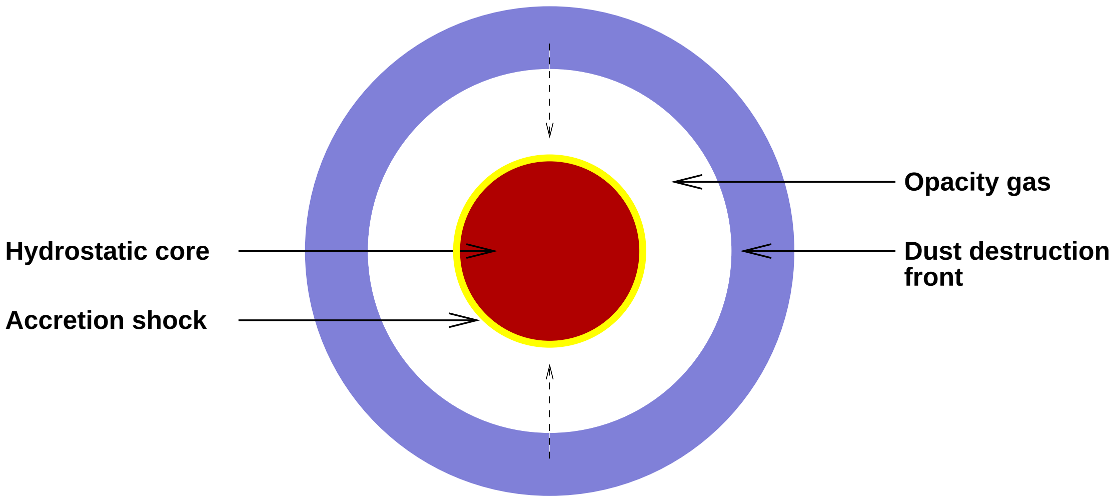
Pre-main-sequence stellar evolution

For spherically symmetric accretion, expect that the structure of the core + infalling envelope looks like (cf Shahler, Shu & Taam 1980):



- A hydrostatic core, initially of low mass due to the non homologous nature of collapse.
- Accretion onto the core at a rate $\dot{M}$, via an accretion shock at the stellar surface.
- An *opacity gap* in the inner region of the flow, because the stellar effective temperature exceeds the dust destruction temperature.

The opacity gap partially decouples the problems of protostellar evolution and infall, as it allows photons produced at the shock to stream out freely.

Still need to specify $\dot{M}$ onto the core. Assume that this is constant.

Evolution for low masses

For masses $M_* \leq M_\odot$, deuterium burning occurs near the center for T exceeding $\approx 10^6$ K:

- Provides sufficient luminosity to maintain the star convectively unstable.
- Convection 'instantaneously' transports accreted deuterium to the center.
- $\rightarrow$ steady-state deuterium burning.

Deuterium burning luminosity is,

$$L_D \simeq \delta \dot{M} = 12 L_\odot \left(\frac{\dot{M}}{10^{-5} \; M_\odot \mathrm{yr}^{-1}} \right)$$

where δ is the nuclear energy per unit mass available via deuterium burning:

$$\delta \equiv [D/H] \frac{XQ}{m_H},$$

where,

- $[D/H] = 2 \times 10^{-5}$ is the fractional interstellar abundance of deuterium by number.
- $X = 0.7$.
- $Q = 5.5$ MeV is the energy available per reaction.

The deuterium burning reaction,

$$^1\mathrm{H} +^2 \mathrm{H} \rightarrow^3 \mathrm{He} + \gamma$$

yields,

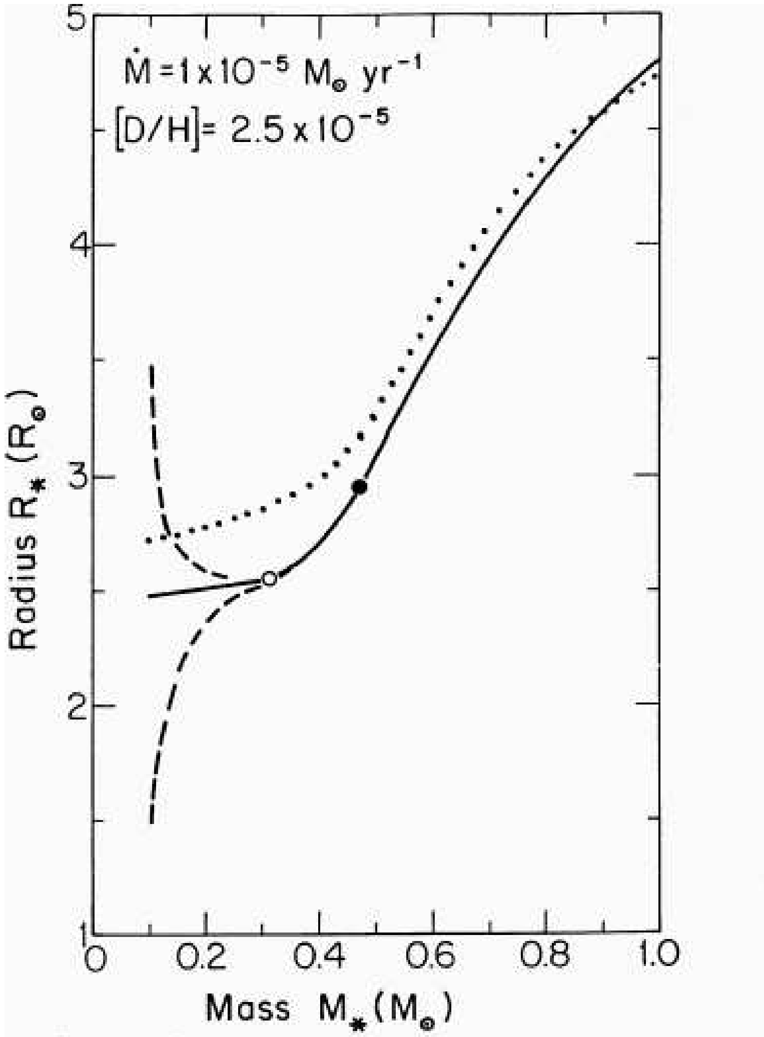
$$\epsilon_D = 4.2 \times 10^7 [D/H] \left(\frac{\rho}{1 \mathrm{~gcm}^{-3}}\right) \left(\frac{T}{10^6 \mathrm{~K}}\right)^{11.8} \mathrm{~erg~g}^{-1} \mathrm{~s}^{-1}.$$

Strong temperature dependence acts as a thermostat, maintaining the core temperature near 10^6 K.

$\rightarrow$ a mass-radius relation that is almost linear during the phase of active deuterium burning.

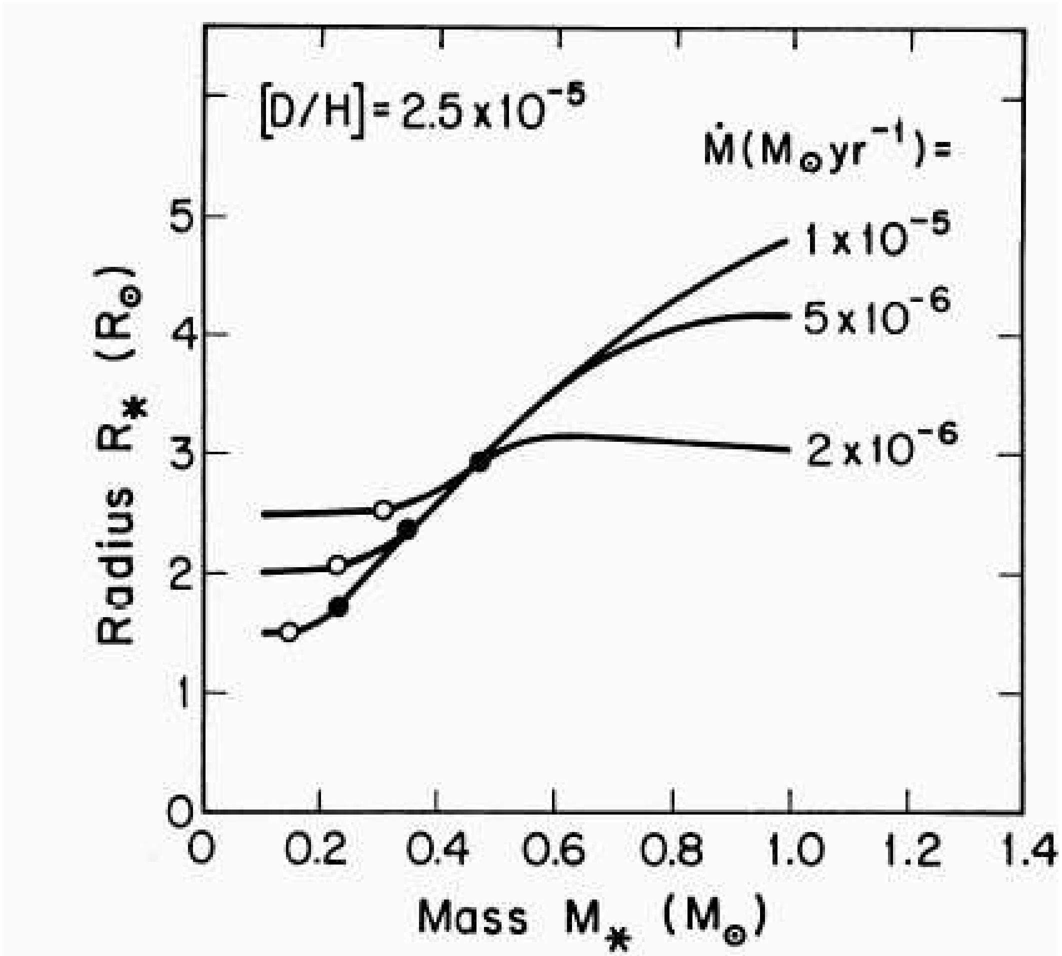
Note: for low mass stars and $\dot{M} = 10^{-5} M_\odot \mathrm{yr}^{-1}$, the accretion time is shorter than the Kelvin-Helmholtz time.

Numerical calculations by Stahler (1988, ApJ,332, 804):



- Approximately linear growth of radius with mass.
- Radii much smaller than Hayashi's protostars.
- Different intial radii converge to a single relation.

Different accretion rates yield different tracks. Lower accretion rates → longer characteristic accretion times relative to the Kelvin-Helmholtz time → gravitational contraction more important.



Radii of $3 - 4\ R_\odot$ are inferred for the largest T Tauri stars, so these radii are observationally plausible.

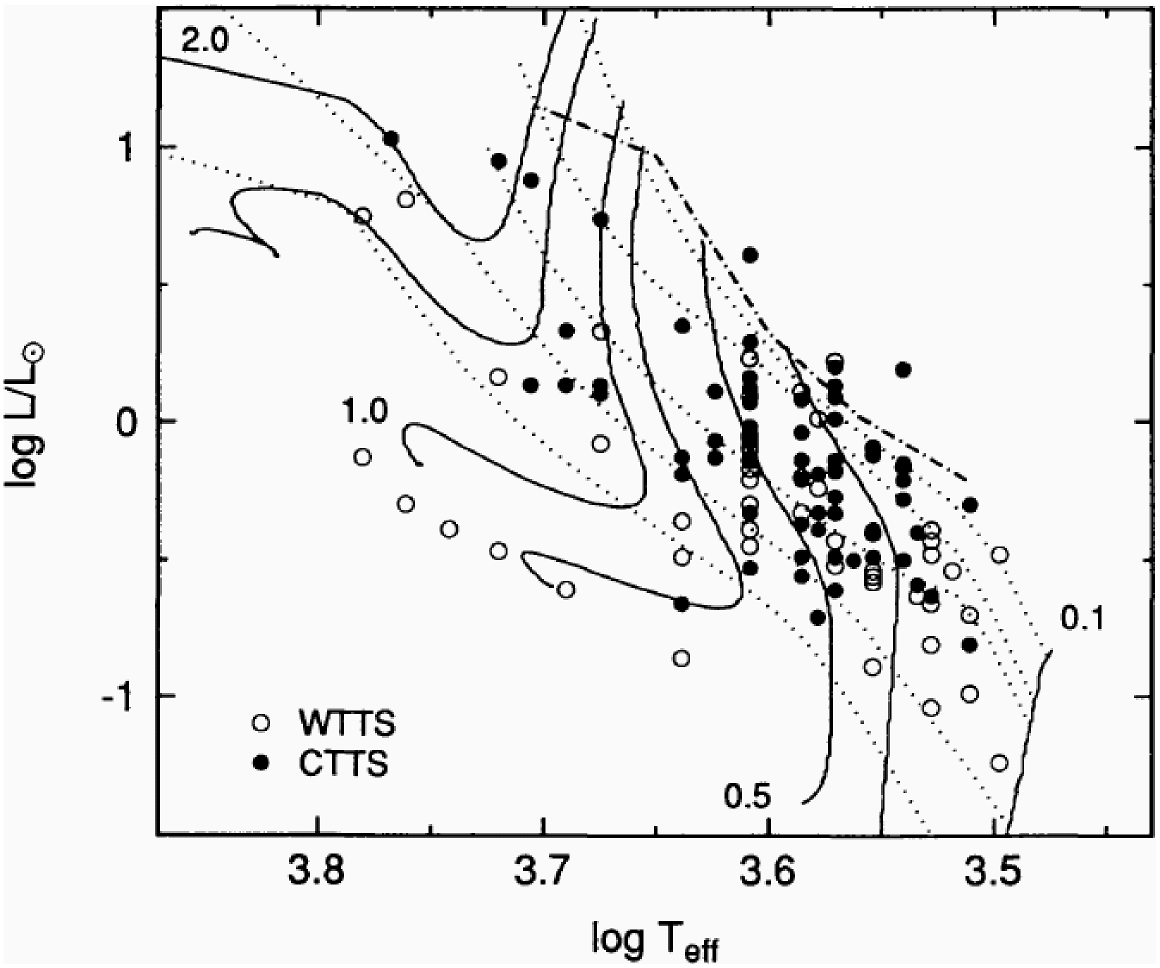
Assume now that the main phase of stellar accretion ends abruptly. Then,

- During the accretion phase, follow $R(M)$ track essentially set by deuterium burning criteria in core. Infall means this phase is not optically visible.
- After accretion ceases, optically visible stars contracts towards ZAMS along traditional Hayashi track.

Boundary between these phases defines a **stellar birthline**, above which no stars should be found in HR diagram.

Obviously a disk has to remain to explain the properties of Classical T Tauri stars. However, the accretion rate in CTTS is typically $\sim 10^{-8}\ M_{\odot}\mathrm{yr}^{-1}$ (Gullbring et al. 1998), so not unreasonable to ignore this as a first approximation.

HR diagram for pre-main-sequence stars in Taurus (Kenyon & Hartmann, 1995, ApJS, 101, 117):

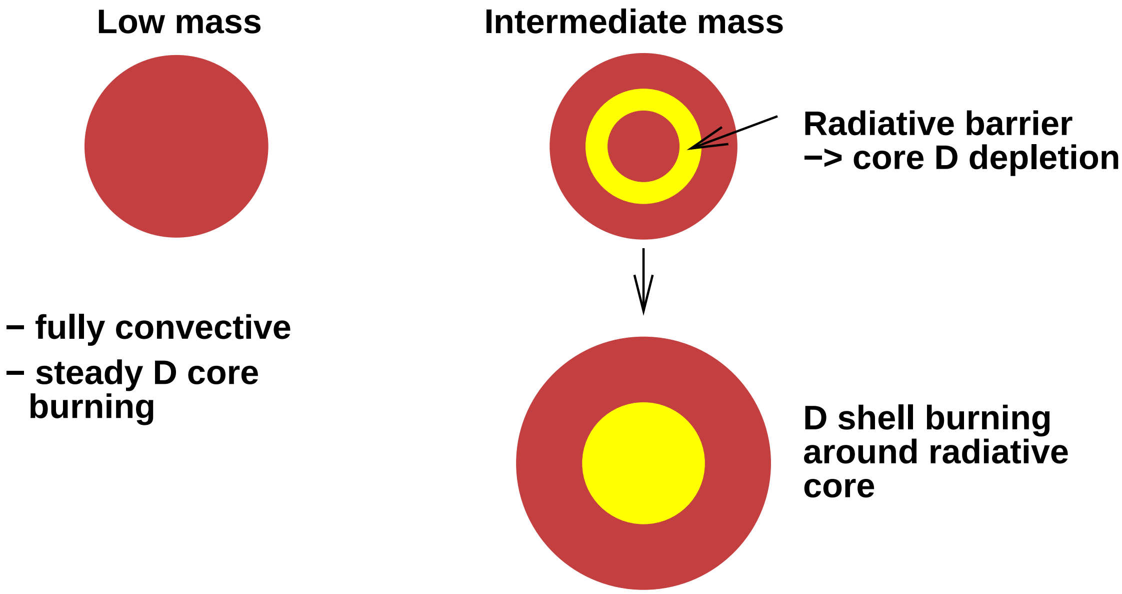


Roughly consistent with the birthline concept. Note also that the classical T Tauri stars (solid circles) on average lie further from the main sequence than weak-lined T Tauri stars (open circles).

Dispersion in the lifetime of disks could be explained via roughly a factor 3 variation in the initial disk mass (Armitage, Clarke & Palla 2002).

More massive stars

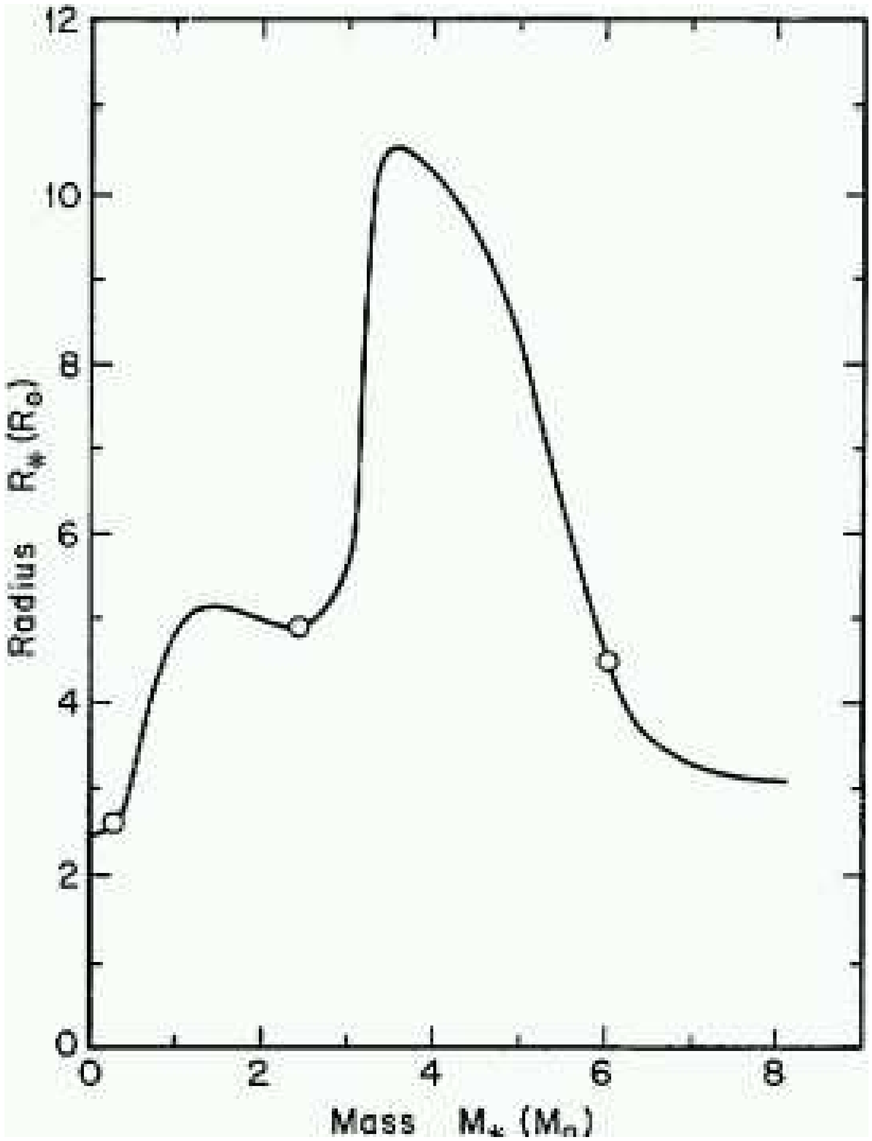
Because the radii are smaller (less luminous) than in the classical theory, more massive stars develop radiative stable regions while accreting.



Shell burning of D drives an increase in the stellar radius (to burn D in a shell, need higher temperatures further out than for core burning $\rightarrow$ greater radii).

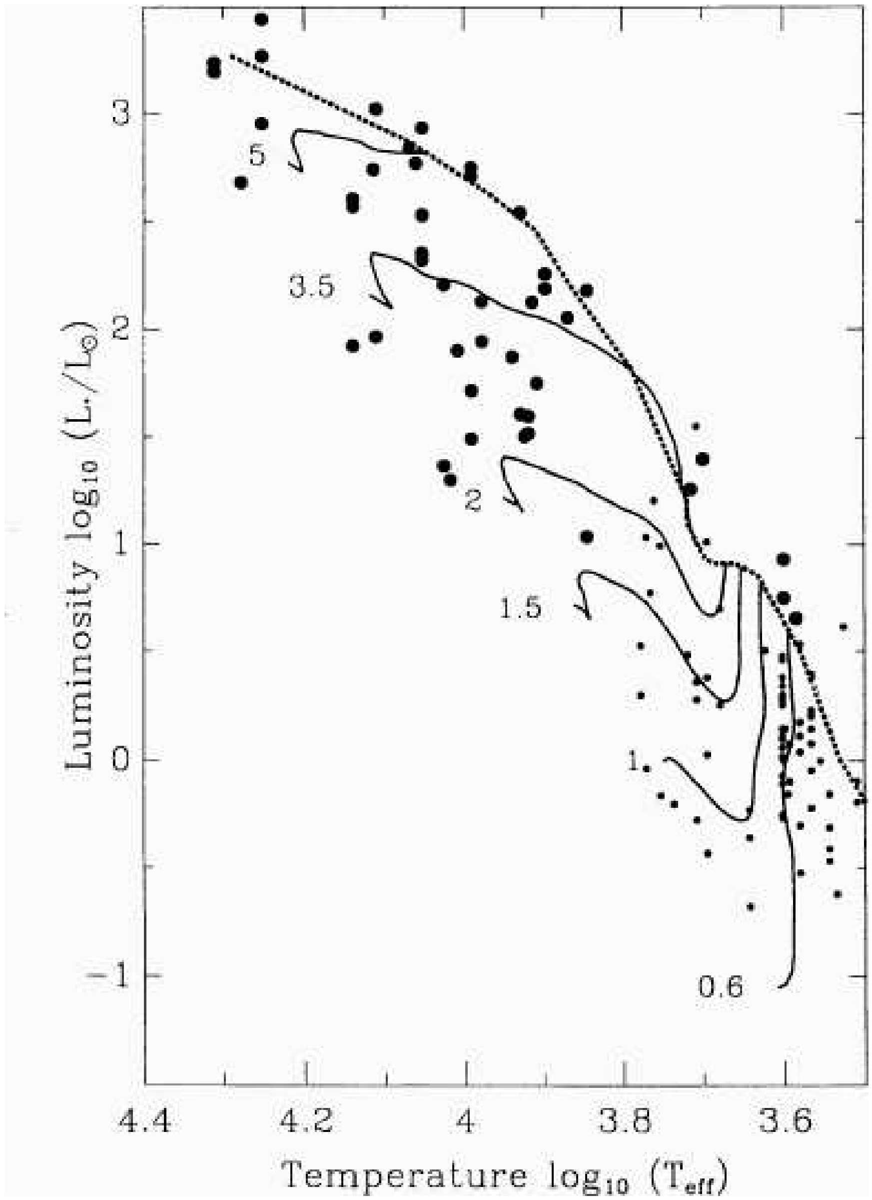
For sufficiently high mass, gravitational contraction dominates and the pre-main-sequence region is confined to close to the ZAMS.

Numerical calculations by Palla & Stahler (1990, ApJ, 360, L47):



Stars more massive that about 8 $M_\odot$ are predicted to have ongoing accretion throughout their pre-main-sequence lifetimes.

HR diagram from Palla & Stahler (1993, ApJ, 418, 414):



Weaknesses of the birthline concept

Some of the assumptions of the birthline concept are questionable:

- **Spherical symmetry**. If accretion occurs via a disk:
  - (i) The boundary conditions at the stellar surface will be different in detail (different entropy).
  - (ii) Geometrically, we should be able to **see the photosphere** during the accretion phase for systems that are close to face-on. These could lie above the birthline.
- **Constant accretion rate**. Reasonable to assume that $\dot{M} \sim c_s^3/G$ to order of magnitude, but unlikely to be a constant.
- **Sudden end to accretion**. Seems unlikely unless there is a causal link to some aspect of stellar evolution (eg jets start up when deuterium burning commences).

Several authors have shown that when reasonable uncertainties in these parameters are included, conclusions derived from pre-main-sequence models are uncertain for ages below around 1 Myr.

References:

- Baraffe et al., 2002, A&A, 382, 563.
- Tout, Livio & Bonnell, 1999, MNRAS, 310, 360.

For greater ages, observations of eclipsing pre-main-sequence binaries provide some evidence for the reliability of model tracks:

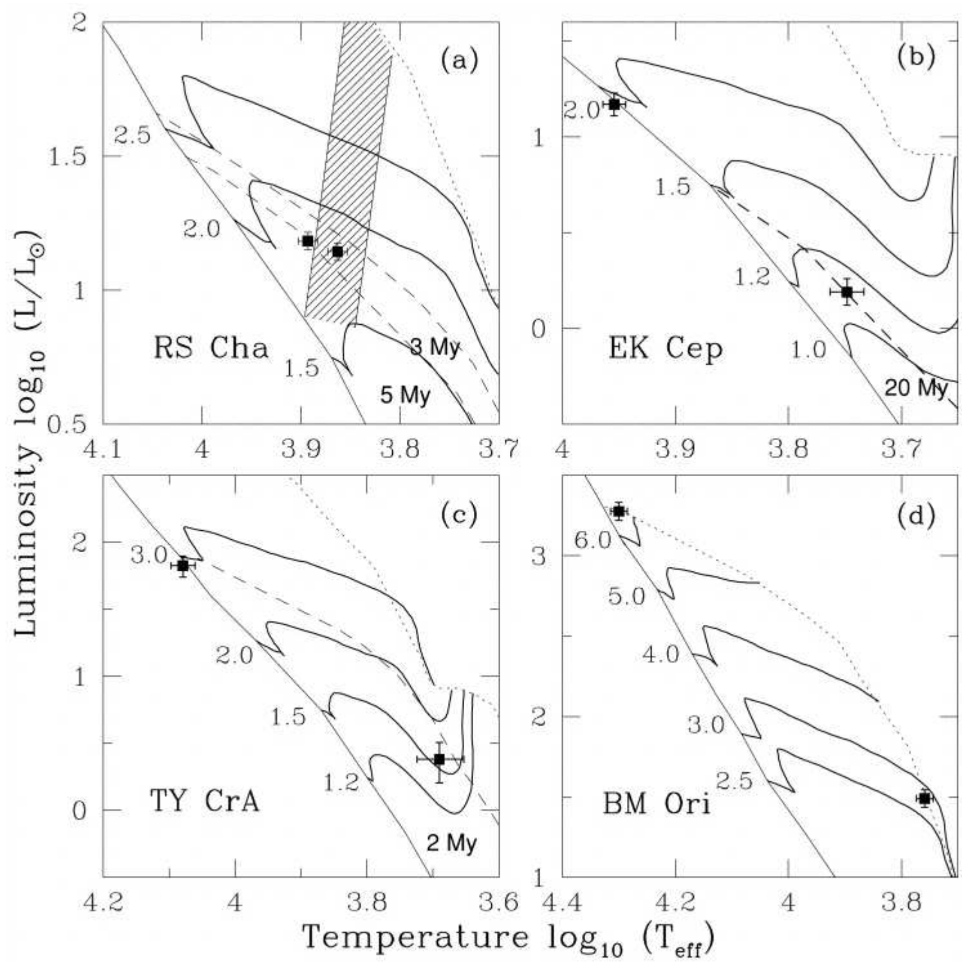


Figure from Palla & Stahler (2001, ApJ, 553, 299).