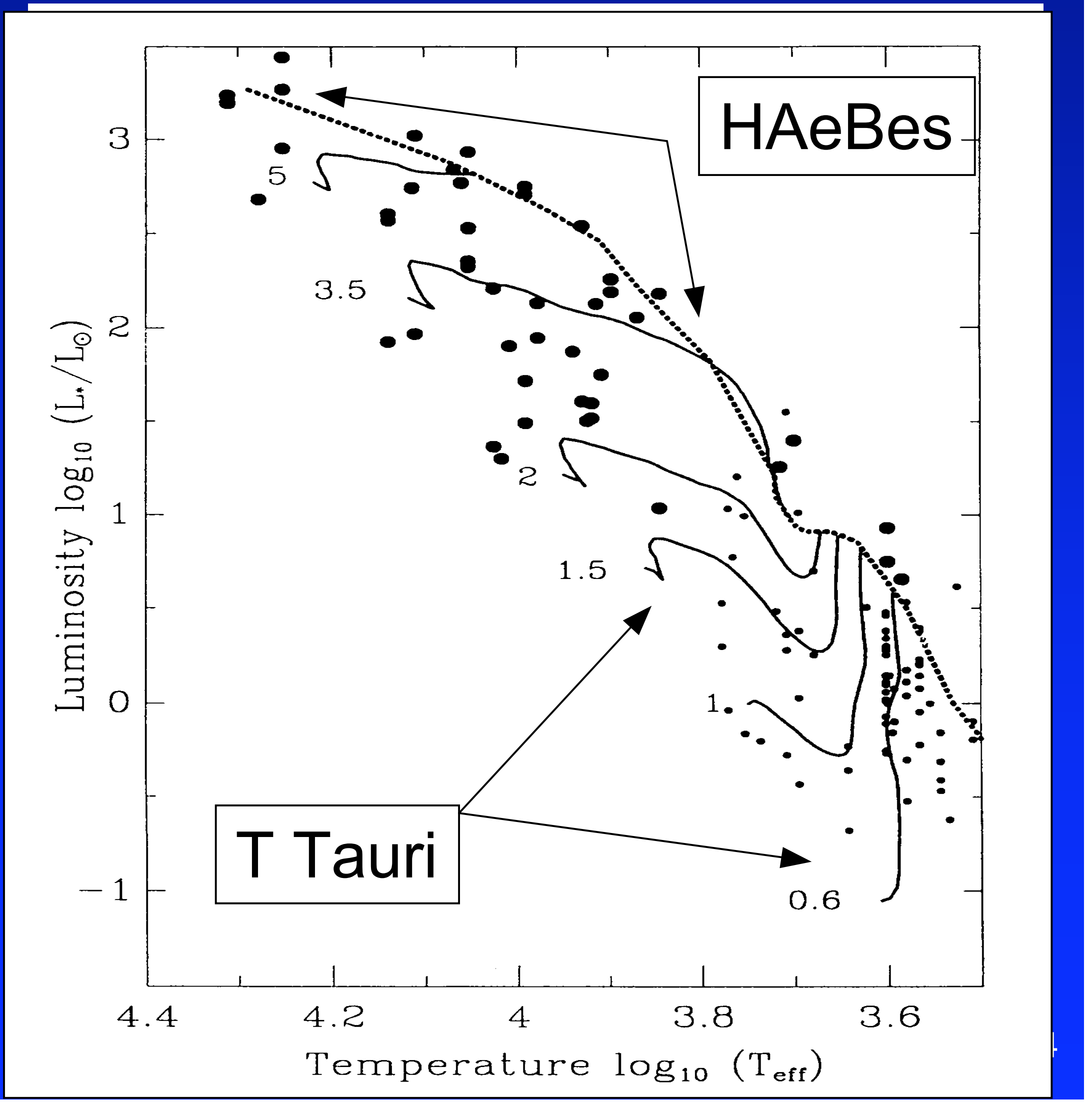
Herbig Ae/Be Stars

- More massive YSO have earlier spectral types, and begin to overlap with the A and B stars
  - Many of the A-type stars have emission lines and other spectral peculiarities
  - To distinguish these stars from older emission line-stars, Herbig (1960 ApJS 4 337) selected a group of Ae or Be type stars with associated bright nebulosity and which were in obscured regions
- These stars have IR excess due to circumstellar dust
  - Circumstellar dust distinguishes YSOs in this mass range from classical Ae and Be type stars
  - Classical Ae and Be stars often have IR excesses
    - + Due to free-free emission from circumstellar gas disk (free-free)

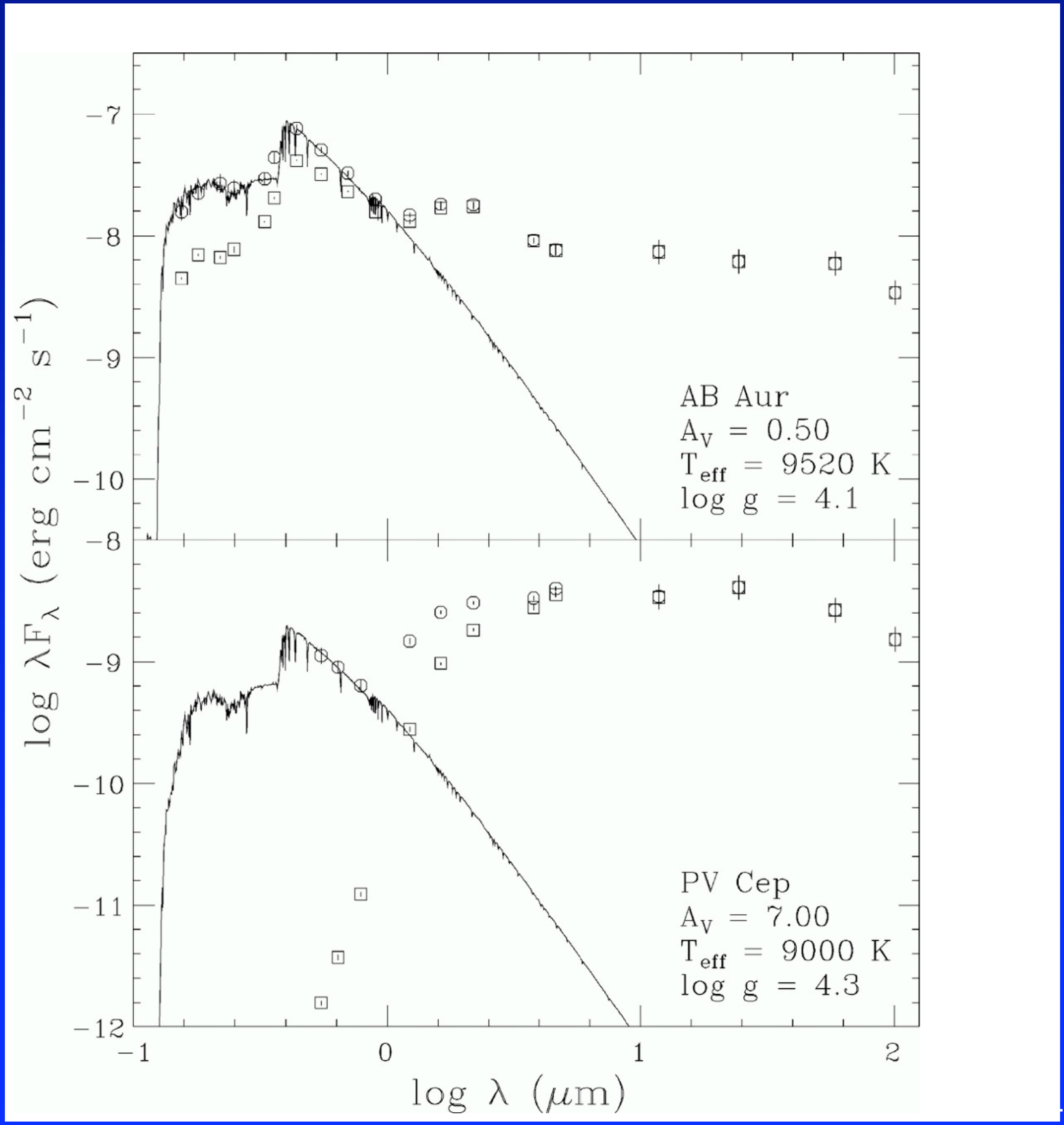
T Tauri Stars & Herbig Ae/Be Stars

- T Tauri stars have long PMS evolution
    - 10-100 Myr
- Herbig Ae/Be stars are 2-10 $M_{\odot}$
    - $t_{PMS} < 10$ Myr
- For M > 5 $M_{\odot}$ there is no PMS phase
    - ***Birthline*** indicates approximate location where YSOs become visible



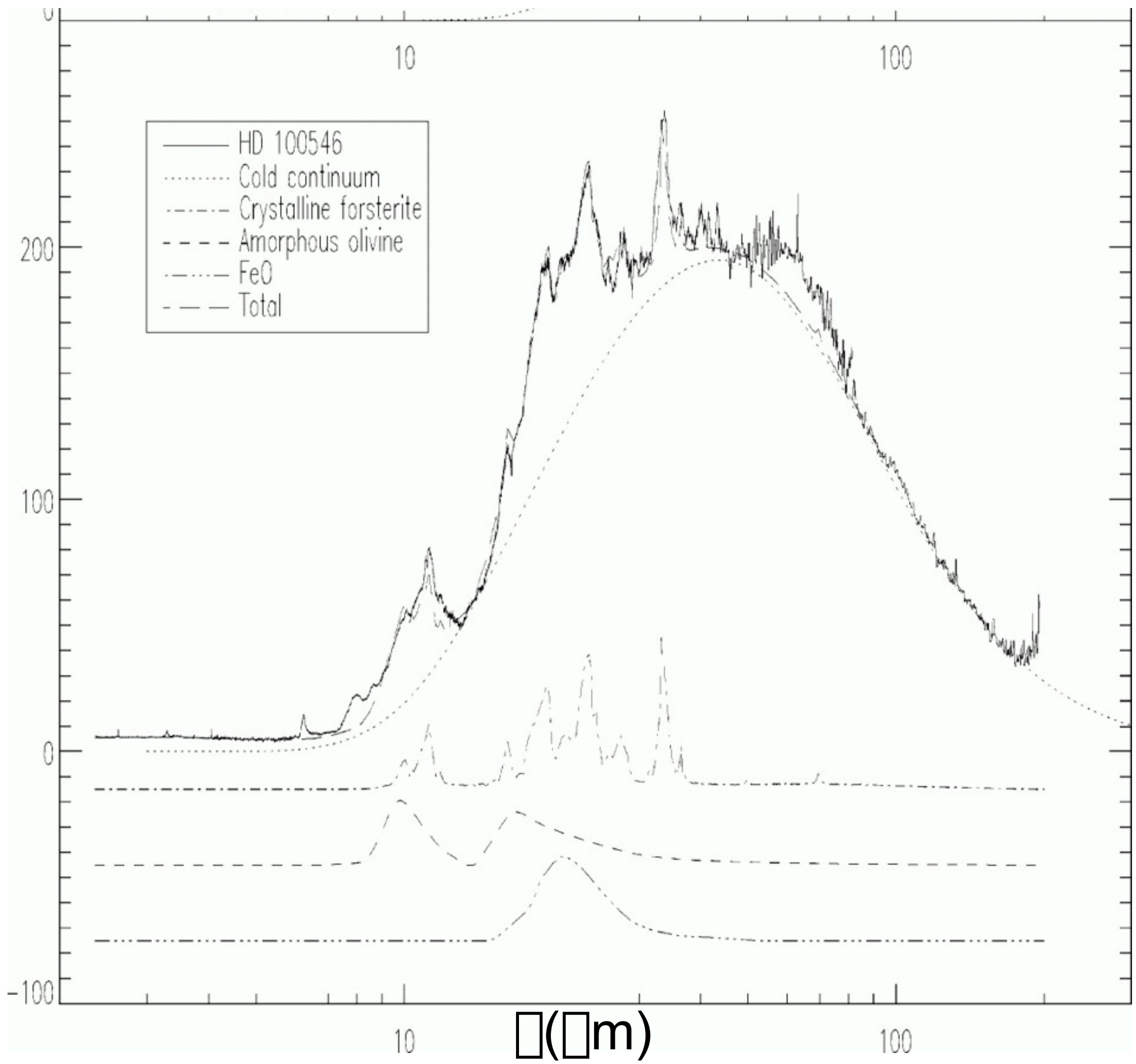
IR Excess of HeAeBe Stars

- Spectral energy distribution (SED) of AB Aur [Hillenbrand et al's (1992) group I] and PV Cep (group II)
  - Squares are observed fluxes
  - Circles are extinction corrected
  - Note the onset of an IR excess already at 1-2 µm



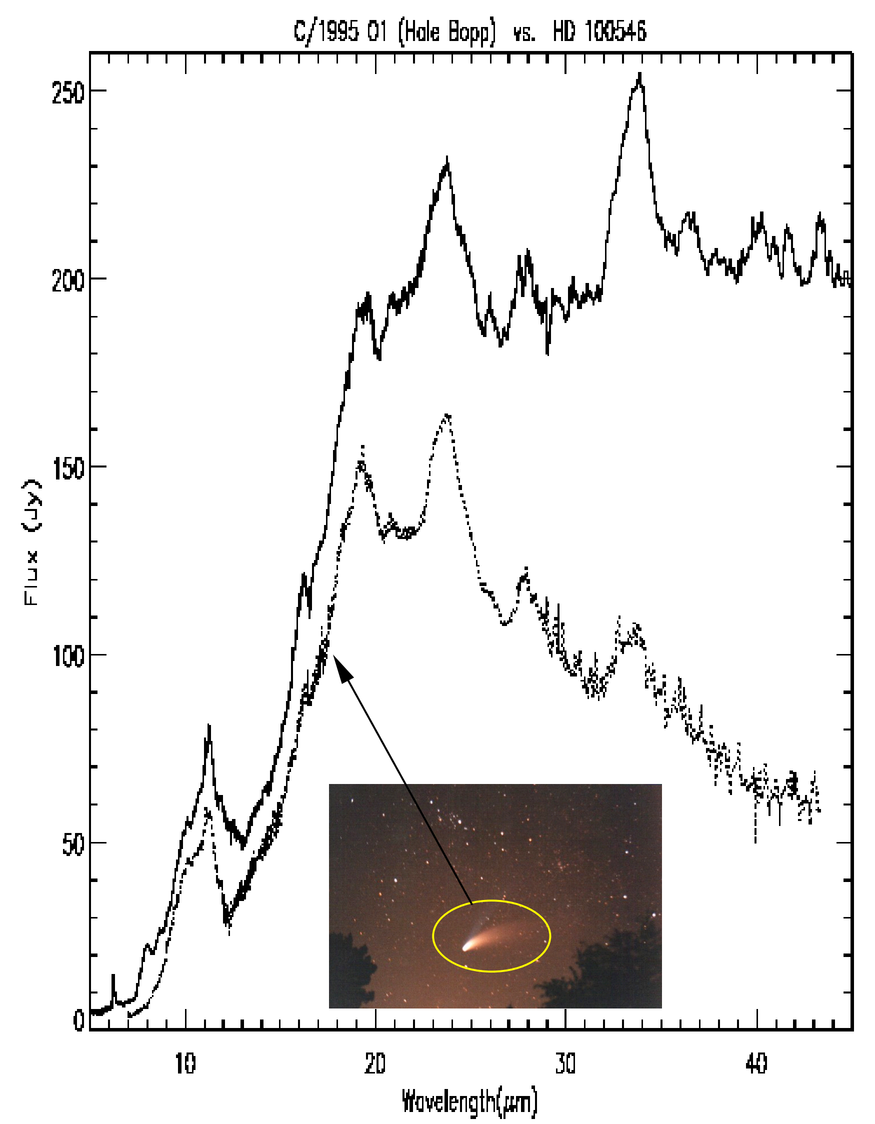
IR Spectra of HAe/Be Stars

- ISO spectra of Hae/Bes show a rich variety of solid state bands
  - Silicates (amorphous and crystalline)
    - + Interstellar silicates are amorphous
  - FeO,
  - polycyclic aromatic hydrocarbons (PAHs),
  - Crystalline H_2O ice



HD 100546 & Comet Hale-Bopp

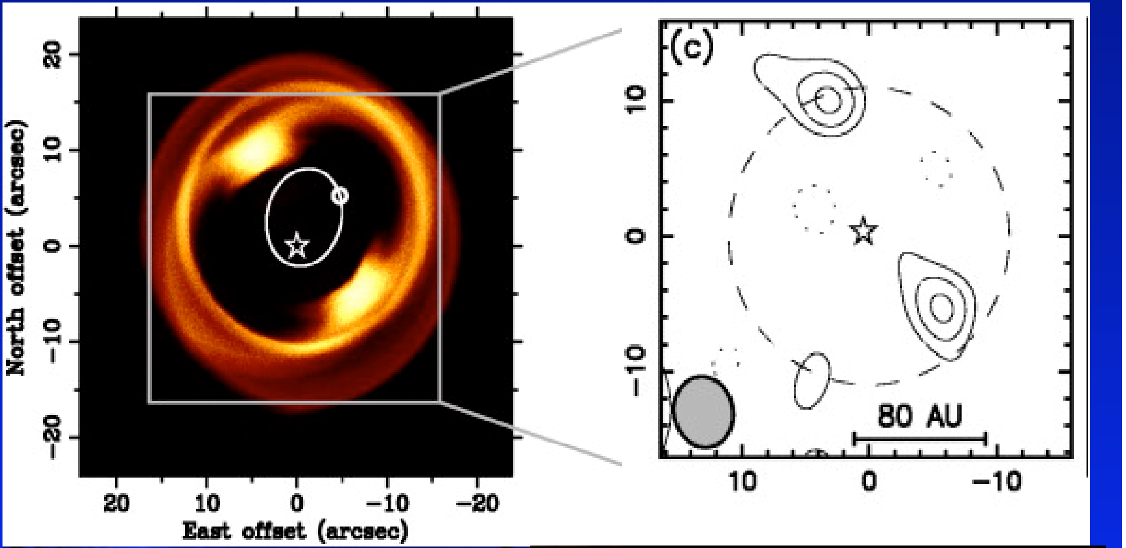
- ISO-SWS spectrum of the Herbig Ae star HD 100546 (full line) compared to the spectrum of comet Hale-Bopp

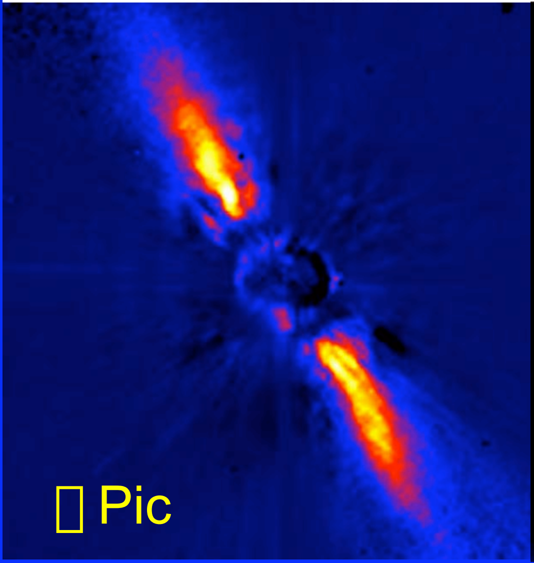


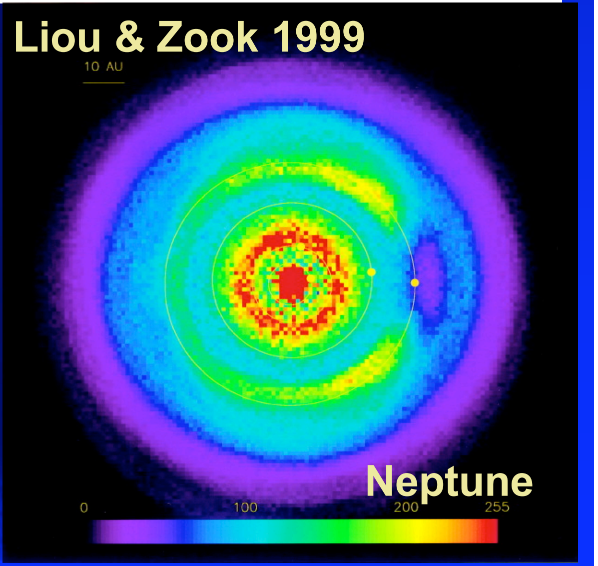
Interplanetary & Interstellar Dust

HAeBes are Progenitors of Debris Disks Stars

- A stars host debris disks
  - Vega, Pic, Fomalhaut
- Dust removed by P-R effect & replenished by erosion of planetisimals
- Warps & blobs may be excited by planets

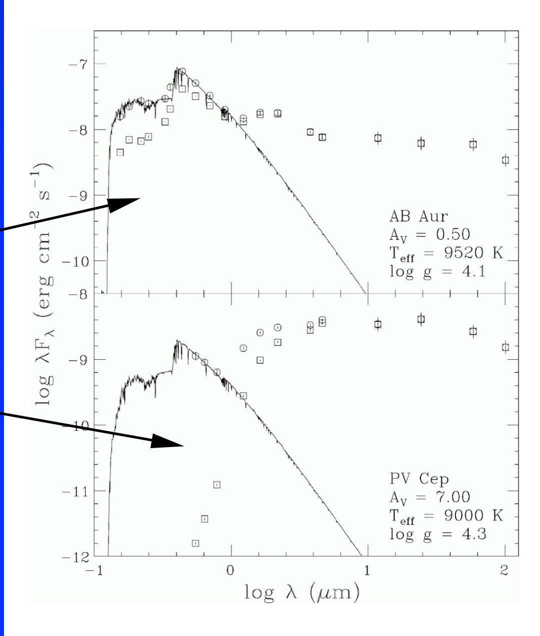






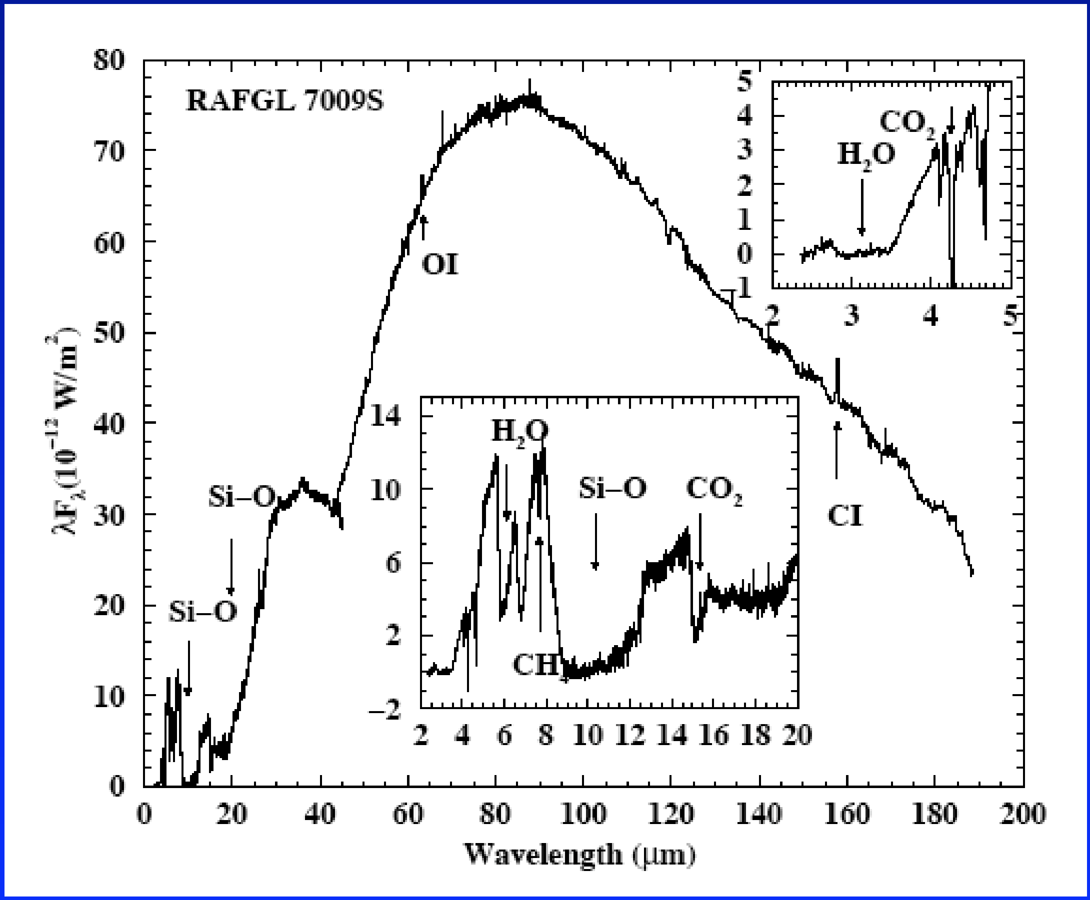
IR Properties of YSO

- IRAS/ISO data for of HAe/Be stars give examples of the information that only IR observations can yield
  - IR observations may yield the only method of study
  - of YSO deeply buried in molecular clouds
  - IR spectral energy distribution classification
    - + $\lambda F_\lambda \sim \lambda^s$
    - + s = -3 star
    - + s = -4/3 accretion disk
      - ◆ s < -4/3 class III
      - ◆ -4/3 < s < 0 class II
      - ◆ s > 0 class I
    - + IR properties of YSO cannot be understood in terms of spherical dust clouds

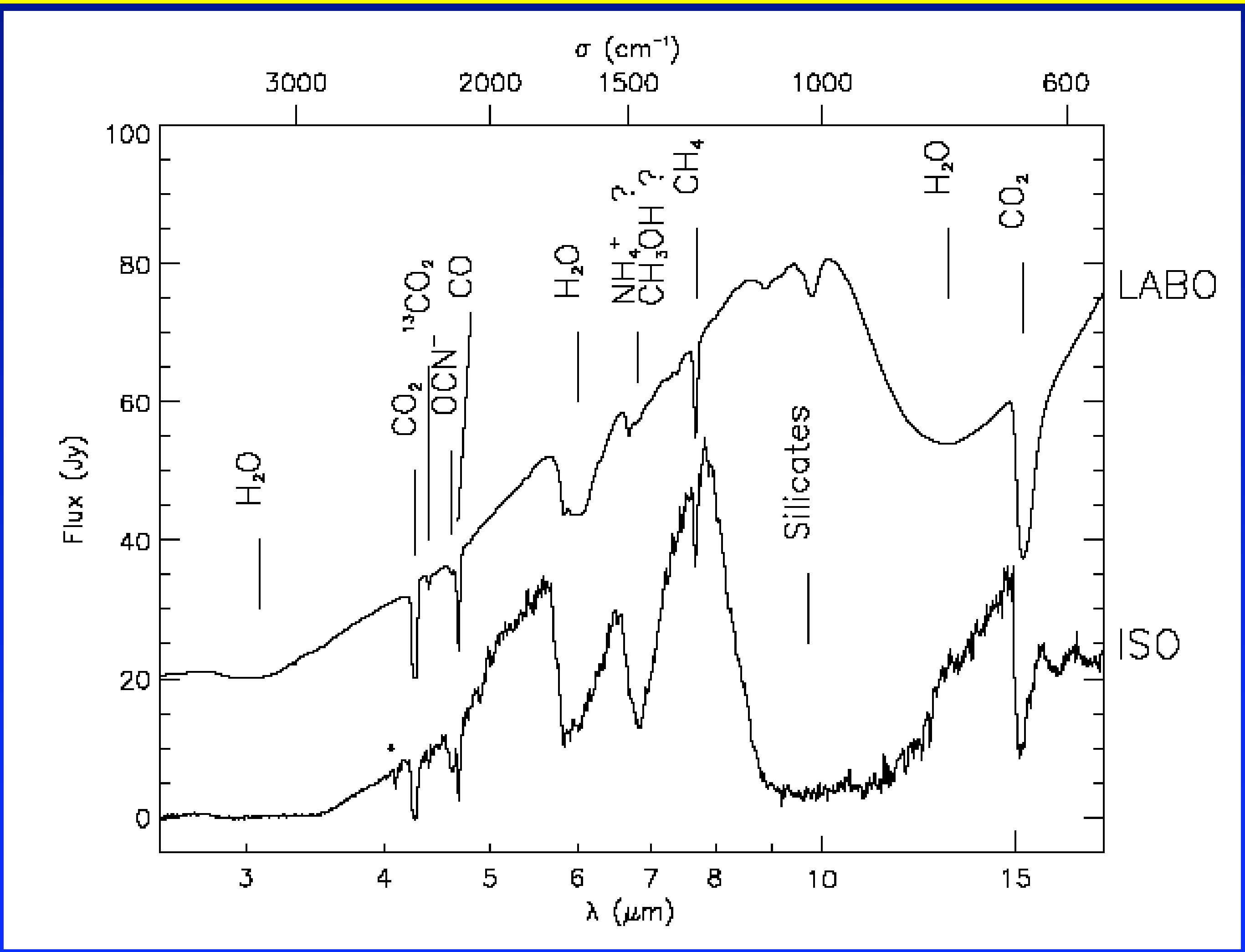


IR Spectra of Class I Objects

- Sources where most of the energy is radiated in the IR
  - Cool dust continuum *T* ≈ 35 K
  - Many absorption features (d'Hendecourt et al. 1996 AA 315 L365)
    - + Deep, broad 9.7 & 18 µm Si absorption
    - + 3 & 6µm H_2O ice
    - + 4.27 & 15.2 µm CO_2 ice
    - + 7.7 µm CH_4



IR Spectra of Class I Objects



- The 2.5-18 μm spectrum of RAFGL 7009S compared to the laboratory spectrum of a ultraviolet photolysed ice mixture H_2O:CO:CH_4:NH_3:O_2

Collapse & Accretion of Stars

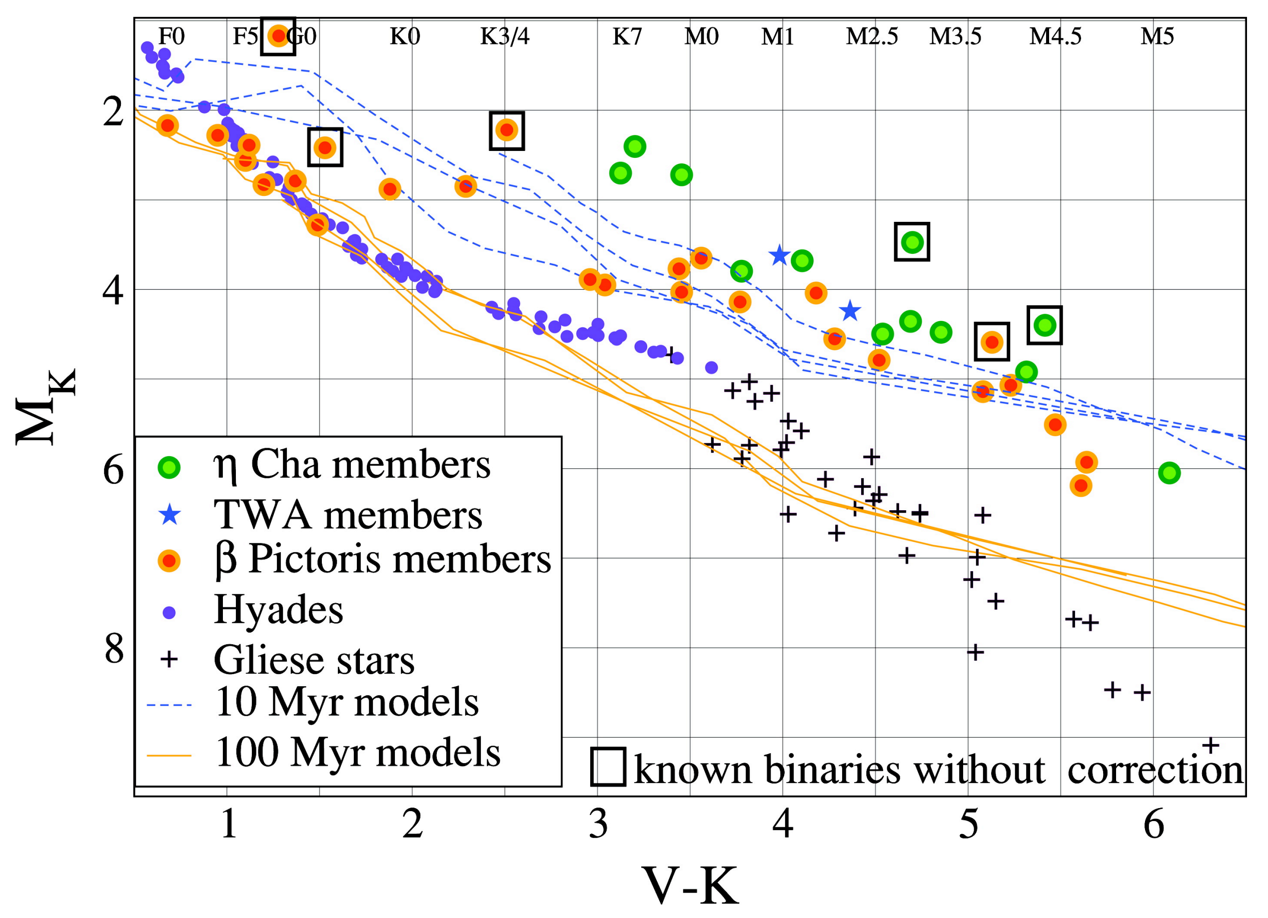
- YSO are not on the main sequence
  - Main sequence?
    - Hydrostatic equilibrium
    - Surface radiant energy loss balanced by thermonuclear burning of H
  - Initially the central temperatures of YSO are too cool for for H fusion
    - Energy lost must be balanced by the release of gravitational potential energy
  - The location of a YSO in the HR diagram is a clue to its age

Pre-Main Sequence Evolution

- A reliable understanding of pre-main sequence evolution would reveal many details of star formation
  - What is the star formation history?
    - How long does star formation last?
    - Which stars form first?
    - What is the relation between young stars in adjacent regions?
    - How long does circumstellar material persist?
  - What is the evolutionary status of various YSO
    - CTTS vs. WTTS?
    - How quickly do planets form?
  - What is the origin of the initial mass function?

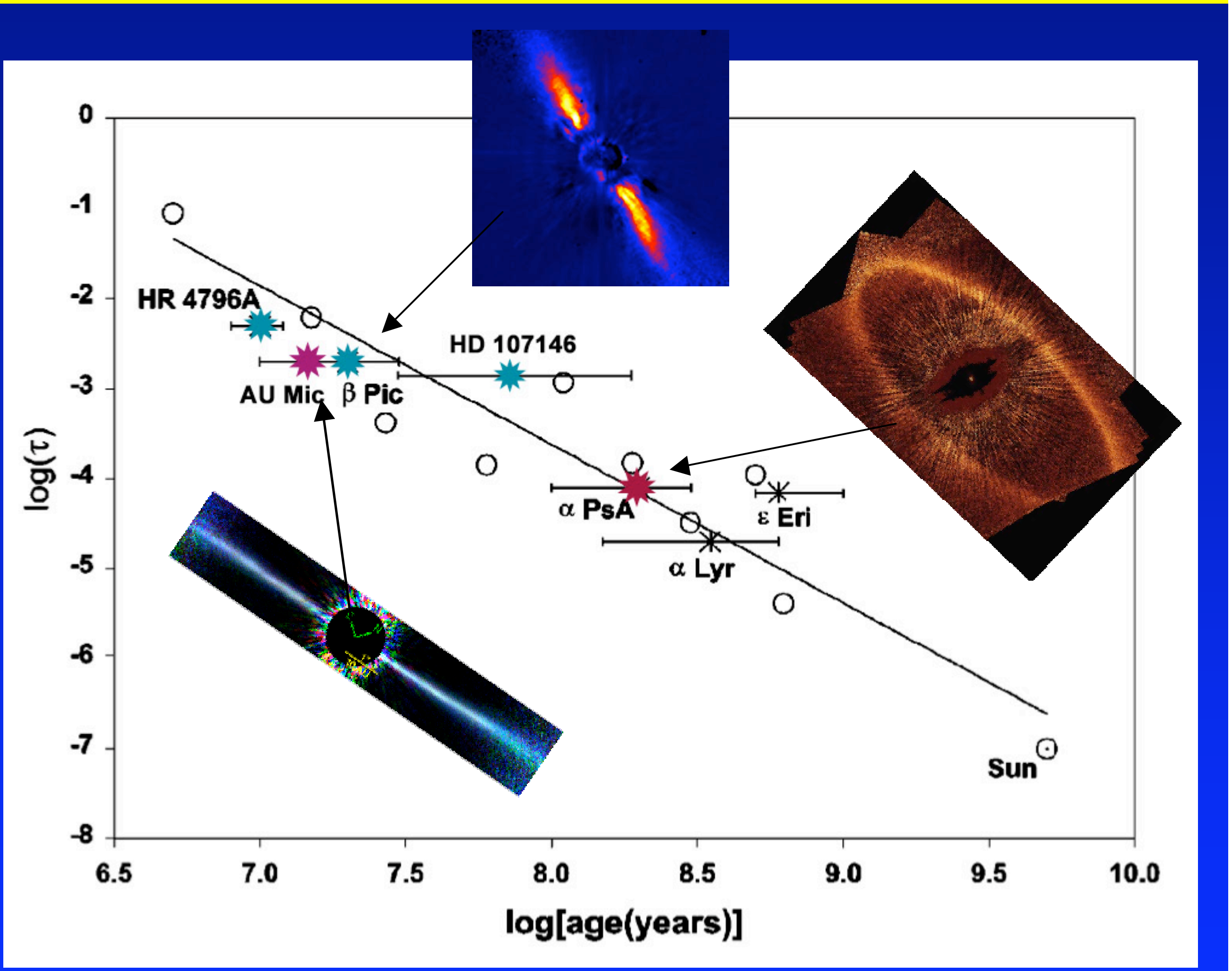
Stars Near the Sun

- Young stars in the solar neighborhood showing M_K vs V-K color of main sequence and pre-main sequence stars
  - All stars have Hipparcos parallaxes
  - Isochrones for solar [Fe/H] from four groups plotted at 10 & 100 Myr
  - Hyades (600 Myr) and late-type Gliese indicate the main sequence



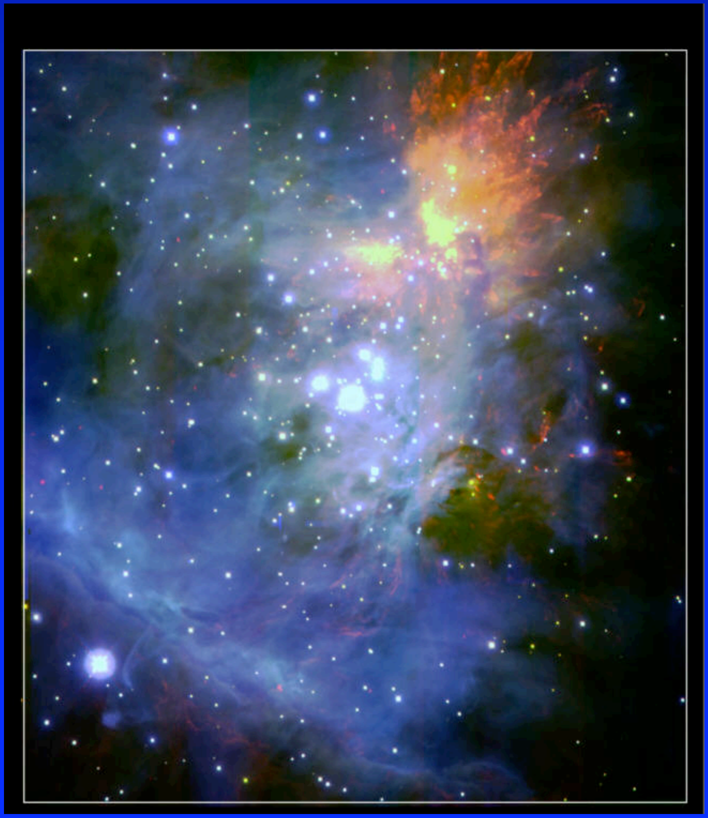
Evolving Circumstellar Environment

- Debris disk studies suggest that the quantity of circumstellar material declines rapidly with age: $M \mu t^{-2}$

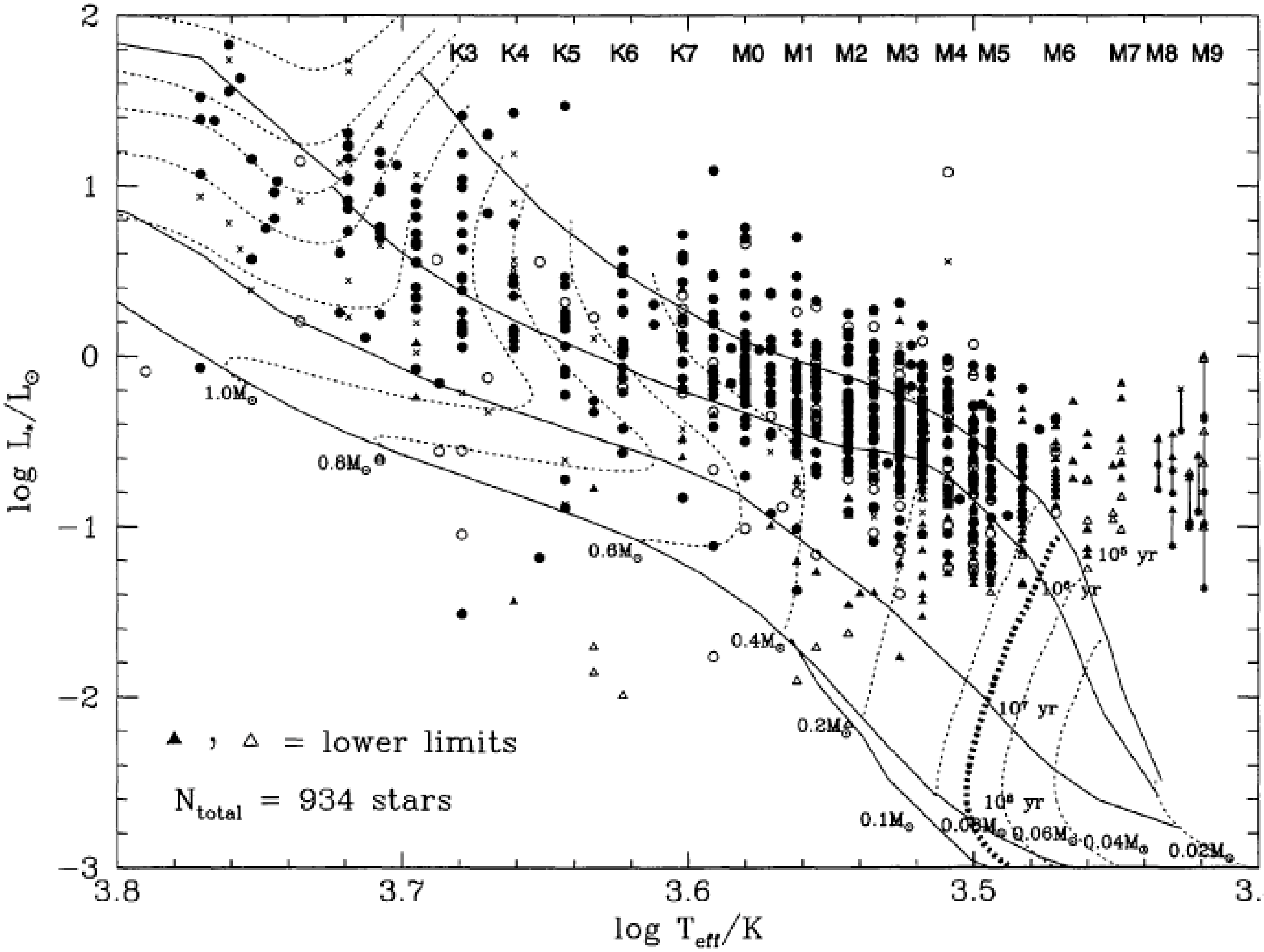


Young Low Mass Stars in Orion

- Spectral type & luminosity for ~ 1700 stars within 2.5 pc of the Trapezium cluster (Hillenbrand 1997 AJ 112 1733)
- Youthful population
  - Lies above the main sequence
  - Age < 1-2 Myr



HR Diagram for Low Mass Stars in Orion



Hillenbrand 1997 AJ 113 1733

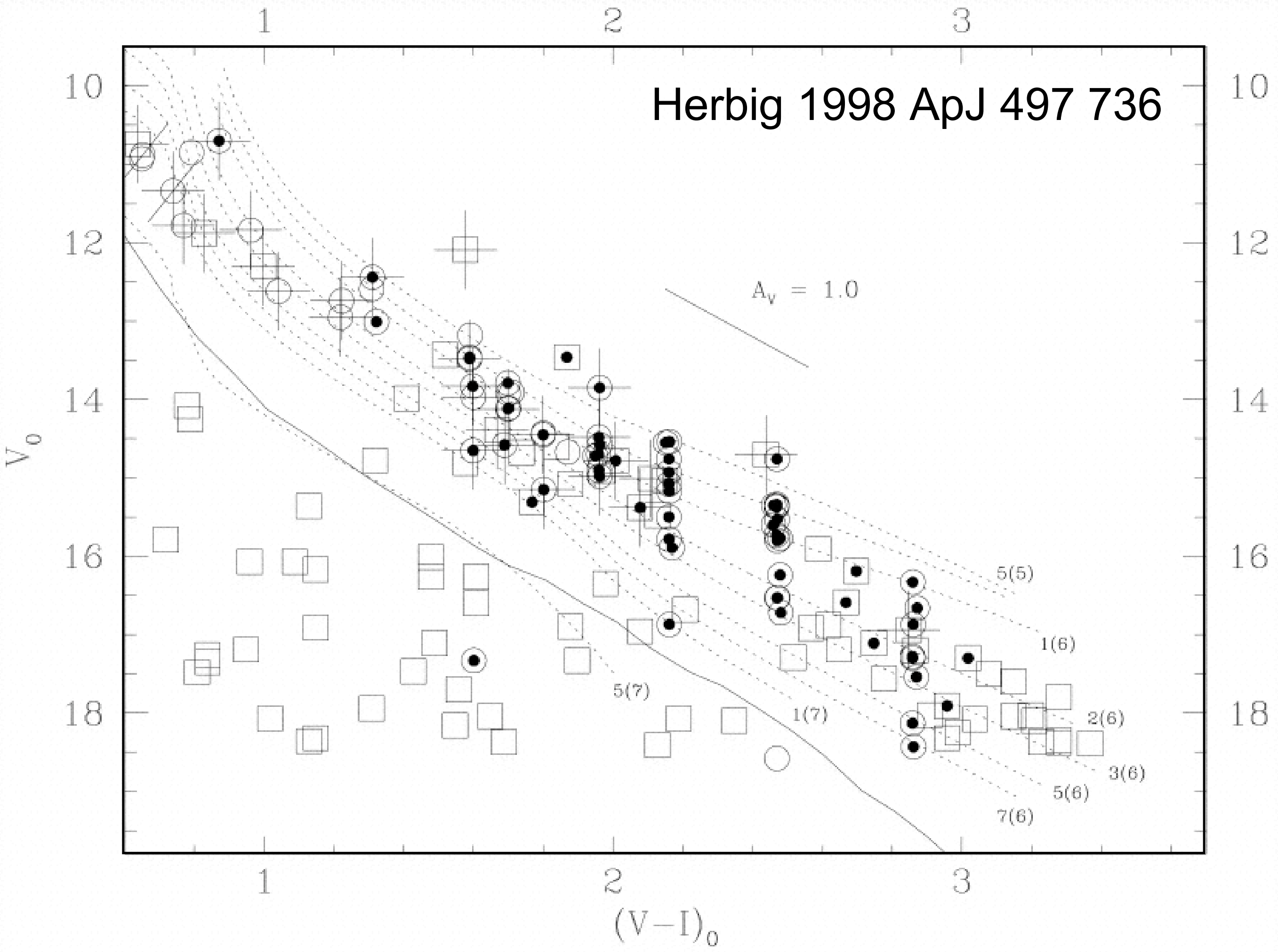
Age Spread in IC 348?

- 110 T Tauri stars in IC 348
  - ● H
  - + ROSAT
- Apparent age ~ 0.7 - 12 Myr
- Mean ~ 1.3 Myr

o Reddening for stars of known spectral type

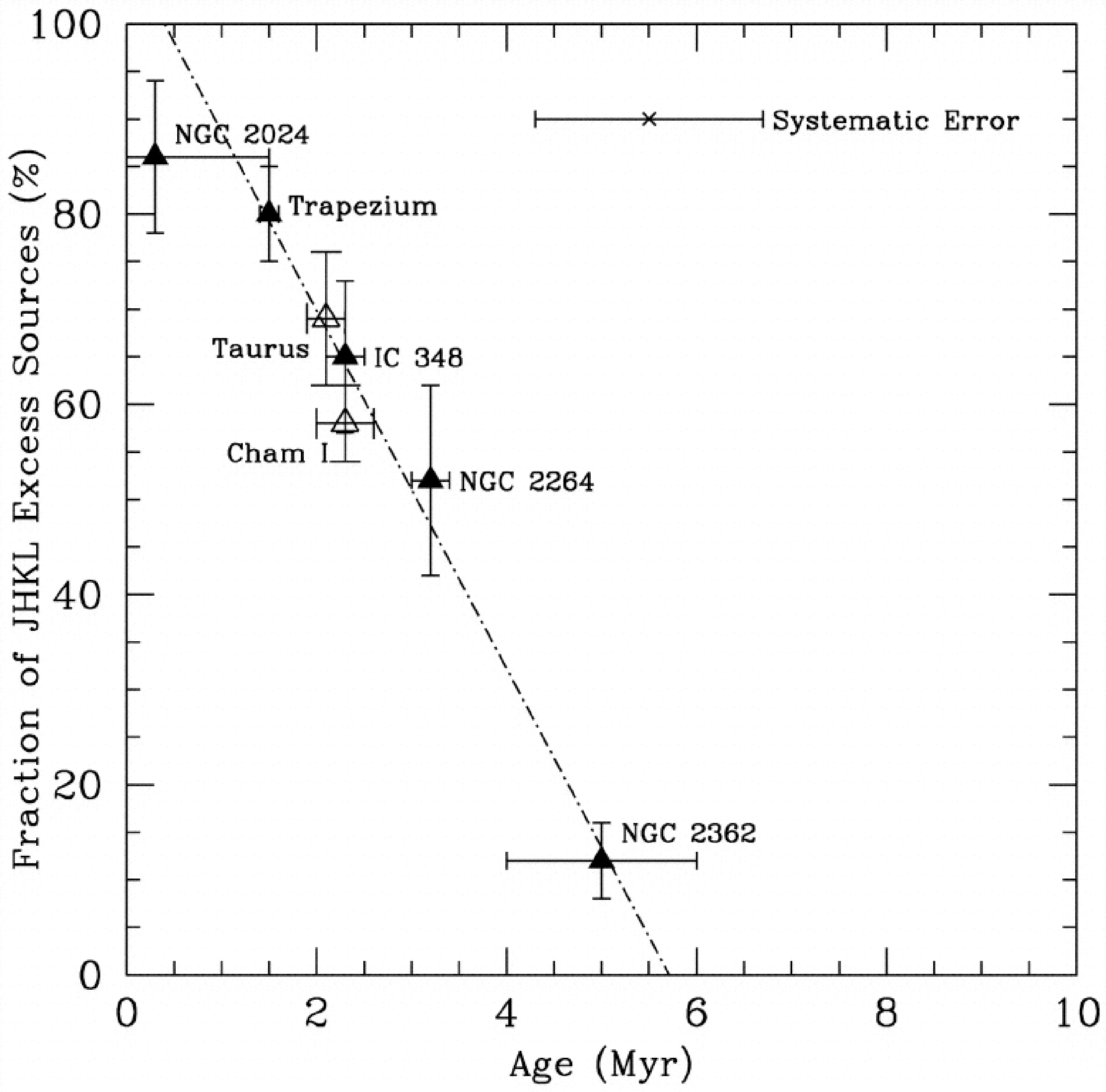
□ A_V = 2.8 mag assumed

/ Astrometric nonmembers


Herbig 1998 ApJ 497 736

Disk Lifetime?

- JHKL excess/disk fraction as a function of mean cluster age (Haisch et al. 2001 ApJL 553 153)
- The decline in the disk fraction vs.age suggests a disk lifetime ~ 6 Myr
  - Vertical bars represent the √*N* errors in derived excess/disk fractions
  - Horizontal bars represent the error in the mean of the individual source ages derived from a single set of PMS tracks
  - Systematic uncertainty is estimated by comparing ages from using different PMS tracks



Estimating Ages

- Derived ages for T Tauri stars depend to some extent on initial location in the HR diagram
  - L & T_{eff} at the end of protostellar accretion
    - Disk accretion during the T Tauri phase (10^{-7} $M_{\odot}$ yr^{-1}) is insignificant
  - Low mass ***protostars*** may finish their primary accretion phase near the ***birthline*** (Stahler 1983 ApJ 274 822)
    - The birthline is generally near the D-burning main sequence
    - Whether the D-burning main sequence defines an exact starting point for for T Tauri stars depends on factors such as how much thermal energy is added during protostellar accretion
    - The youngest low mass stars are observed near the birthline, but a definitive observational test does not yet exist
    - D-burning is insignificant for more massive stars ($M > 5$ $M_{\odot}$)

Pre-Main Sequence Evolution

- Before a YSO reaches the main sequence its interior is too cool for H fusion
  - The star contracts so that gravitational potential energy makes up for energy lost from the surface
- Pre-main sequence stars have convective interiors and hence nearly isentropic

$$P\rho^{-\gamma} = K$$

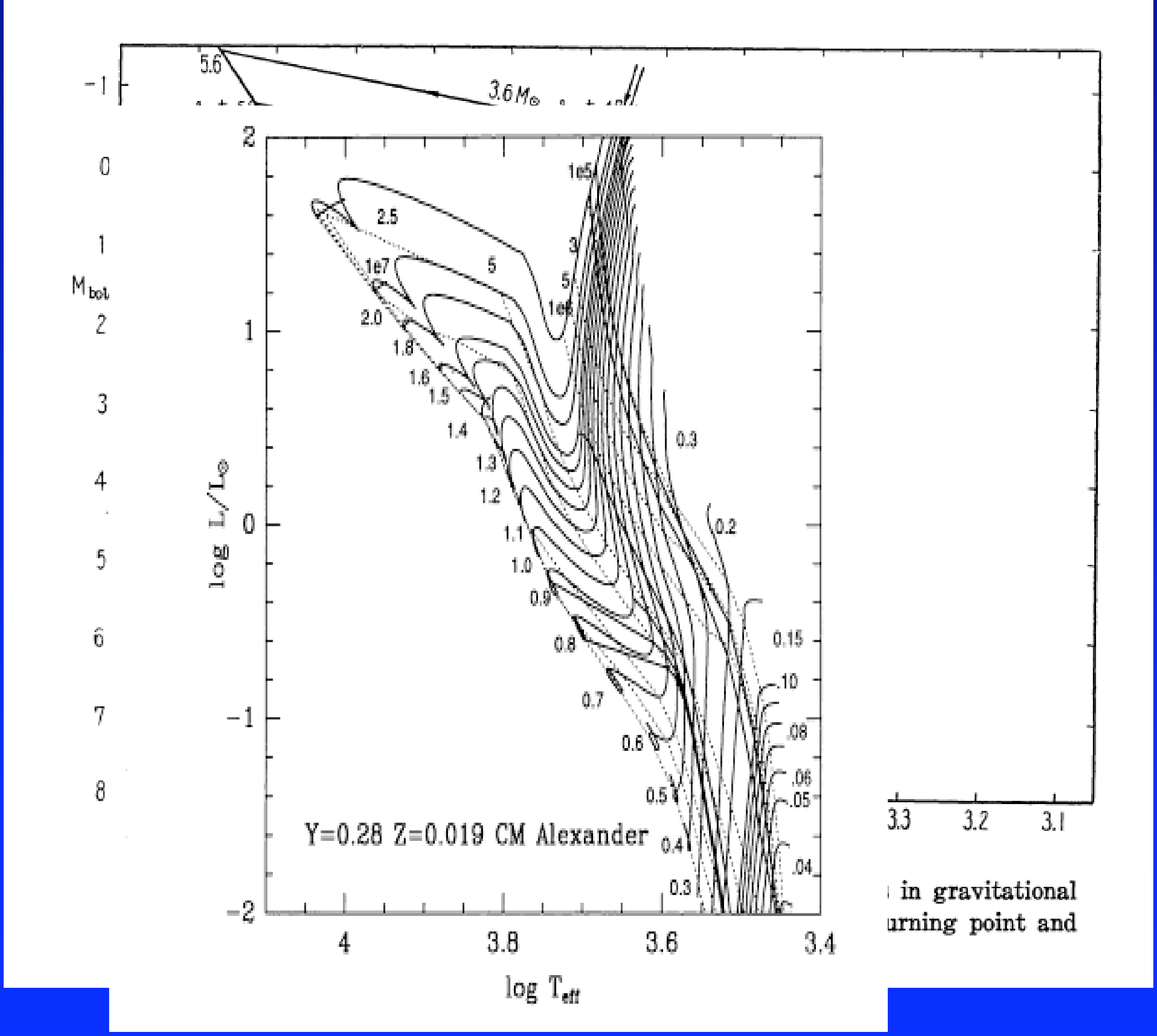
  where $n = 1/(\gamma-1)$ is the polytropic index
- $\gamma = 5/3$ corresponds to $n = 3/2$ ***polytrope***
  - Mass radius relation $M_* R_*^{1/3} = K$
    - K is determined by the boundary condition between the convective interior and the radiative atmosphere

Hayashi Tracks

- Hayashi (1961 PASJ 13 450) discovered a “forbidden zone” on the HR diagram
  - Opacity drops rapidly < 4000 K when H recombines
  - Photosphere must have large optical depth
    - Low opacity makes it impossible to match the radiative atmosphere to the convective interior
  - Initial contraction of low mass pre-main sequence stars tends to be at approximately constant temperature

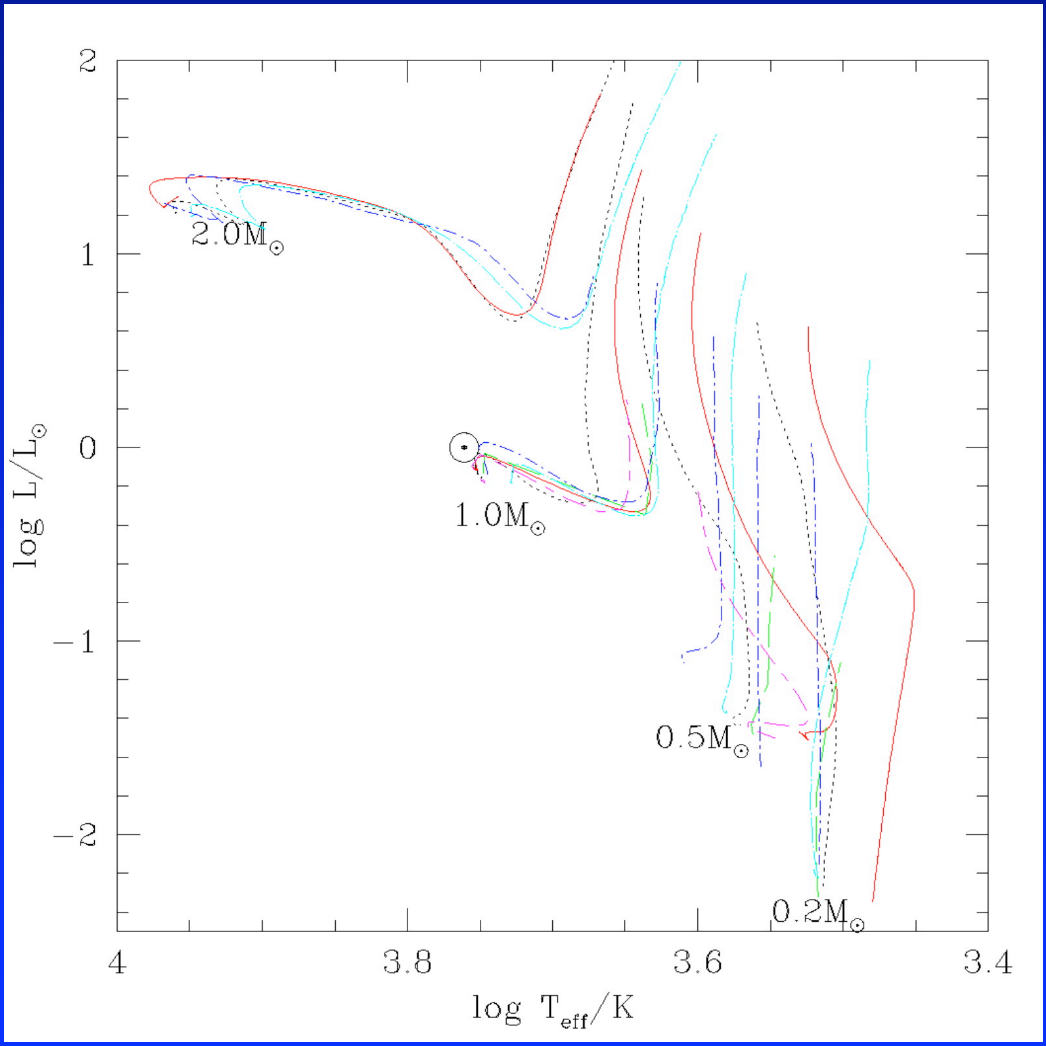
Hayashi Tracks

- Hayashi 1961 PASJ 13 450
- D'Antona & Mazzitelli 1994 ApJS 90 467



Theoretical (Dis)Agreement

- Variation between pre-main-sequence contraction tracks for masses
  - Swenson et al. 1994 ApJ 425 286 (solid)
  - D'Antona & Mazzitelli 1994 ApJS 90 467 (dotted)
  - Baraffe et al. 1998 A&A 337 403, (long-dash)
  - Palla & Stahler 1999 ApJ 525 772 (dotshort-dash)
  - Yi et al. 2001 ApJS 136 417 (long-dashshort-dash)



Evolution of Polytropes

- The gravitational potential energy of polytrope is

$$W = -\frac{3}{5-n}\frac{GM^2}{R} = -\frac{6}{7}\frac{GM^2}{R}$$

For n = 3/2

By the Virial theorem

$$2T + W = 0$$

Total energy

$$E = T + W = -\frac{3}{7}\frac{GM^2}{R}$$

$$L = \frac{dE}{dt} = -\frac{3}{7}\frac{GM^2}{R^2}\frac{dR}{dt}$$

Hayashi Contraction

- The negative sign indicates that a decrease in the total stellar energy results in positive luminosity
  - By the virial theorem half of the gravitational potential energy is converted into thermal energy and half is radiated
    - + Negative specific heat capacity
  - Consider Hayashi evolution is described by

$$T_{eff} = (L / 4\pi\sigma R^{2})^{1/4} \approx \text{const.}$$

Kelvin-Helmholtz Timescale

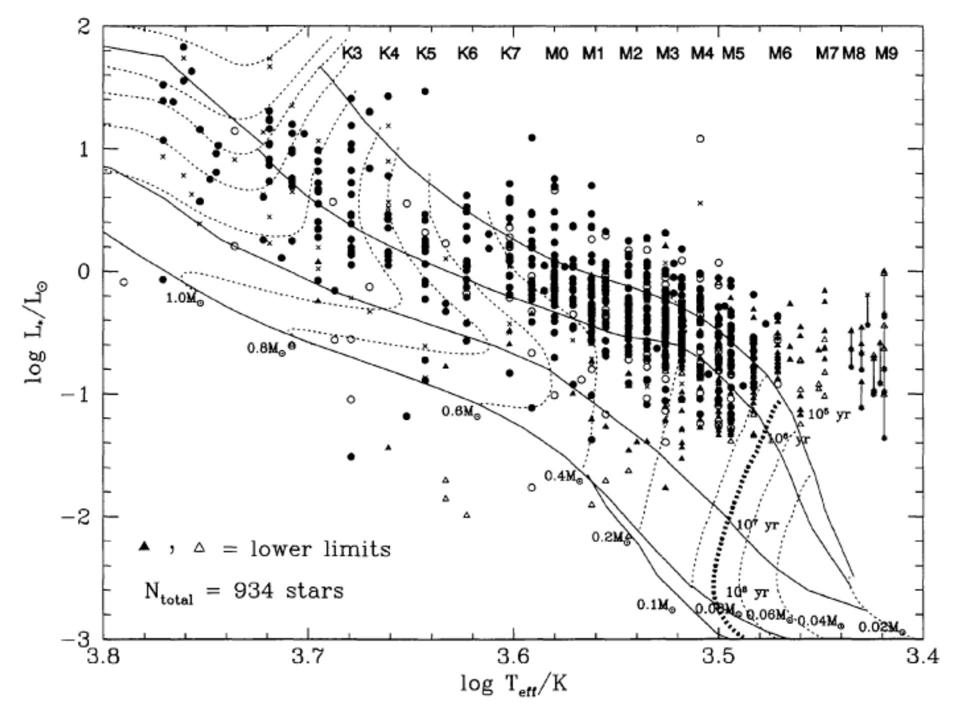
- Combining the contraction luminosity with T_{eff} = const. yields

$$L = L_0 \left(\frac{3t}{\tau_{KH}} \right)^{-2/3} \quad \text{where } \tau_{KH} = \frac{3}{7} \frac{GM^2}{L_0 R_0}$$

- τ_{KH} is the Kelvin-Helmholtz timescale ~ *E/L*
  - As the star ages it contracts and becomes fainter
  - The rate of decrease in *L* (and *R*) slows with time
- For a PMS object 0.8 $M_\odot$, 2 $R_\odot$, & 1 $L_\odot$
  - τ_{KH} = 4.3 x 10^6 yr and Hayashi contraction time is τ_{KH}/3 = 1.4 x 10^6 yr

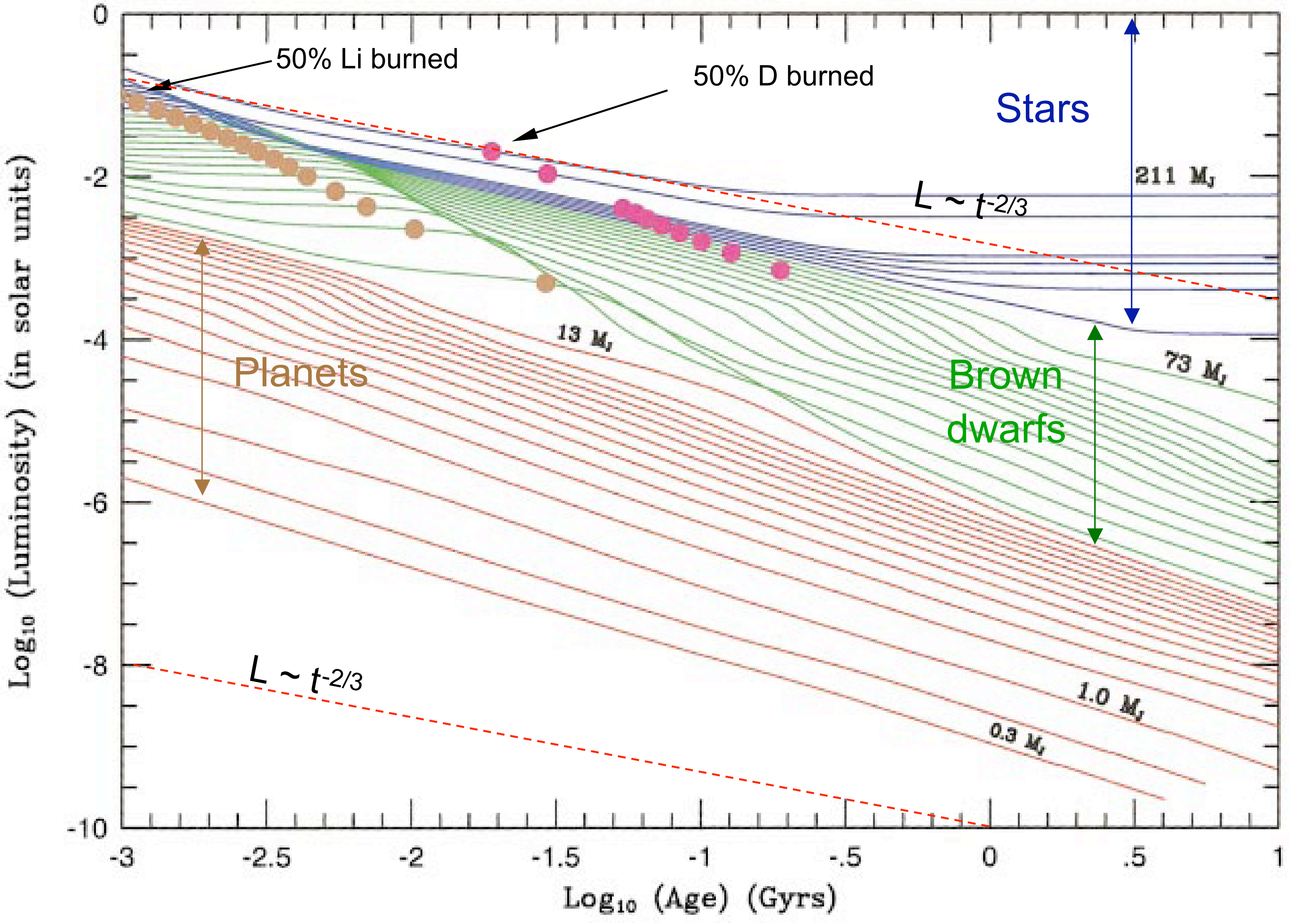
Hayashi Contraction

- A factor of 10 in age corresponds to a factor of $10^{2/3}$ or 1.7 mag. dimmer
  - A discrepancy with detailed models arises between 1-3 x 10^5 yr due to D-burning which occurs when central temperatures reach ≈ 10^6 K
  - D-burning slows stellar contraction, which continues when D is exhausted
  - Contraction is halted again by H fusion on the main sequence



Contraction of Low Mass Stars/Brown Dwarfs

Burrows et al. 1997 ApJ 491 856

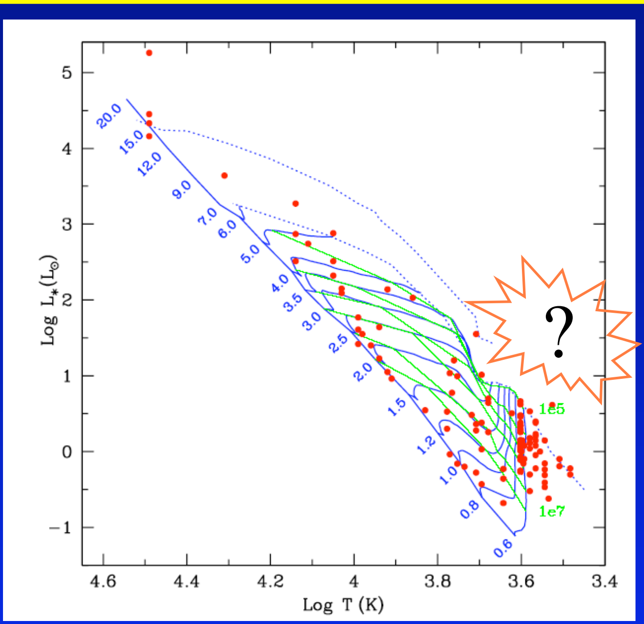


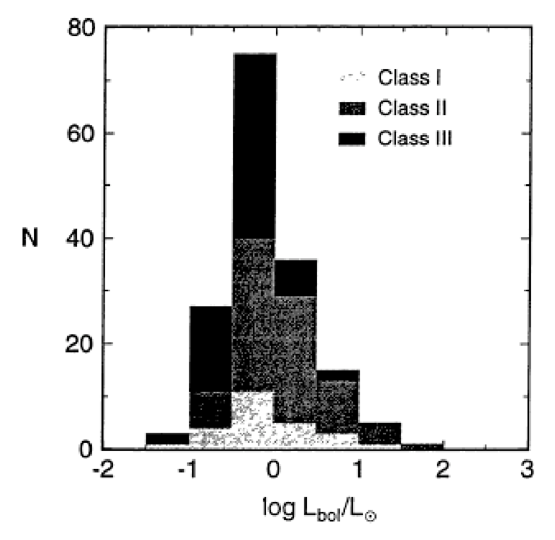
Convective/Radiative Tracks

- Low mass stars remain convective until they reach the main sequence ($n = 3/2$ polytrope)
  - Path is ~ vertical on the HR diagram
  - More massive stars (> 0.7 $M_{\odot}$) develop a radiative core (Henyey et al. 1955 PASP 67 154)
    - + Subsequent contraction is at L ~ constant
    - + Radiative stars have a well defined mass-luminosity relation
  - Stars < 0.3 $M_{\odot}$ are completely convective on the main sequence

Formation of Protostars

- Pre-main sequence tracks assume that low mass stars are formed high on convective Hayashi tracks
  - Why are there so few of these objects?
  - Perhaps stars evolve quickly through this region?
    - + $\tau_{KH} \sim M^2 / LR$
    - +For a uniform star formation rate $N(t) \sim L^{-3/2}$ when $L \sim t^{-2/3}$
  - Young stars are also likely to be the most heavily extincted
    - +But class I and III sources have the same median luminosity (Keyon & Hartmann 1995 ApJS 101 117)



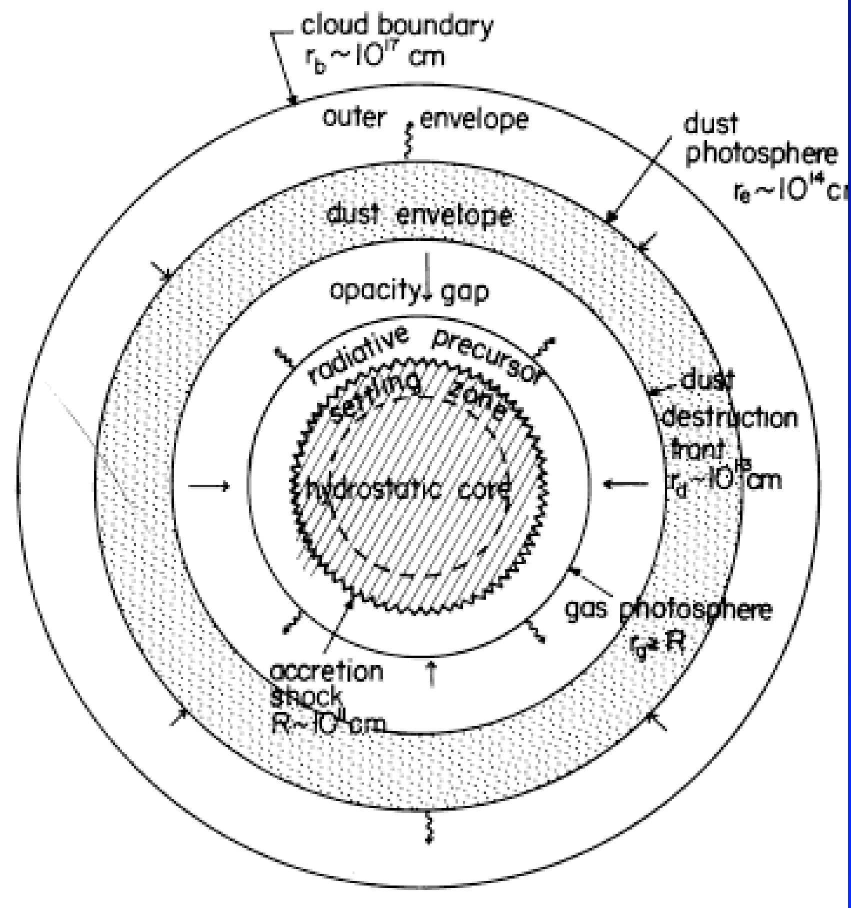


Formation Timescales

- Stars cannot form arbitrarily high on Hayashi tracks (arbitrarily large *R*)
  - Finite time is required to accumulate the stellar matter
  - Characteristic accretion rate is $dM/dt \sim c^3/G$
    - + 2×10^{-6} $(T/10\text{ K})$ $M_\odot\ \text{yr}^{-1}$
    - + Time to assemble 1 $M_\odot$ star from a 20 K NH_3 core is 0.2 Myr
- Where does the gravitational potential energy go?

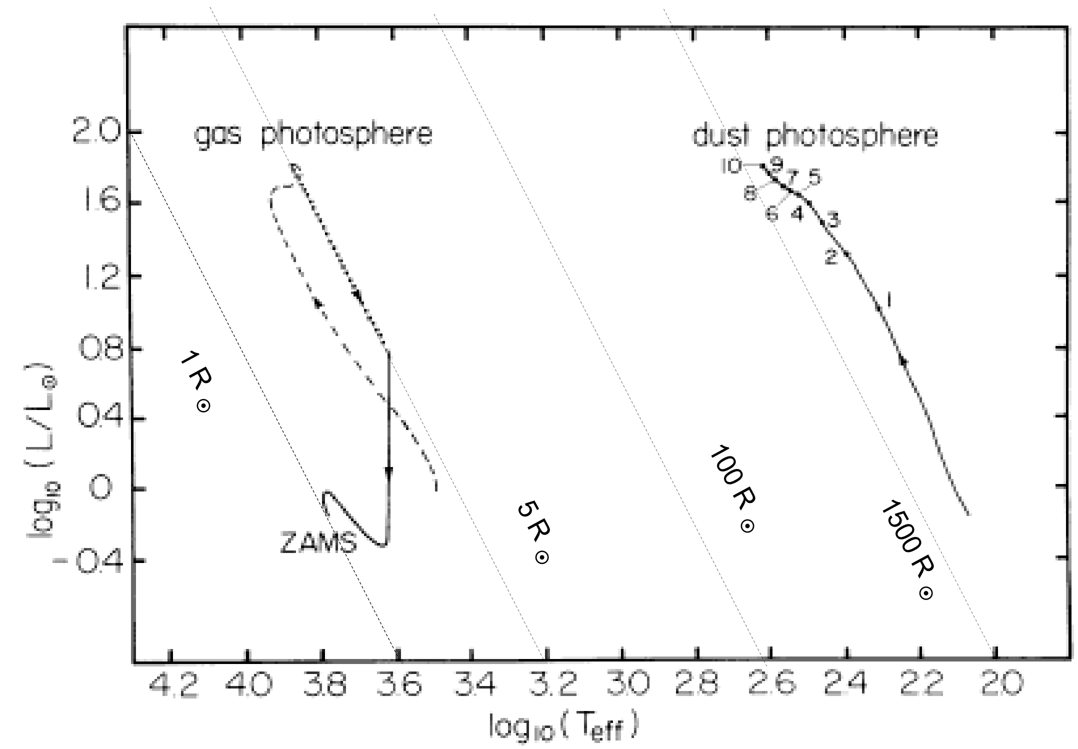
Where Does the Energy Go?

- Stahler Shu & Tamm (ApJ 1980 241 637) conclude efficient escape of accretion energy
  - Accretion energy is absorbed by the surrounding *spherical* dusty envelope
  - A 1 $M_\odot$ protostar emerges with a radius ~ 5 $R_\odot$



Where Does the Energy Go?

- $M_o = 0.01\ M_\odot$ $R_o = 3.5\ R_\odot$
- $dM/dt = 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$ for 10^5 yr
  - Accretion *shut off* at 1 $M_\odot$
  - Gas photosphere cools at constant *R* for ~ 1 day
  - Loiters for ~ 3000 yr on the D main-sequence
  - Followed by Hayashi contraction
- Accretion energy must be trapped to produce a protostellar core in hydrostatic equilibrium
- From the virial theorem computing the radius of a protostellar core reduces to finding the fraction of energy (including D-burning) trapped



The Birthline

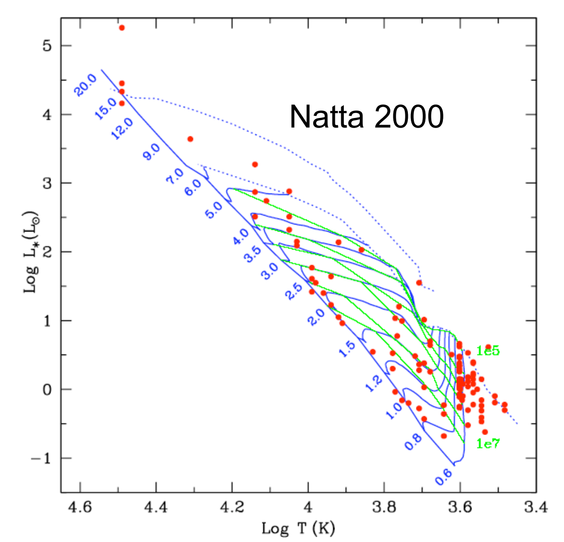
- Schematically star formation consists of two steps
  - Formation of a core in hydrostatic equilibrium
  - Quasi-static contraction to the main sequence
- Step (1) is complex
  - 3-d Radiation-MHD
  - Vast range of spatial scales $R \sim 10^{11}$ - 10^{17} cm
- Stahler (1983 ApJ 274 822) says skip (1)
  - D-burning enforces a strong mass-radius relation once accretion terminates

The Birthline

- For large *dM/dt* deuterium is replenished and mixed into the convective core
  - Maintains significant D abundance
- D burning rate is very sensitive to temperature, □~ $T^{14.8}$
  - In hydrostatic equilibrium $T_{core} \sim M_p/R_p$
    - \+ If the core temperature drops the protostar radius contracts until D burning re-ignites
    - \+ The increase in L_p causes the protostar to expand
    - \+ D-burning enforces a constant M_p/R_p
    - \+ The D main-sequence mass-radius relation defines the protostellar ***birthline***

Comparison with Observations

- Comparison with Taurus-Auriga T Tauri stars suggests rough agreement with the positions of the most luminous optically-visible stars
  - A few objects may lie above the birthline
  - Note—we have no way to estimate masses for class I objects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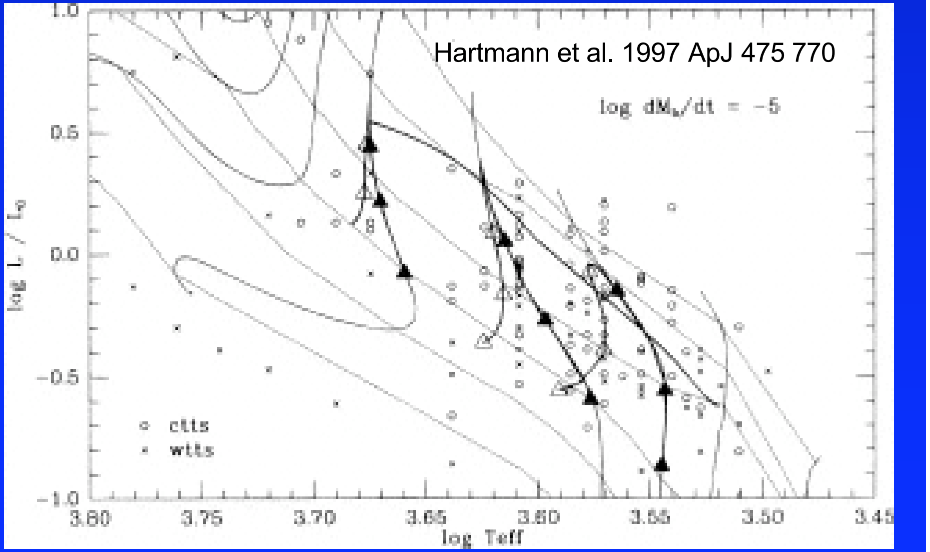
Hartmann et al. 1997 ApJ 475 770

Comparison with Observations

- There is nothing in the birthline calculations which forbids accreting protostars to lie above the D-burning main sequence
- By construction we have no details on core formation
  - The location of the Taurus-Auriga population implies a mass radius relation

    $$R \approx 6\ (M\ /\ \mathrm{M}_\odot\ )\ \mathrm{R}_\odot$$

    or an accretion luminosity

    $$L = 10\ \mathrm{L}_\odot\ (dM/dt\ /\ 2 \times 10^{-6}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1})$$

    for our characteristic *dM/dt*

Comparison with Observations

- Comparison with the luminosity function for Class I objects implies very log mass accretion rates—median $dM/dt \sim 10^{-7}\,M_\odot$
  - Episodic accretion?
  - FU Orionis phenomenon - 10^4 variation in L