Einführung in die Astronomie II
Teil 9

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Overview part 9

- stellar evolution
  - star formation
  - evolution after the MS

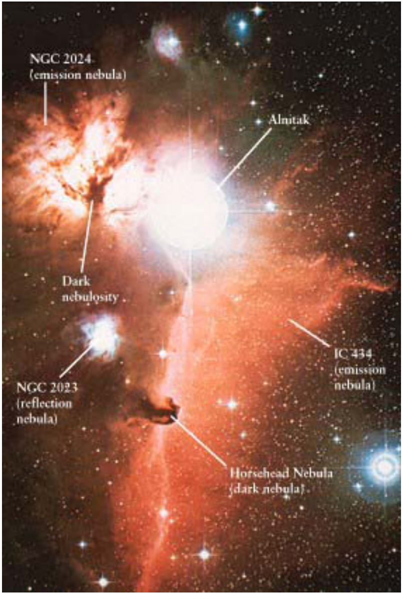
star formation

- *stellar evolution*: how stars are “born”, “live”, and “die”
- Sun: vast but not infinite amount of nuclear fuel
  $\rightarrow$ cannot shine forever!
- stars must have a “beginning” and an “end”
- stellar lifetime very much larger than that of humans
  $\rightarrow$ impossible to watch single star lifecycle
- have to piece information together from observations of different stars at different ages

star formation

- where do stars come from?
- *interstellar medium*: thin gas plus dust particles that "fill" the interstellar space
- $\rightarrow$ next chapter
- Example: Orion *nebula* $\rightarrow$ cloud in interstellar space

Orion nebula



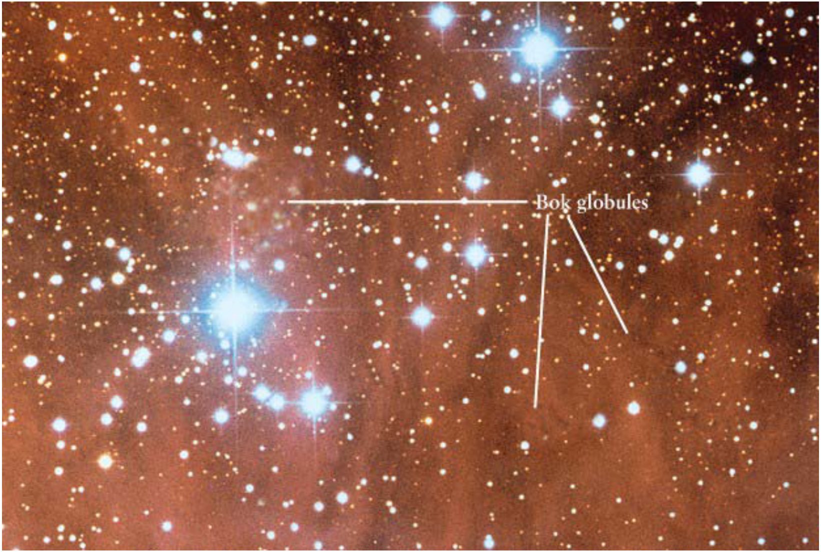
star formation

- in general: interstellar cloud $\rightarrow$ nebula or *nebulosity*
- *emission nebula*: emits light by itself, shows emission line spectrum of a hot, thin gas (e.g., Orion nebula)
- many emission nebulae are known
- direct evidence for hot gas in interstellar space
- typical temperatures: $\approx 10,000\,\mathrm{K}$
- typical masses: 100–$10,000\,\mathrm{M}_\odot$
- size of several pc's $\rightarrow$ density quite low
  few 1000 H-atoms/cm^3
  (Earth atmosphere: 10^{19} atoms/cm^3

Formation of Protostars

- *protostar*:
  first stage of a future main-sequence star
- for a protostar to form
  $\rightarrow$ gravity must overwhelm pressure
- $\rightarrow$ cold gas (low pressures!)
- best (only) locations: dark nebulae
  $\rightarrow$ *Barnard objects*
- *Bok globules*: small spherical dark nebulae

Bok globules



Formation of Protostars

- Bok globules look like inner core of Barnard objects
- densities: 100-10000 particles/cm^3 (quite high)
- temperatures: 10 K
- Barnard objects: few 1000 $\mathrm{M}_\odot$, 10 pc diameter
- about standard cosmic abundances (74% H, 25% He, 1% rest)

- densest parts can contract by their own gravity
- $\rightarrow$ form protostars
- contain enough masses to form multiple protostars
- $\rightarrow$ *stellar nurseries*

Jeans mass !!

- spherical cloud, density ρ
- gravitationally bound $\rightarrow$
- virial theorem applies

$$2K + U = 0$$

  - K: kinetic internal energy
  - U: gravitational potential energy

$$U \approx \frac{3}{5}\frac{GM^2}{R}$$

$$K = \frac{3}{2}NkT = \frac{3}{2}\frac{M}{\mu m_{\rm H}}kT$$

Jeans mass !!

- cloud will collapse if

$$2K < |U|$$

- therefore

$$\frac{3MkT}{2\mu m_{\mathrm{H}}} < \frac{3}{5}\frac{GM^2}{R}$$

- with

$$R = \left(\frac{3M}{4\pi\rho}\right)^{1/3}$$

- we have as condition for collapse $M > M_J$ with

$$M_J = \left(\frac{5kT}{6\mu m_{\mathrm{H}}}\right)^{3/2}\sqrt{\frac{3}{4\pi\rho}}$$

- *M_J: Jeans mass*

Jeans mass

- diffuse cloud
  - $T = 50\,\mathrm{K}$, $n = 500\,\mathrm{cm}^{-3}$
  - $\rightarrow \rho = 8.4 \times 10^{-22}\,\mathrm{g}$
  - $M_J \approx 1500\,\mathrm{M}_\odot$
  - 10 times larger than typical mass
- giant molecular cloud
  - $T = 150\,\mathrm{K}$, $n = 10^8\,\mathrm{cm}^{-3}$
  - $M_J \approx 17\,\mathrm{M}_\odot$

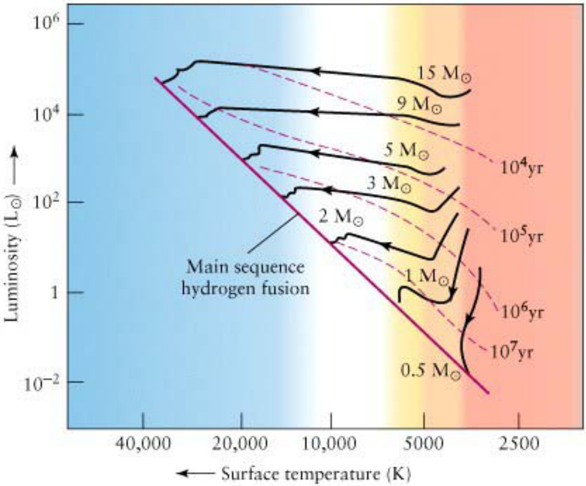
Formation of Protostars

- details described by model calculations (Hayashi):
- initial cool blob of gas, several times the size of the solar system
- pressure too low to counteract gravity
- $\rightarrow$ blob contracts
- gravitational energy is converted into thermal energy
- $\rightarrow$ gas heats up and begins to glow (thermally)
- Energy transported outward mostly by convection

Formation of Protostars

- few thousand years after begin of collapse
  $\rightarrow$ surface temperatures reach 2000–3000 K
- still large radius $\rightarrow$ large luminosity
- Example: $1\,M_\odot$ after 1000 years of contraction
  $\rightarrow 20\,R_\odot$, $100\,L_\odot$
- *no thermonuclear reactions*, all energy comes from the contraction!

pre-MS tracks !!



Formation of Protostars

- show evolution as a "track" in the HRD → *evolutionary track*
- protostars cool when they start to emit light
  → tracks begin near the right (low temperature) end of the HRD
- observations hard → light is shrouded by the surrounding dark nebula
- → *cocoon nebula*: absorbs most of the protostar's light in the visible

Protostars in the Omega nebula

Formation of Protostars

- protostars can be seen in IR wavelengths:
  - absorbed light warms dust in the cocoon nebula to few 100 K
  - warm dust radiates in the IR!
  - cocoon nebula relatively transparent to IR
  - compare visible to IR images!

Mass loss and gain

- formation of stars not simply contraction
- much of the cold dense material is actually ejected from the protostar
- this ejected material can sweep the surrounding clear
- $\rightarrow$ protostar can become visible!

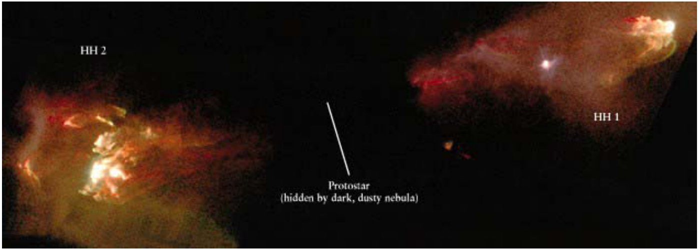
T Tauri stars

- protostars with absorption and emission lines
- L changes irregularly within days
- $< 3\,M_\odot$, $\approx 10^6$ years old
- above the MS
- emission lines indicate mass loss with $80\,\mathrm{km\,s^{-1}}$ speeds
- eject 10^{-8} to $10^{-7}\,M_\odot/\mathrm{yr}$ (Sun: $10^{-14}\,M_\odot/\mathrm{yr}$)
- T Tauri phase can last 10^7 yr
- $\rightarrow 1\,M_\odot$ is lost!
- mass of final MS stars can be significantly less than that of the original cloud

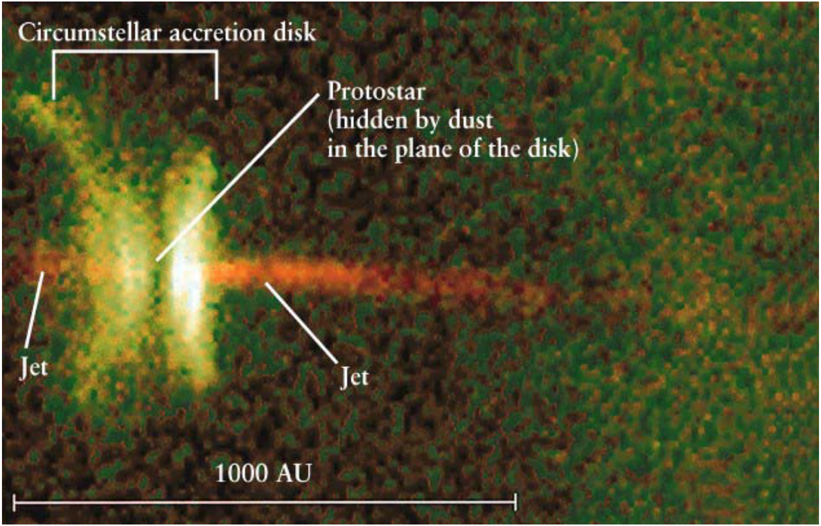
T Tauri stars

- $> 3\,M_\odot$: no T Tauri phase
- but mass loss due to large *radiation pressure* close to the surface
- $\rightarrow$ *stellar wind*
- *bipolar outflow*: evidence of opposite jets of gas streaming away with several $100\,\mathrm{km\,s^{-1}}$
- found in many young stars!
- jets collide with surrounding material
- $\rightarrow$ produce high density knots of hot, glowing material
- $\rightarrow$ *Herbig-Haro objects*

Herbig-Haro objects



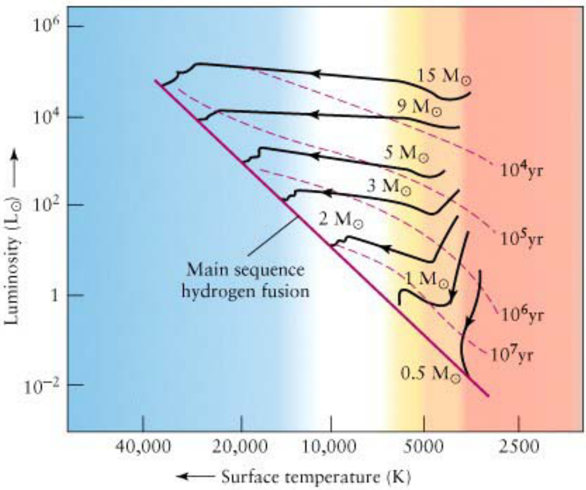
Protostar


Circumstellar accretion disk
Protostar
(hidden by dust
in the plane of the disk)
Jet
Jet
1000 AU

Herbig-Haro objects

- HH objects change position, size, shape, brightness within years
- observations $\rightarrow$ all young stars eject material in jets some time during their evolution
- short lived (10^4 to 10^5 years)
- but powerful enough to eject more mass than what remains on the MS star!

pre-MS tracks



$1\,M_\odot$ protostar

- material is very opaque
- $\rightarrow$ energy is more efficiently transported by convection than by radiation
- surface temperature stays roughly constant as the object shrinks
- $\rightarrow$ L decreases and the track moves downward in the HRD
- same time: internal temperature of protostar increases
- $\rightarrow$ material ionizes $\rightarrow$ less opaque

$1\,M_\odot$ protostar

- energy transported by radiation in the inner, ionized parts and by convection in the outer, cooler layers
- overall, this makes it *easier* for radiation to escape
- $\rightarrow$ L and surface T increase
- after some time, central T reaches $> 10^6\,\mathrm{K}$
- $\rightarrow$ thermonuclear fusion starts
- energy and heat produced eventually stops further contraction
- star reaches hydrostatic equilibrium and settles on the MS

$> 4\,M_\odot$ protostar

- contracts and heats much faster
- H-burning starts quicker
- L stabilizes quickly but star continues to shrink to reach final equilibrium
- T increases at constant $L \rightarrow$ horizontal track in the HRD
- greater mass leads to greater pressure and temperature in the core
- $\rightarrow$ larger temperature difference compared to $1\,M_\odot$ star

$> 4\,M_\odot$ protostar

- leads to convective inner regions in massive stars
- envelope relatively low density and transparent $\rightarrow$
- outer layers transport energy by radiation

$< 0.8\,M_\odot$ protostar

- interior temperatures stay too low to completely ionize the interior
- $\rightarrow$ remains fully convective
- if mass is too low ($\approx< 0.07\,M_\odot$)
  $\rightarrow$ no H burning will start (too cool)
  $\rightarrow$ *brown dwarf*
- intermediate objects to Jovian planets

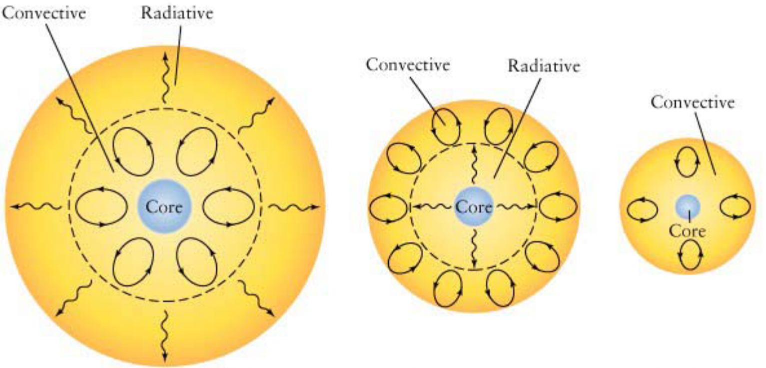
Protostars

- eventually, stars reach the main sequence and spend most of their lifetime on it
- more massive stars are (much more) luminous that lower mass stars
- protostars $> 100\,M_{\odot}$: become extremely luminous
- internal pressures rise too high for gravity to counteract
- $\rightarrow$ outer layers expelled, star disrupted

Protostars

- MS stars have masses from $\approx 0.08\,M_\odot$ (very frequent) to $100\,M_\odot$ (rare)
- Note: higher mass stars rush through their pre-MS evolution much faster than low mass stars!
- 20,000 years for $10\,M_\odot$, 10 million years for $1\,M_\odot$

MS stars !!

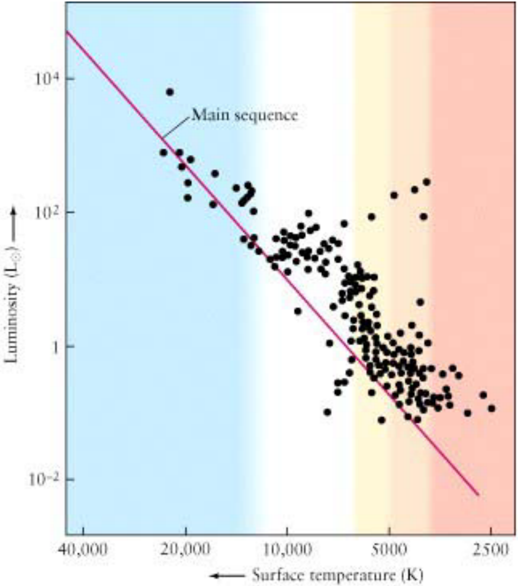


a Mass more than about 4 $M_\odot$ b Mass between about 4 $M_\odot$ and 0.8 $M_\odot$ c Mass less than 0.8 $M_\odot$

Young Stellar Clusters

- dark nebulae contain thousands of $M_\odot$
- $\rightarrow$ stars from in *clusters*
- include stars with a range of masses, all formed at about the same time
- $\rightarrow$ clusters are useful to observe evolution of stars

Young Stellar Clusters



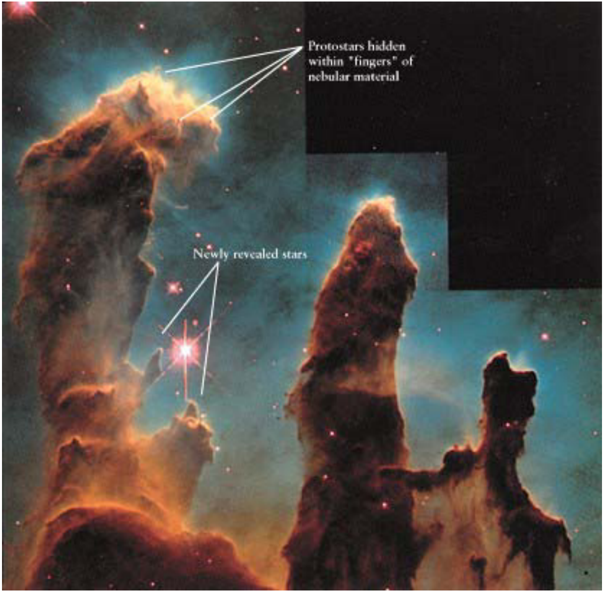
Young Stellar Clusters !!

- stars within a cluster start to form at the same time
- but they reach the MS at different times
- high-mass stars become quickly extremely luminous O and B stars
- their UV radiation produces H II regions

Young Stellar Clusters

- low mass stars are still evolving toward the MS!
- their evolution can be disturbed by the nearby OB stars
- Example: Eagle nebula: OB stars produce pillars and strip material from the low mass protostars

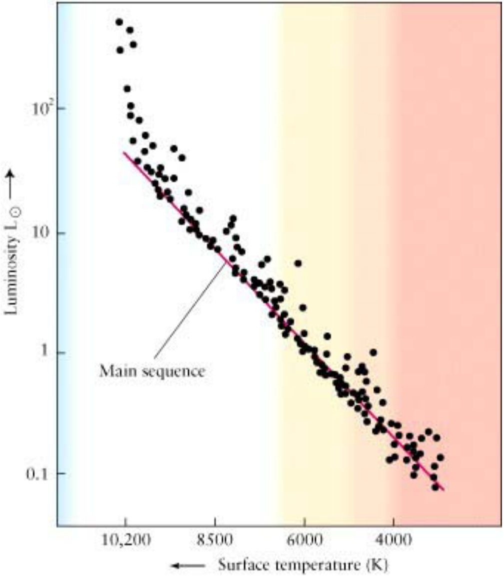
Eagle nebula



Young Stellar Clusters

- this can limit the mass that these stars actually reach!
- HRD of young clusters shows the state of evolution of the different masses
- older clusters: massive stars begin to move off the MS!
- can be used to determine age of the cluster!

Young Stellar Clusters



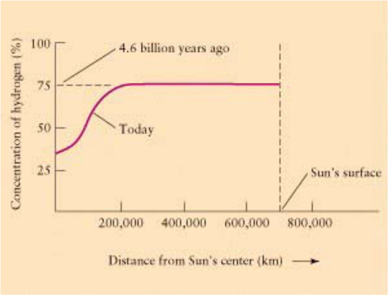
Young Stellar Clusters

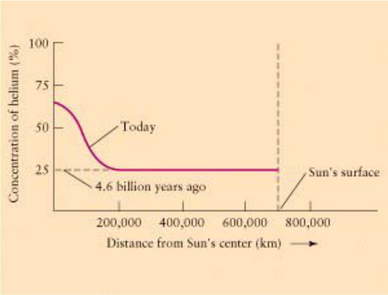
- *open cluster* or *galactic cluster*: loose collection of stars barely bound by gravitation
- *stellar association*: loose collection of stars not bound by gravitation
- stellar association typically dominated by OB stars
  $\rightarrow$ *OB association*

Post-MS evolution !!

- Main Sequence (MS): core H-burning
- alters composition of the core!
- Sun: formed with 74% H, 25% He
- now: more He than H in the core!
- $\rightarrow$ H fuel will eventually be exhausted!
- $\rightarrow$ *main sequence lifetime*
- Sun: $\approx 10^{10}$ years

The Sun


Concentration of hydrogen (%)
100
75
50
25
4.6 billion years ago
Today
Sun's surface
200,000
400,000
600,000
800,000
Distance from Sun's center (km)


Concentration of helium (%)
100
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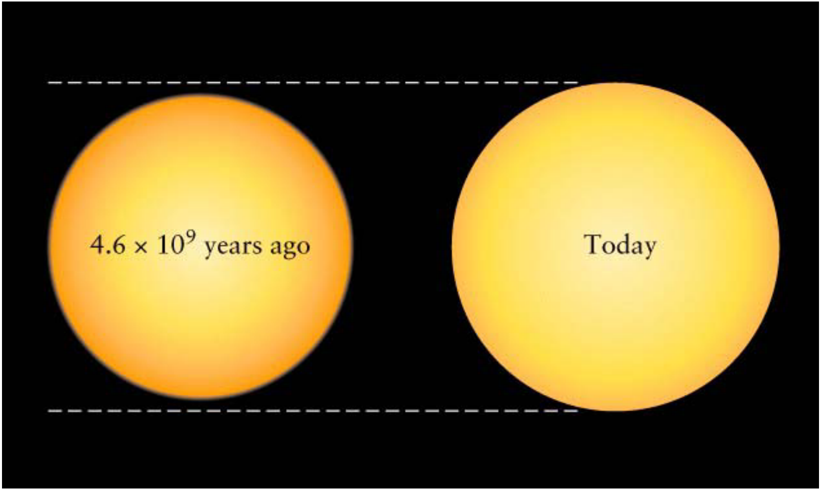
4.6 billion years ago
Sun's surface
200,000
400,000
600,000
800,000
Distance from Sun's center (km)

Post-MS evolution

- H burning: 4 H nuclei $\rightarrow$ 1 He nucleus
- reduces number of particles in the core
- core contracts
- T, ρ, P increase!
- $\rightarrow$ more H burning $\rightarrow$ L increases!
- radius and T (atmosphere) of the star also change!
- Sun: 40% more L, 6% larger radius, $+300\,\mathrm{K}$ in T_{eff}

The Sun



Post-MS evolution

- increased core T also heats layers just above it
- $\rightarrow$ H burning starts in the surrounding region
- increases MS lifetime a few million years

Post-MS evolution

- lifetime, t, depends strongly on mass of the star

$$t \propto \frac{M}{L}$$

- M-L relationship:

$$L \propto M^{3.5}$$

- $\rightarrow$ MS lifetime of a star with mass M is

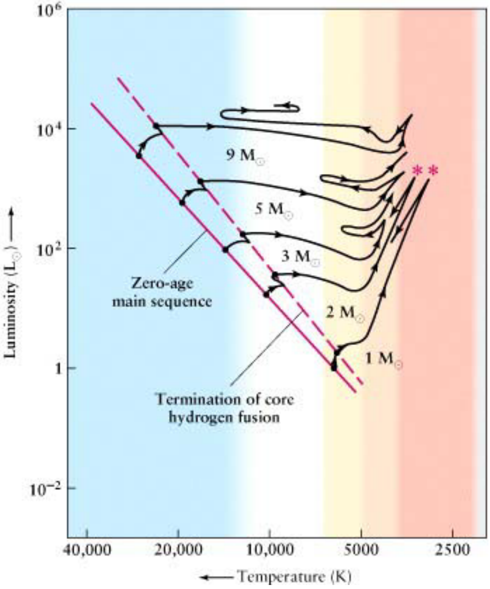
$$t \propto \frac{1}{M^{2.5}}$$

- massive stars spend only a very short time on the MS
- low mass stars spend eons on it!

Post-MS evolution !!

- core H used up:
- $\rightarrow$ H burning continues in shell around the core!
  $\rightarrow$ *shell hydrogen burning*
- end of core H burning increases core T:
- core contracts ... see above
- this also increases T in the shell source
- He produced by the shell source rains on the core
- core of a $1\,M_\odot$ stars shrinks to $\approx 1/3$ within a few 100 million years
- central T increases from $15 \times 10^6\,K$ to $100 \times 10^6\,K$

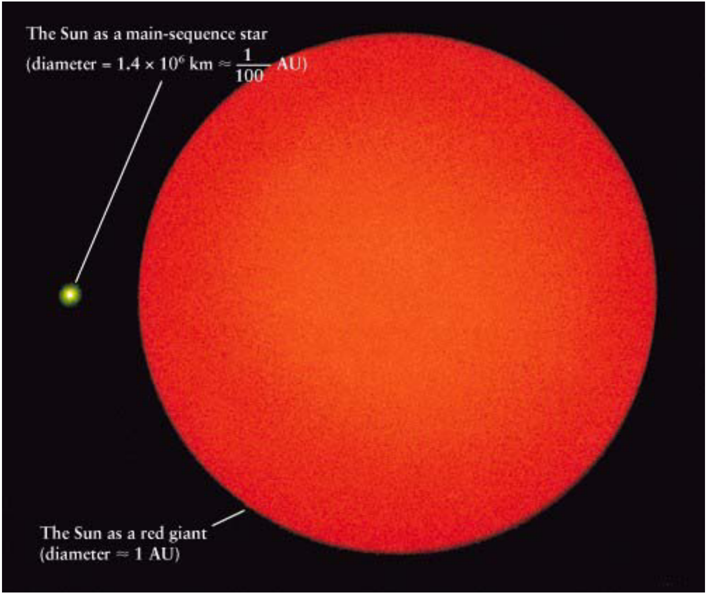
Post-MS tracks



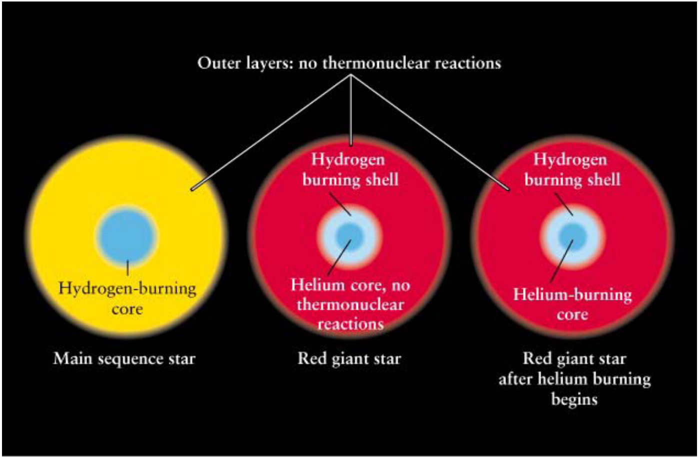
Post-MS evolution

- during this time, L increases substantially
- $\rightarrow$ internal pressures rise
- $\rightarrow$ the outer layers expand enormously
- $\rightarrow$ and cool down at the same time to about 3500 K or less
- the star becomes a *Red Giant*
- envelope only loosely bound
  $\rightarrow$ *mass loss* via a *stellar wind*
- material is blown off the star at $10\,\mathrm{km\,s^{-1}}$ at a rate of $10^{-7}\,\mathrm{M_\odot/yr}$

Red Giants


The Sun as a main-sequence star
(diameter = 1.4×10^6 km $\approx \frac{1}{100}$ AU)
The Sun as a red giant
(diameter $\approx$ 1 AU)

Post-MS structure !!



Helium burning

- He is useful as nuclear fuel
- however, He burning needs at least 100 million K to start!
- initially, the core temperature of a RG is too low
- but core contracts due to more He being added and eventually can start *core He burning*:

Helium burning

- first and key reaction: 3 ^{4}He to ^{12}C: the *triple α process*
- proceeds in 2 steps

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \leftrightarrow {}^{8}\mathrm{Be}$$

$$^{8}\mathrm{Be} + {}^{4}\mathrm{He} \leftrightarrow {}^{12}\mathrm{C} + \gamma$$

Helium burning

- with enough ^{12}C around, further α captures can occur simultaneously:

$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma$$

$$^{16}\mathrm{O} + {}^{4}\mathrm{He} \rightarrow {}^{20}\mathrm{Ne} + \gamma$$

- going beyond ^{20}Ne in this way is rare in normal stars!
- He burning re-stabilizes the core (no more contraction!)
- He fuel lasts on $\approx$ 20% of the original H burning time!

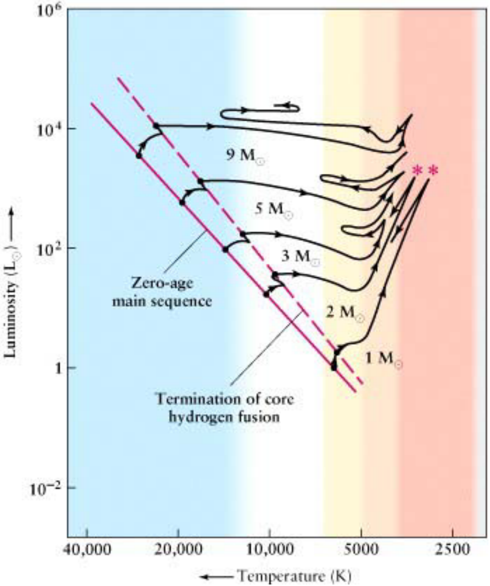
Helium flash !!

- He burning starts differently for stars with different masses:
- $M > 2...3\,\mathrm{M}_\odot$: gradual start
- lower masses:
- pressures in the core so large that the material is *electron degenerate*
- in this case, P does *not* depend on T!
- when He burning starts, it releases energy
- $\rightarrow$ T increases

Helium flash !!

- but P does not increase!
- rising T increases energy production of the He burning!
- $\rightarrow$ *BOOM*
- $\rightarrow$ He burning starts *explosive*
  $\rightarrow$ *helium flash*
- L reaches briefly that of a whole galaxy!
- eventually, T is so large that the electron degeneracy is removed
  $\rightarrow$ core can expand and cool
- settles down to He core burning

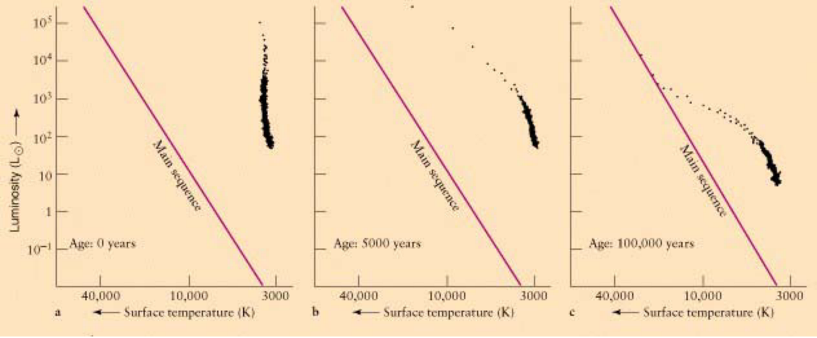
Helium flash



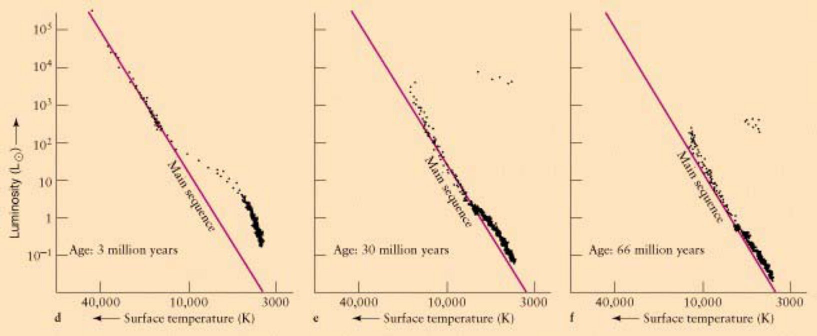
Helium flash

- He flash is not visible, too short!
- core He burning actually *reduces* L of the star:
  core expansion cools H shell source $\rightarrow$ less output
- envelope shrinks
- $\rightarrow$ star reduces L, R and increases outer temperature

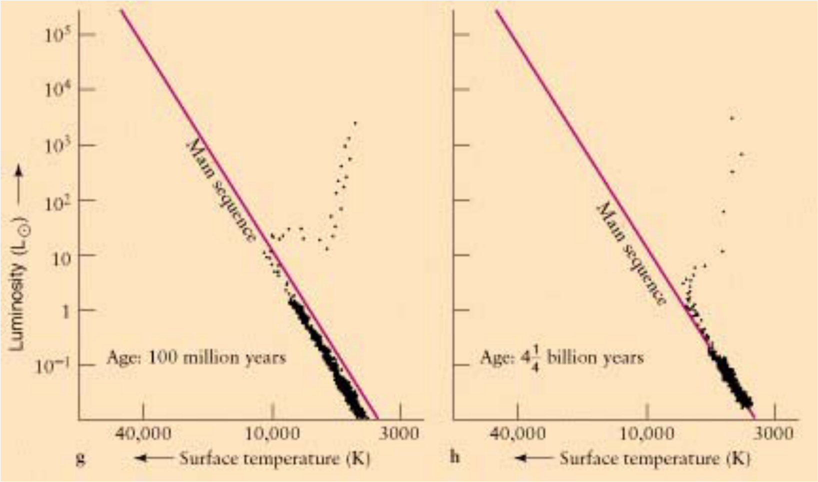
cluster evolution



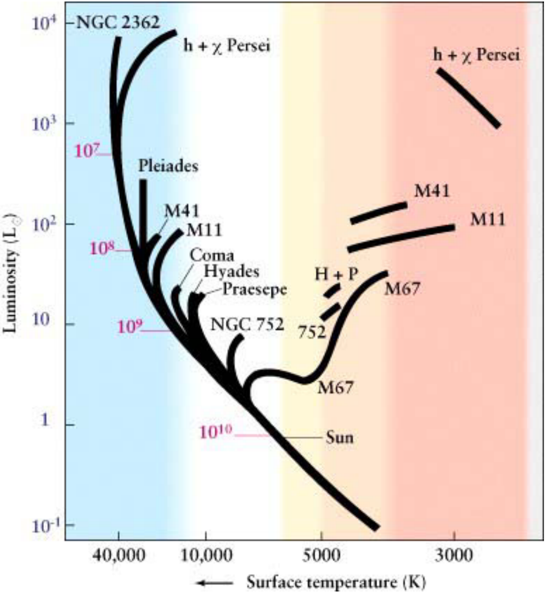
cluster evolution



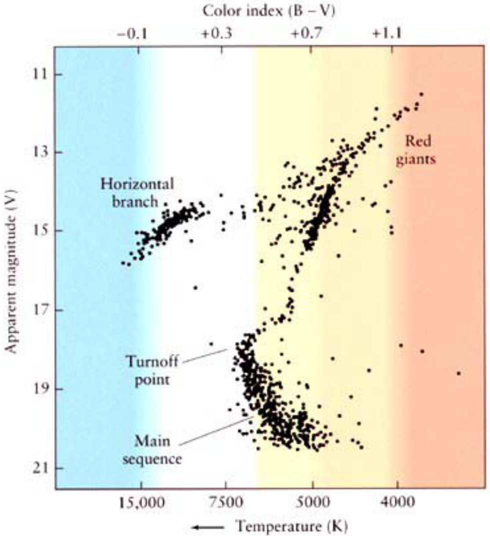
cluster evolution



HRD of open clusters



HRD of globular (old) cluster



Pulsating stars

- sometimes stars can show pulsating atmospheres
- this periodically changes radius, temperature and L
- $\rightarrow$ *pulsating variables*
- related to a *instability strip* in the HRD
- convection limits the cooler edge of the instability strip
- changes in ionization limit the hotter edge of the instability strip
- different types:

Pulsating stars !!

- *Mira variables*: cool giants, periods of months to years, L changes by a factor of 100 or more
- *Cepheid variables*: bright, very regular pulsating variables
  - driven by changes in the opacity of the envelope
  - show a *period-luminosity relation*: dimmer Cepheids pulsate faster
  - *Type I Cepheids*: metal poor stars
  - *Type II Cepheids*: metal rich stars
  - different $P - L$ relationships

Pulsating stars

- *RR Lyra variables*: lower mass stars, $100\,\mathrm{L}_\odot$
- periods $< 1\,\mathrm{d}$
- metal poor stars found in globular clusters
- show a $P - L$ relationship (different from Cepheids)

Pulsating stars