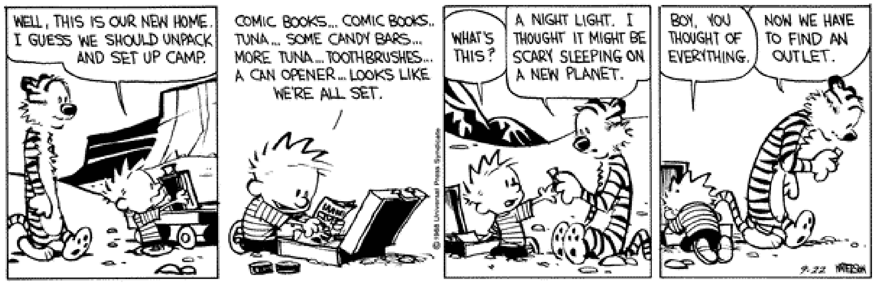
Observational ISM and Star Formation



<u>This Class (Lecture 21):</u>

Britt Lundgren & Kijeong Yim (Najita et al.)

<u>Next Class:</u>

Jerry Shiao & Sandor Van Wassenhove (Watson et al.)

Music: *For Science* – They Might Be Giants

Astro/Ph

Infrared Extinction Toward Nearby Star-Forming Regions

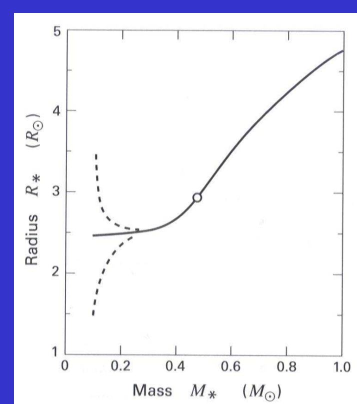
– K.M. Flaherty, J.L. Pipher, S.T. Megeath, E.M. Winston, R.A. Gutermuth, J. Muzerolle, & G.G. Fazio

- New estimate of the interstellar extinction law for the Spitzer IRAC bands.
- Differs systematically from previous determination of the extinction law, which was dominated by the diffuse ISM.
- This could be due to the different dust properties of the dense molecular clouds and the diffuse ISM.
- A flatter extinction curve from 4 – 8 micron than before.

Outline

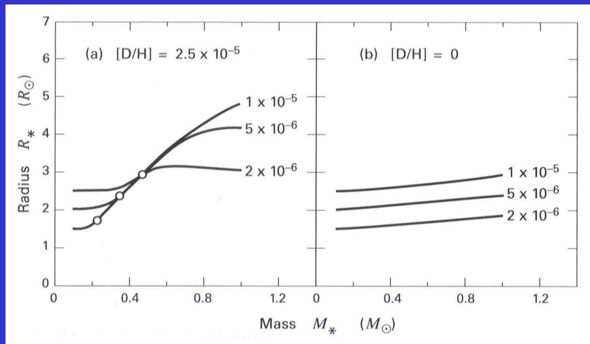
- Deuterium burning toward the main sequence
- Where was the Sun born?

Deuterium Burning



- Nuclear reactions start at center (at ~0.3 $M_\odot$ 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.

Deuterium Burning

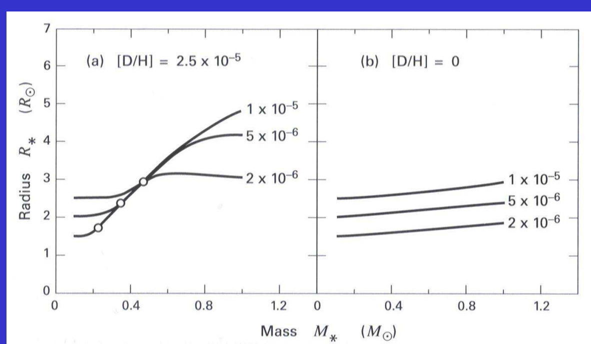


Stahler & Palla 2004

- $^2H + ^1H \rightarrow ^3He + \Delta E$
  $\Delta E \sim 5.5$ MeV, important from 10^6 K
- Protostellar size increase depends partly on accretion rate but the deuterium burning is more important.
- Deuterium burning is very temperature sensitive.
  - An increase of T causes more deuterium burning
  - Thus, more heat, which increases protostellar radius
  - This, lowers T again

Feedback of Deuterium

Deuterium burning



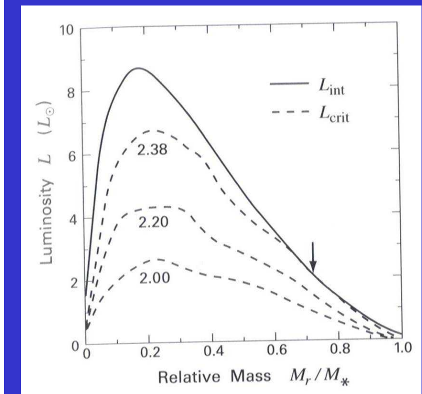
Stahler & Palla 2004

- Deuterium burning acts as kind of thermostat keeping the protostellar core at that evolutionary stage at about 10^6K.
- Steady supply by new Deuterium from infalling gas via convection necessary to maintain thermostat.

Protostellar vs. Pre-main Sequence Evolution

- After the deuterium burning has ceased, protostars contract quasi-statically again, gaining energy from gravitational contraction.
- For low-mass protostars, the end of deuterium burning roughly coincides with the end of the main accretion phase because no additional deuterium is supplied to the core center.
- From now on, the main luminosity does not stem from the accretion shock anymore but from the gravitational quasi-static contraction.
- One can identify this point with the end of the protostellar and the beginning of the pre-main sequence phase in low-mass stellar evolution → The "birthline" on the HR diagram

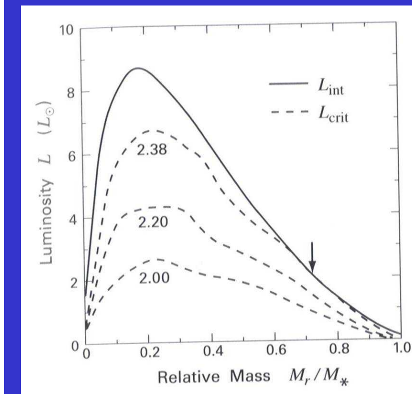
Critical L: Radiative



- Shrinking releases gravitational energy while surface temperature stays approximately constant.
- The critical luminosity L_{crit} is the maximum value carried by radiative diffusion.
  - $L_{crit} = 1\ L_\odot\ \ M_*^{11/2} R_*^{-1/2}$
- For growing protostars, L_{crit} rises sharply surpassing interior luminosity.

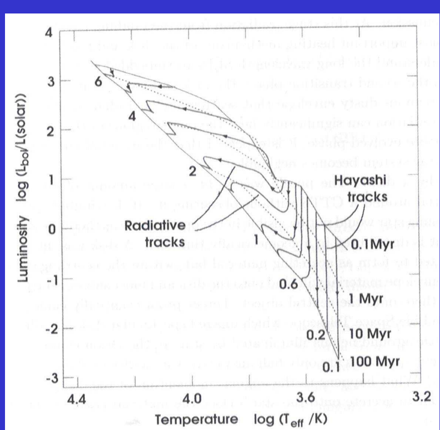
Stahler & Palla 2004

To ZAMS



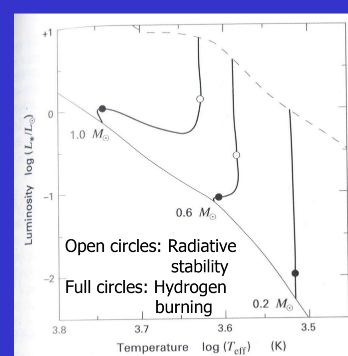
- Since $L = 4\pi R^2 \sigma_B T_{eff}^4 \propto R_*^2$, the luminosity decreases and falls below Lcrit. → Radiative core forms
- A shrinking outer convective layer still surrounds the radiative core
- Slow contraction, internal energy, temperature, and luminosity increases until hydrogen burning starts → ZAMS.
  - Stars below $\sim 0.4 M_\odot$ reach the ZAMS still fully convective.

HR Diagram



- The birthline was found first observationally as the locus where stars first appear in the HR diagram emanating from their dusty natal envelope.
- Theoretically, one can define the birthline at the time where the main accretion has stopped (no infalling envelope)
- Pre-main sequence star gains the main luminosity from gravitational contraction.

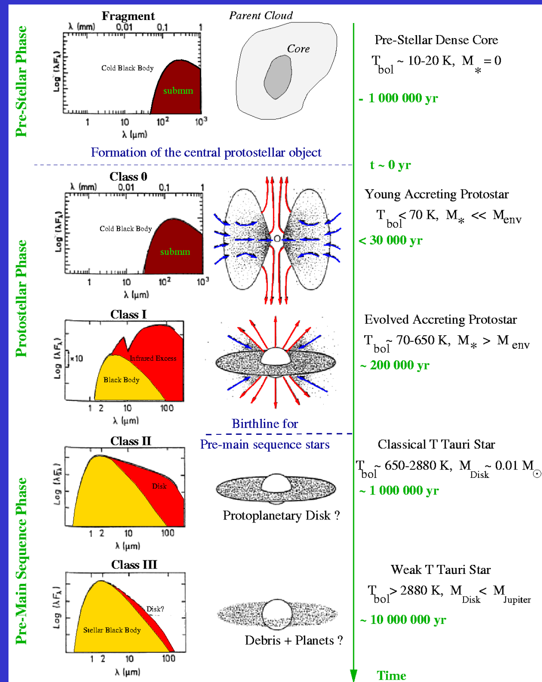
Movement on the HR



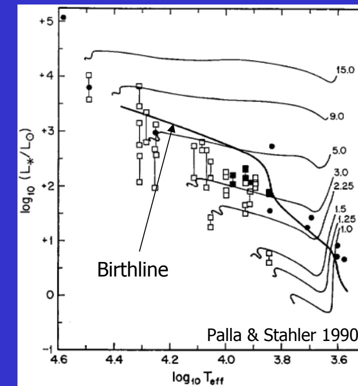
Stahler & Palla 2004

- So from the birthline, the low-mass stars start quasi-static contraction in their still convective phase
- They move vertically downward the so-called Hayashi tracks.
- After the cores become radiative, they start to increase their temperature (& luminosity) moving left on the radiative tracks (Henyey track).

Connection to the SEDs



More Massive Protostars



- Intermediate-mass protostars are already fully radiative when accretion stops; no vertical Hayashi track
- High-mass stars have short Kelvin-Helmholtz contraction time-scale and start H-burning, enter the ZAMS, before ending main accretion phase.
  - No (visible) pre-main sequence evolution since H-burning occurs in the deeply embedded phase.

Lithium Depletion

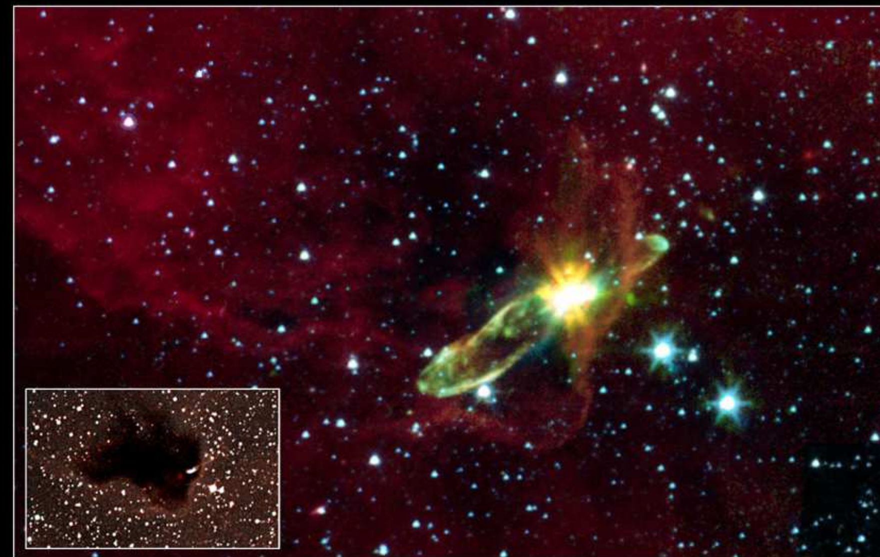
- Due to the highly convective lower-mass stars, lithium is transported to the center, where it can burn (3×10^6 K)
- The abundance of lithium, as measured at the surface is depleted
  - A simple age estimate
- For pre-main sequence stars > 0.9 $M_{\odot}$, the complete destruction of lithium is avoided
  - Convection retreats more quickly
  - Stars > 1.3 $M_{\odot}$ have very little lithium surface depletion
- Although this is broadly consistent with data, cluster members with similar L and T_{eff} may exhibit substantial spreads in surface lithium.

To the Main Sequence

- When central temp reaches 10^7 K, we have hydrogen fusion
- Once the fusion energy balances surface loss from radiation, we have a main sequence star → ZAMS

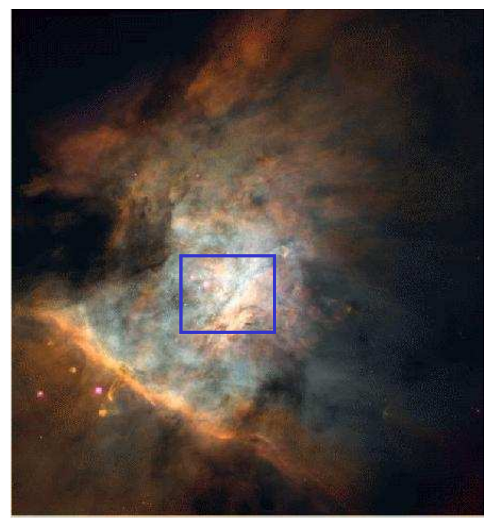
Where was the Sun Born?

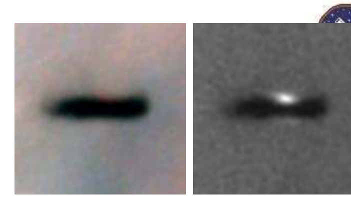
In relative isolation (Taurus, Bok globules,…)?



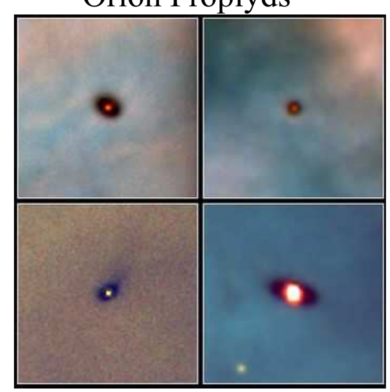
Or as part of a rich cluster (more likely)?

The radiation environment can be quite harsh in clusters:

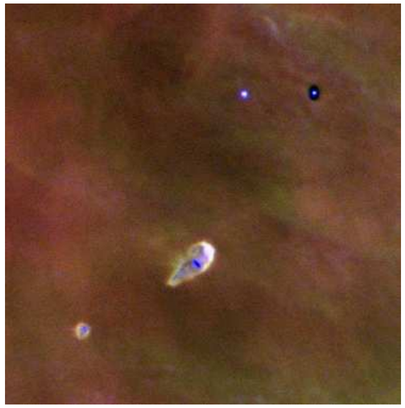


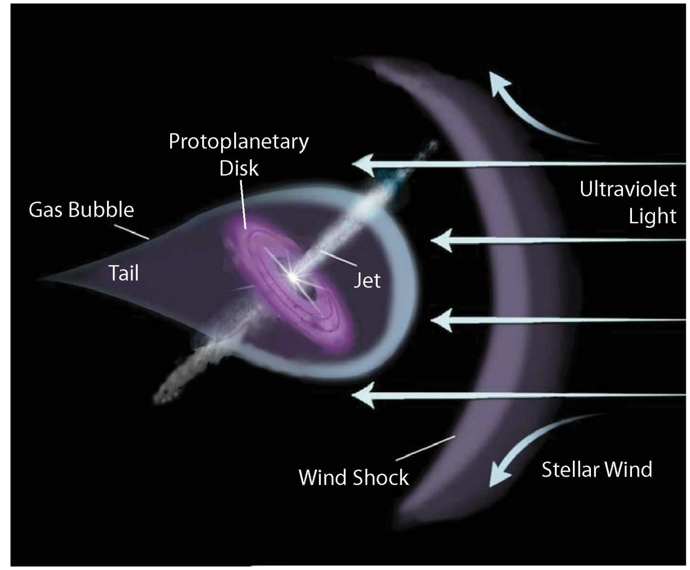


Orion Proplyds



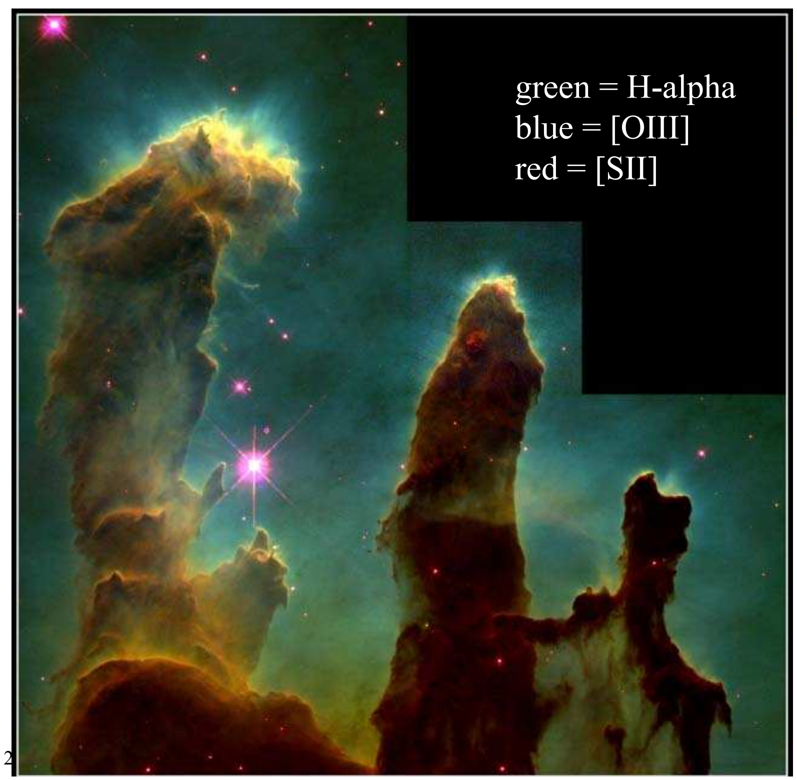
For stars still accreting gas/dust, *photoevaporation* can dramatically shorten the disk lifetime:





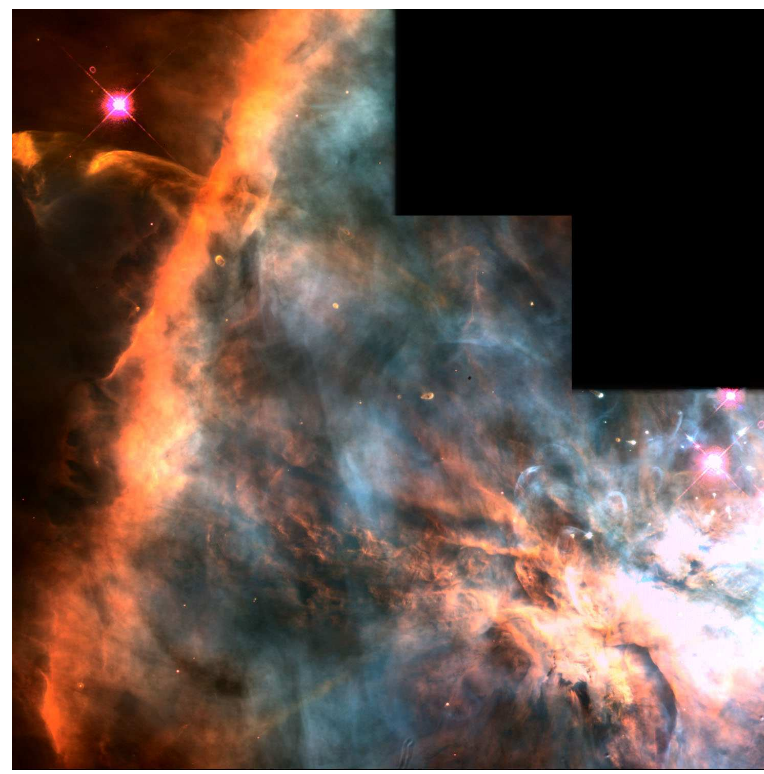
1.5 pc

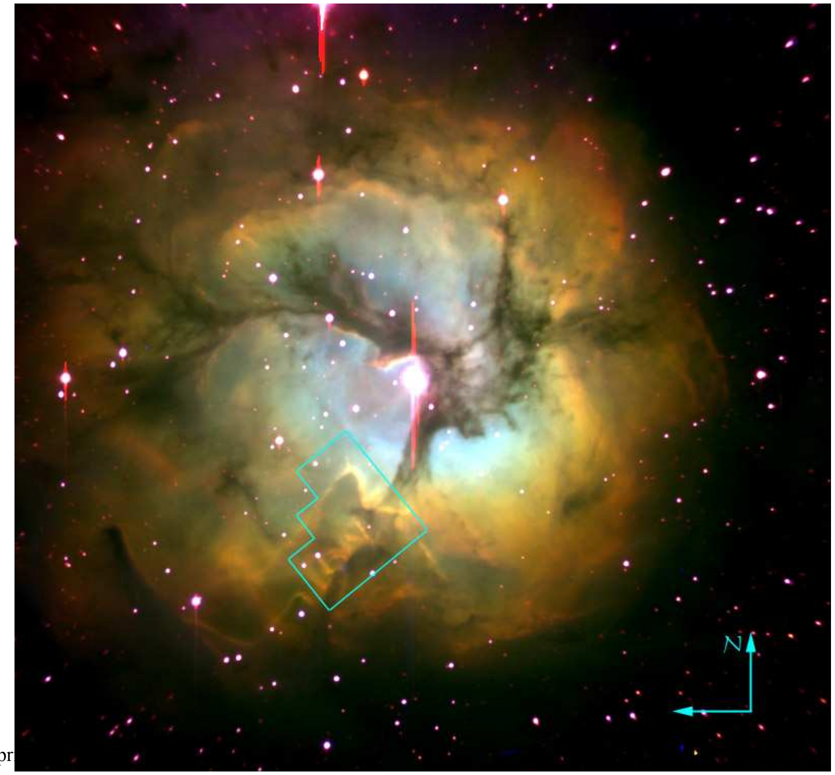
1000AU



0.3 pc

1000AU





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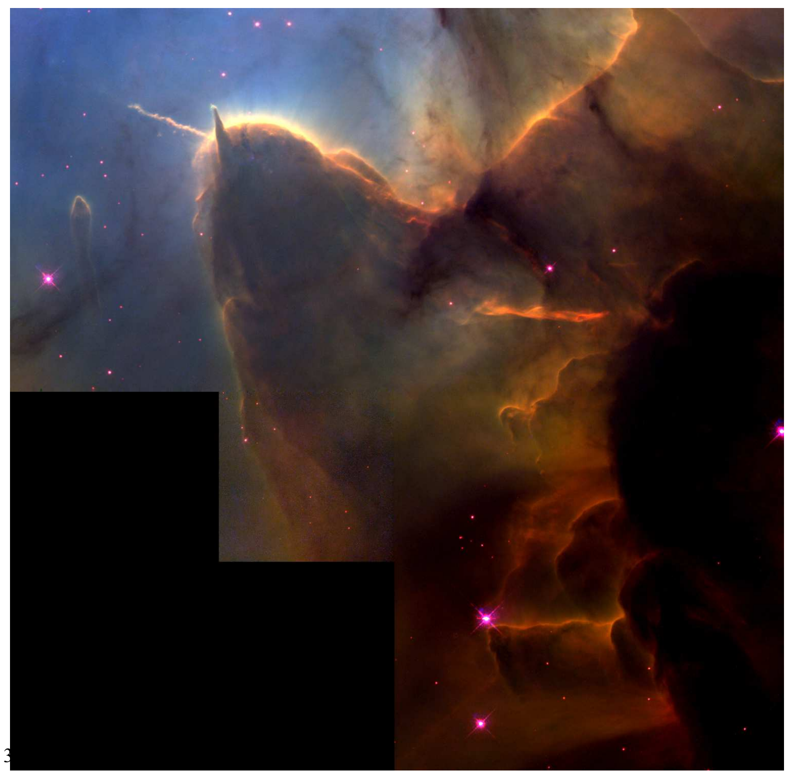

Must therefore consider *environment* in clusters!