THE STRUCTURE OF MAIN-SEQUENCE STARS

- main-sequence phase: hydrogen core burning phase
  - ▷ zero-age main sequence (ZAMS): homogeneous composition

Scaling relations for main-sequence stars

- use dimensional analysis to derive scaling relations (relations of the form $L \propto M^{\gamma}$)
- replace differential equations by characteristic quantities (e.g. $dP/dr \sim P/R$, $\rho \sim M/R^3$)
- hydrostatic equilibrium $\rightarrow P \sim \frac{GM^2}{R^4}$ (1)
- radiative transfer $\rightarrow L \propto \frac{R^4 T^4}{\kappa M}$ (2)
- to derive luminosity–mass relationship, specify equation of state and opacity law

(1) massive stars: ideal-gas law, electron scattering opacity, i.e.

▷ $P = \frac{\rho}{\mu m_H} kT \sim \frac{kT}{\mu m_H}\left(\frac{M}{R^3}\right)$ and $\kappa \simeq \kappa_{Th} = \text{constant}$

$$\Rightarrow \frac{kT}{\mu m_H} \sim \frac{GM}{R} \quad (3)$$

▷ substituting (3) into (2): $L \propto \frac{\mu^4 M^3}{\kappa_{Th}}$

(2) low-mass stars: ideal-gas law, Kramer's opacity law, i.e. $\kappa \propto \rho T^{-3.5}$

$$\Rightarrow L \propto \frac{\mu^{7.5} M^{5.5}}{R^{0.5}}$$

- mass–radius relationship
  - ▷ central temperature determined by characteristic nuclear-burning temperature (hydrogen fusion: $T_c \sim 10^7\,K$; helium fusion: $T_c \sim 10^8\,K$)
  - ▷ from (3) $\Rightarrow R \propto M$ (in reality $R \propto M^{0.6-0.8}$)

(3) very massive stars: radiation pressure, electron scattering opacity, i.e.

▷ $P = \frac{1}{3} a T^4 \rightarrow T \sim \frac{M^{1/2}}{R} \Rightarrow L \propto M$

- power-law index in mass–luminosity relationship decreases from ~ 5 (low-mass) to 3 (massive) and 1 (very massive)
- near a solar mass: $L \simeq L_{\odot}\left(\frac{M}{M_{\odot}}\right)^4$
- main-sequence lifetime: $T_{MS} \propto M/L$

$$\text{typically: } T_{MS} = 10^{10}\,\text{yr}\left(\frac{M}{M_{\odot}}\right)^{-3}$$

- pressure is inverse proportional to the mean molecular weight μ
  - ▷ higher μ (fewer particles) implies higher temperature to produce the same pressure, but T_c is fixed (hydrogen burning (thermostat): $T_c \sim 10^7\,K$)
  - ▷ during H-burning μ increases from ~ 0.62 to ~ 1.34

$\rightarrow$ radius increases by a factor of ~ 2 (equation [3])

- opacity at low temperatures depends strongly on metallicity (for bound-free opacity: $\kappa \propto Z$)
  - ▷ low-metallicity stars are much more luminous at a given mass and have proportionately shorter lifetimes
  - ▷ mass-radius relationship only weakly dependent on metallicity
  - → low-metallicity stars are much hotter
  - ▷ subdwarfs: low-metallicity main-sequence stars lying just below the main sequence

General properties of homogeneous stars:

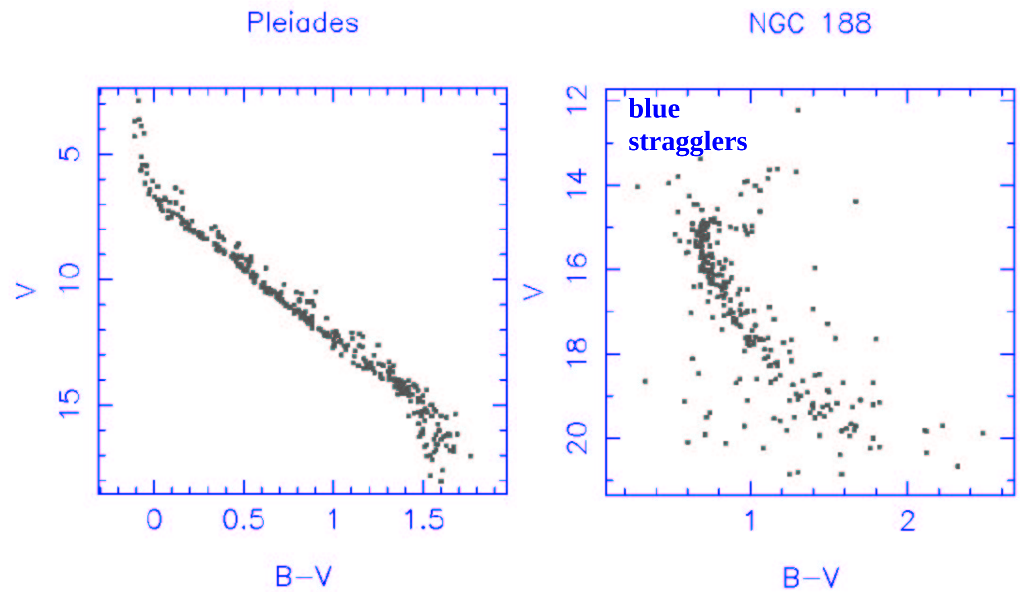
	Upper main sequence ($M_s > 1.5\,M_\odot$)	Lower main sequence ($M_s < 1.5\,M_\odot$)
core	convective; well mixed	radiative
ϵ	CNO cycle	PP chain
κ	electron scattering	Kramer's opacity $\kappa \simeq \kappa_3 \rho T^{-3.5}$
surface	H fully ionized	H/He neutral
	energy transport by radiation	convection zone just below surface

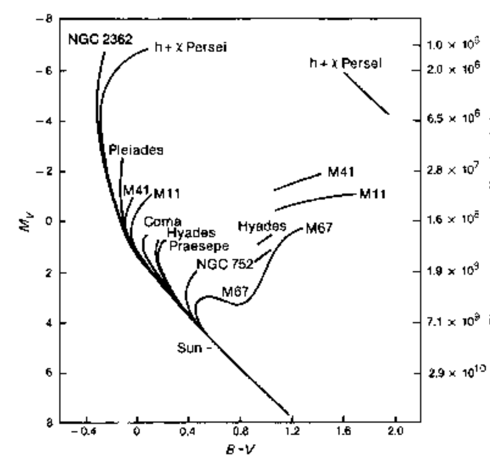
N.B. T_c is an increasing function of M_s; ρ_c decreases as M_s increases.

- Hydrogen-burning limit: $M_s \simeq 0.08\,M_\odot$
  - ▷ low-mass objects (brown dwarfs) do not burn hydrogen, since they are supported by electron degeneracy
- Giants, supergiants and white dwarfs cannot be chemically homogeneous stars supported by nuclear burning

Turnoff Ages in Open Clusters

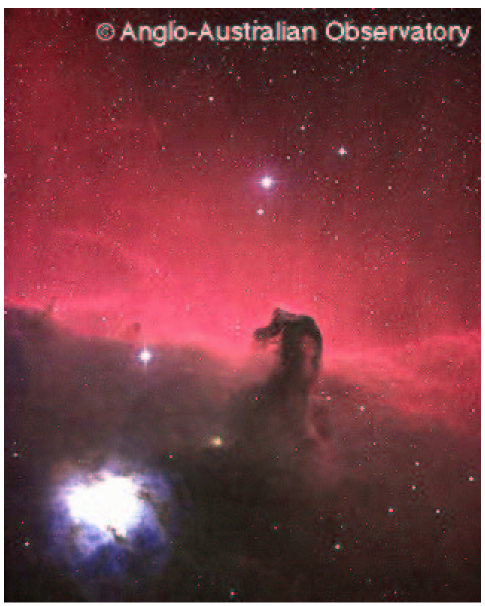
$$T = 10^{10}\,\text{yr}\left(\frac{L_{TO}}{L_\odot}\right)^{-3/4}$$





Star Formation (I)

Orion Nebula



STAR FORMATION

Star-Forming Regions

a) Massive stars

- born in OB associations in warm molecular clouds
- produce brilliant HII regions
- shape their environment
  - ▷ photoionization
  - ▷ stellar winds
  - ▷ supernovae

  → induce further (low-mass) star formation?

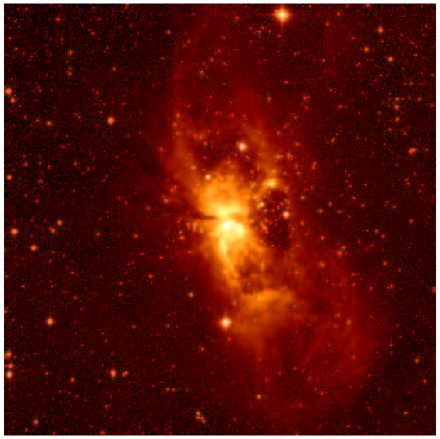
b) Low-mass stars

- born in cold, dark molecular clouds ($T \simeq 10\,K$)
- Bok globules
- near massive stars?
- recent: most low-mass stars appear to be born in cluster-like environments
- but: most low-mass stars are not found in clusters → embedded clusters do not survive

  Relationship between massive and low-mass star formation?

  - ▷ massive stars trigger low-mass star formation?
  - ▷ massive stars terminate low-mass star formation?

Star Formation (II)



massive star +
cluster of low-mas stars

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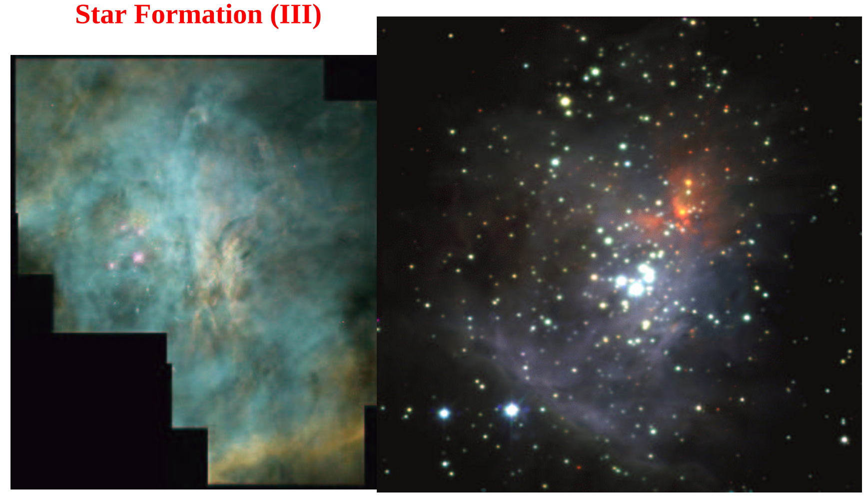
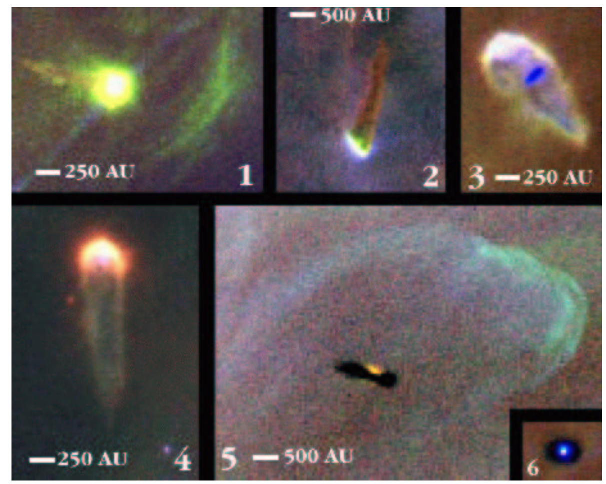
Bok globules

Star Formation (III)

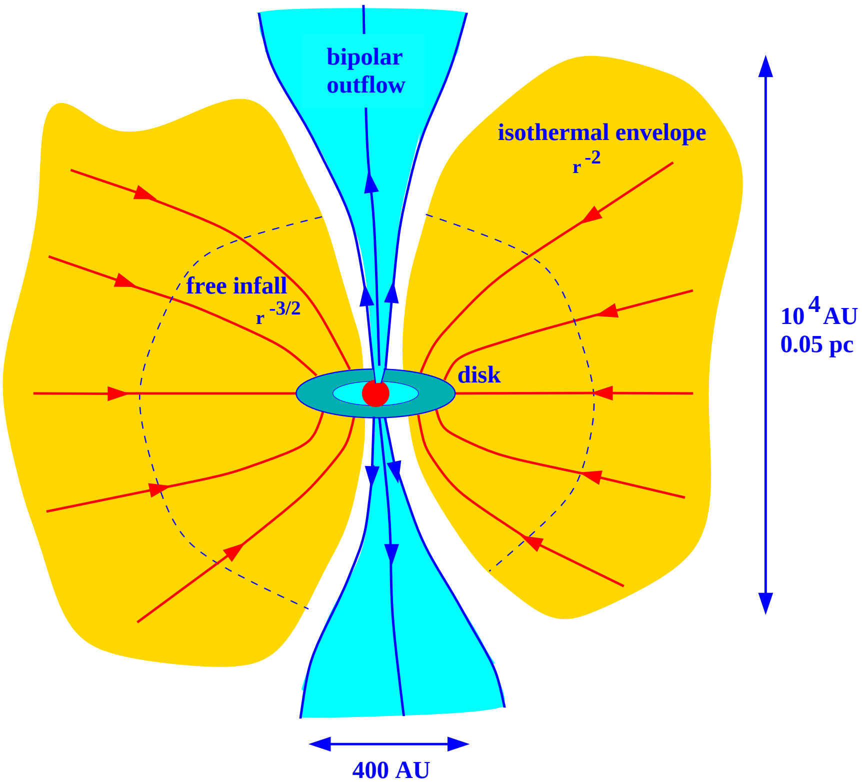


The Trapezium Cluster (IR)

HST



Dusty Disks in Orion (seen as dark silhouettes)



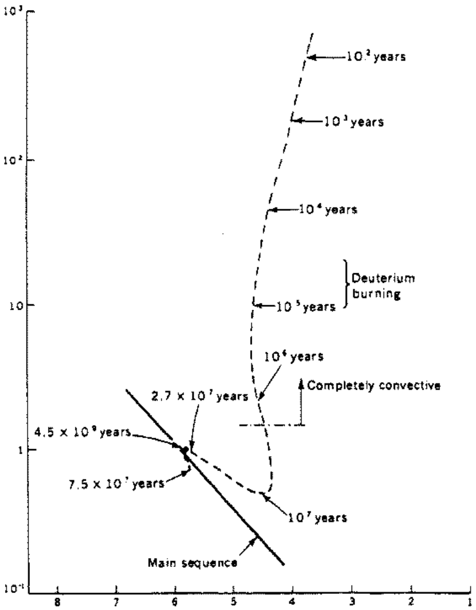
Protostar Structure

Stellar Collapse (Low-mass)

- cool, molecular cores (H_2) collapse when their mass exceeds the Jeans Mass
  - ▷ no thermal pressure support if $P_c = \rho/(\mu m_H) kT < GM^2/(4\pi R^4)$
  - ▷ or $M > M_J \simeq 6\,M_\odot \left(\frac{T}{10\,K}\right)^{3/2} \left(\frac{n_{H_2}}{10^{10}\,m^{-3}}\right)^{-1/2}$
- collapse triggered:
  - ▷ by loss of magnetic support
  - ▷ by collision with other cores
  - ▷ by compression caused by nearby supernovae
- inside-out isothermal collapse (i.e. efficient radiation of energy) from $\sim 10^6\,R_\odot$ to $\sim 5\,R_\odot$
- timescale: $t_{dyn} \sim 1/\sqrt{4\,G\rho} \sim 10^5 - 10^6$ yr
- collapse stops when material becomes optically thick and can no longer remain isothermal (protostar)
- the angular-momentum problem
  - ▷ each molecular core has a small amount of angular momentum (due to the velocity shear caused by the Galactic rotation)
  - ▷ characteristic $\Delta v/\Delta R \sim 0.3$km/s/ly
  - → characteristic, specific angular momentum $j \sim (\Delta v/\Delta R\, R_{cloud})\, R_{cloud} \sim 3 \times 10^{16}\,m^2\,s^{-1}$
  - ▷ cores cannot collapse directly
  - → formation of an accretion disk

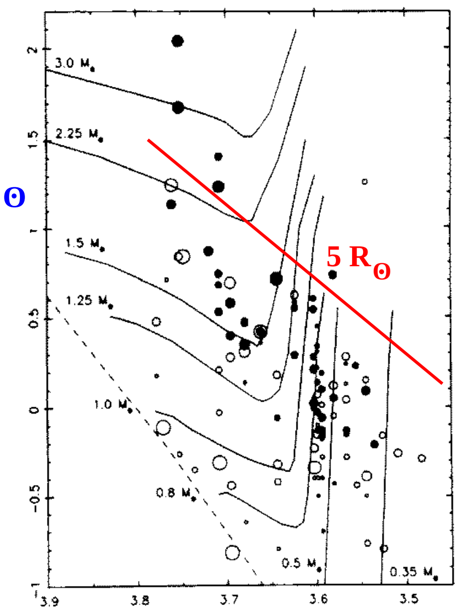
Pre-Main-Sequence Evolution

L/L$_\Theta$



T_{eff} (1000 K)

log L/L$_\Theta$



log T_{eff}

- ▷ characteristic disk size from angular-momentum conservation $j = rv_\perp = rv_{Kepler} = \sqrt{GMr}$

  → $r_{min} = j^2/GM \sim 10^4\,R_\odot \simeq 50\,AU$

- Solution: Formation of binary systems and planetary systems which store the angular momentum (Jupiter: 99 % of angular momentum in solar system)

  → most stars should have planetary systems and/or stellar companions

  → stars are initially rotating rapidly (spin-down for stars like the Sun by magnetic braking)

- inflow/outflow: $\sim 1/3$ of material accreted is ejected from the accreting protostar → bipolar jets

Pre-main-sequence evolution

- Old picture: stars are born with large radii ($\sim 100\,R_\odot$) and slowly contract to the main sequence
  - ▷ energy source: gravitational energy
  - ▷ contraction stops when the central temperature reaches $10^7\,K$ and H-burning starts (main sequence)
  - ▷ note: D already burns at $T_c \sim 10^6\,K$ → temporarily halts contraction

- Modern picture: stars are born with small radii ($\sim 5\,R_\odot$) and small masses

  → first appearance in the H-R diagram on the stellar birthline (where accretion timescale is comparable to Kelvin-Helmholtz timescale: $t_{\dot M} \equiv M/\dot{M} \sim t_{KH} = GM^2/(2RL)$)

  - ▷ continued accretion as embedded protostars/T Tauri stars until the mass is exhausted or accretion stops because of dynamical interactions with other cores/stars