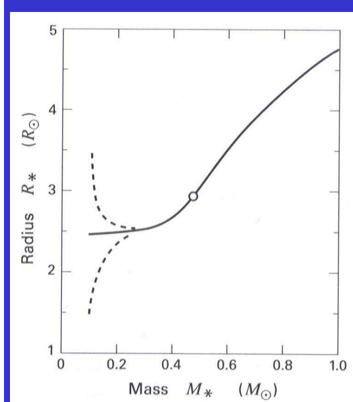
- Luminosity is dominated by accretion
  - There are small/negligible contributions from early fusion processes and contraction
- The gravitational energy released per unit accreted mass is essentially the gravitational potential GM_*/R_*, so
  - $L_{acc} = G(dM/dt)M_*/R_*$
    $= 61 L_{sun} ((dM/dt)/10^{-5} M_{sun}/yr) (M_*/1 M_{sun}) (R_*/5 R_{sun})^{-1}$

Protostellar Mass-Radius



- Adding infalling mass shells, the protostar can be described by its entropy profile $s(M_r)$, reflecting the changing conditions at the accretion shock.
- Since s represents heat content of each added mass shell, an increase of $s(M_r)$ causes a swelling of the protostar.

Protostellar Mass-Radius



- In the absence of nuclear burning, an increasing $s(M_r)$ arises naturally with rising M_*.
- The velocity of the infalling gas and hence the accretion shock and L_{acc} increases.
  → Protostellar radius increases with time.
- Suppose initial core very large, then lower infall velocity
  - Low L_{acc} and $s(M_r)$ would dip at beginning of protostellar evolution
  - Initial decrease of R_*
  - Opposite effect for very small initial state.

Deuterium Burning

- The ratio M_*/R_* rises fast and interior temperatures increase again.
- Nuclear reactions start at center (at ~0.3 Msun deuterium burning at ~10^6K).
- Convection begins because deuterium fusion produces too much energy to be transported radiatively through opaque interior
- Protostellar interior is well mixed and provides its own deuterium to center for further fusion processes.
- However, convection is local phenomenon, some regions can be convective whereas others remain radiatively stable.