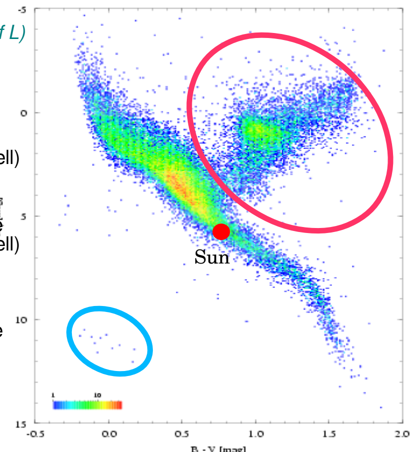
Stars: beyond the Main Sequence

Main-sequence
1) first and dominant stage in life,
2) H → He in the core *(subtle rise of L)*
3) >80% stars in MS

Low-mass stars
1) Ascend Red Giant Branch (H shell)
2) Red clump/Horizontal branch
   (He → C in core, H shell)
3) Asymptotic Giant Branch (H, He shell)
4) Env. ejection → White Dwarf

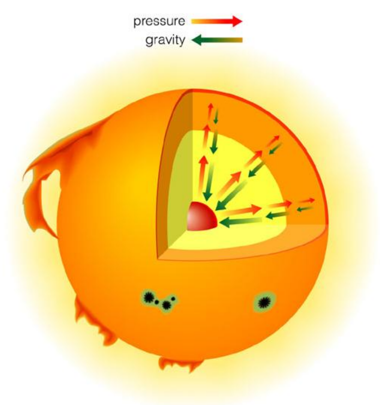
Intermediate-mass stars
1) Expand at L~const, ignite He in core
2) Asymptotic Giant Branch (H, He shell)
   Some: "super-AGB" (H, He, C shell)
3) Env. ejection → White Dwarf

High-mass stars
1) Expand at L~const, ignite He in core
2) Fusion in stages, up to Si → Fe
3) Core collapse → Neutron star, Black hole



Hipparcos HRD

Star's life: Protracted battle with gravity



ALWAYS
To support weight:
⇒ need high pressure

MOSTLY
⇒ need high temperature
⇒ will loose energy
⇒ need energy source:
- Gravitational contraction
- Nuclear fusion

Ultimately,
Can something else than thermal pressure balance gravity?

Degeneracy for a White Dwarf or degenerate core

using wave-particle duality

$$M=1M_\odot, R=6000\ km, \text{electron mean spacing } d \sim \frac{1}{n_e^{1/3}} \sim 10^{-12}\ m$$

$$\text{De Broglie wavelength } \lambda \sim \frac{h}{p} \sim \frac{h}{m_e v} \sim 10^{-12} m \left(\frac{10^9 K}{T}\right)^{1/2}$$

→ *typically $\lambda > d$ in white dwarfs*

1. *Wave nature of electrons becomes relevant*
2. *Electrons are fermion: they do not like to be close; this exclusion provides pressure*

electron degeneracy pressure: $P \propto n_e^{5/3} \propto \rho^{5/3} \rightarrow R \propto M^{-1/3}$

Sirius B (1 $M_\odot$) smaller than typical white dwarfs (0.6 $M_\odot$)

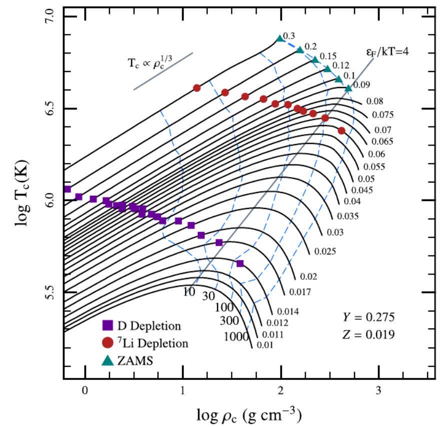
(compare with MS: $P = nkT$ plus $T \sim$ constant $\rightarrow R \propto M$)

Can $M \rightarrow \infty$? No, would need $v > c$ → Chandrasekhar limit: $M < 1.4 M_\odot$

White dwarfs are supported against gravity by pressure from degenerate electrons (ions irrelevant). This pressure depends only on density, not on temperature.
-- also centre of evolved low-mass stars, brown-dwarfs, Jupiter, metals...

Brown dwarf ($M < 0.08\ M_\odot$)

no H fusion → never becomes star



Paxton et al., 2011, ApJS 192:3

Ultimately,
Can something else than thermal pressure balance gravity?

Below ~0.08 $M_\odot$, objects become degenerate before becoming hot enough to ignite H fusion
→ *Brown dwarfs*

Below ~0.013 $M_\odot$, no fusion at all (not even D)
→ *Planet?*

Low-mass star (M < 8 $M_\odot$)

gradual exhaustion of H & He
ends due to mass loss

Main sequence — Core H burning; for ~1$M_\odot$, dM/dt ~ 10^{-14} $M_\odot$/yr, live ~10^{10} yr $(M/M_\odot)^{-3}$

↓

Red Giant — Dense core + tenuous envelope; ~100 $R_\odot$, ~10^8 yr, shell H burning, mass loss dM/dt ~ 10^{-7} $M_\odot$/yr; envelope convective, core shrinks *(why?)*

↓

Red clump/Horizontal Branch — T_{core}~10^8 K, He fuses in core, but H shell dominates L; ~10% of main-sequence lifetime; move to blue if metal-poor

↓

Asymptotic Giant — C/O core + extremely tenuous envelope, ~600 $R_\odot$; ~10^6 yr, 10^5 $L_\odot$, shell He/H burning, He shell flashes; end of AGB: dM/dt ~ 10^{-5} $M_\odot$/yr, removes whole envelope

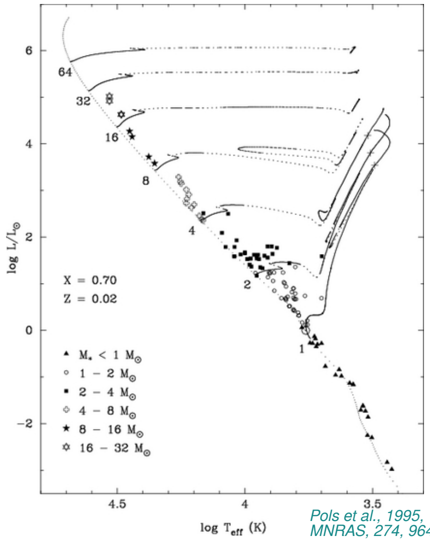
↓

White dwarf — Dense C/O, ~0.6 $M_\odot$, ~ 0.01 $R_\odot$, e^- degeneracy, cools from ~10^5 K to few 10^3 K in ~10^{10} yr

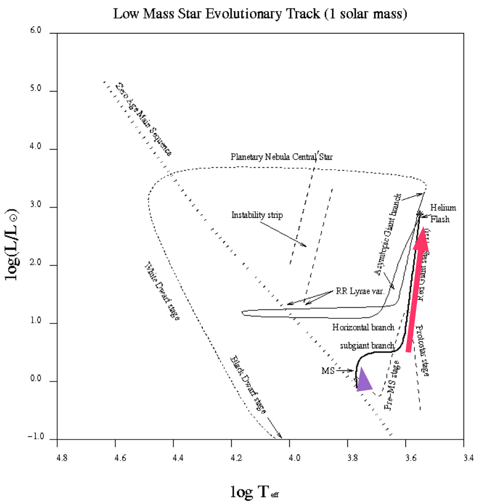
+planetary nebula — Few 0.1 $M_\odot$, expansion speed ~20 km/s, fluoresces for ~10^4 yr

Net effect of a star's life: mass loss → metal enrichment of the interstellar medium

Evolutionary tracks: what happens depends on mass



Pols et al., 1995, MNRAS, 274, 964



$L = 4\pi R^2 \sigma T^4$

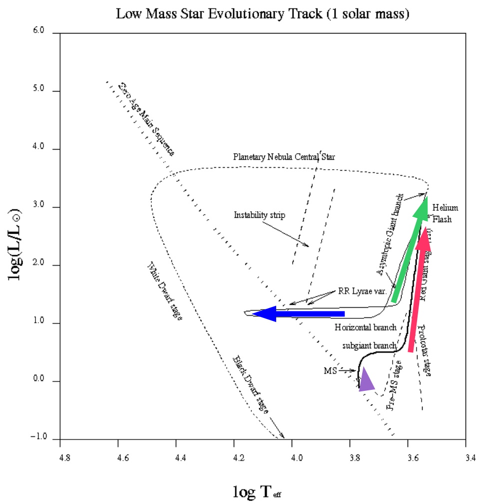
Main-sequence
Earlier: lower L; paradox of the 'faint young sun'

Red giant branch
Shell H burning around degenerate He core.
Dense core sets properties of shell; e.g., $T \sim M_{core}/R_{core}$.
Thus, core determines *L*.
Star *has to* transport this → large radius increase.

As core increases, so does T (and L drastically; why?)

Until He ignites → He flash

From http://www.ngcsu.edu/Academic/Sciences/physics/jones/astr1020home/evoltracks.htm



$L = 4\pi R^2 \sigma T^4$

Main-sequence
Earlier: lower L; paradox of the 'faint young sun'

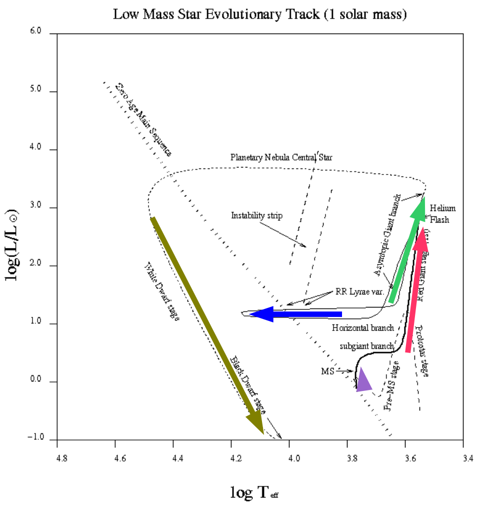
Red giant branch
Shell H burning
Big, luminous (cook planets)

Red clump/Horizontal branch
Core He burning
Core bigger → T_{shell} lower
→ less luminous, less big
Hotter if metal-poor

Asymptotic Giant branch
Shell H & He burning
Luminosity increases with increasing core mass, star becomes very big.

Ends when L so high that envelope blown off

From http://www.ngcsu.edu/Academic/Sciences/physics/jones/astr1020home/evoltracks.htm



$L = 4\,\pi\; R^2\;\sigma\; T^4$

Main-sequence
Earlier: lower L; paradox
of the 'faint young sun'

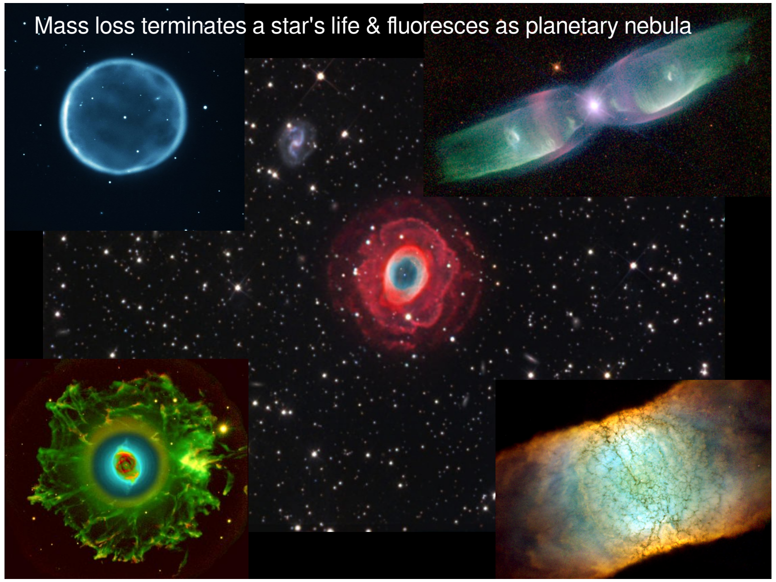
Red giant branch
Shell H burning
Big, luminous (cook planets)

Red clump/Horizontal branch
Core He burning
Bit less big & luminous
Hotter if metal-poor

Asymptotic Giant branch
Shell H & He burning
Very big (engulfing planets)

White Dwarf branch
Naked stellar core
Born very hot
Cools off slowly

From http://www.ngcsu.edu/Academic/Sciences/physics/jones/astr1020home/evoltracks.htm



Extra Notes: Planetary Nebula

1) what are they?

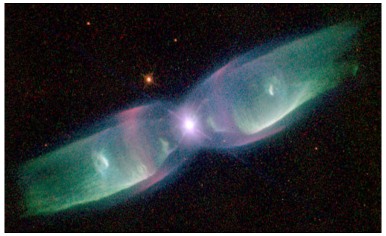
Transient fluorescence around
new-born, hot white dwarfs
Live ~10^4 yr
Where is the gas from?
Slow expansion (20 km/s)

2) what are the colors?

'False colors,' montage of
narrow-band images
e.g.,red --> N I
green--> Hα
blue --> O III

3) why aren't they all spherical?

Rotation?
Binaries?



Extra Notes: degeneracy pressure

1. Wave nature of electrons becomes relevant

2. Electrons are fermion: they do not like to be close; this exclusion provides pressure

Pauli's exclusion principle: $(\Delta x_i)^3 (\Delta p_i)^3 \sim \hbar^3$

Fermi momentum: $p_F \sim \frac{1}{\Delta x_i} \sim n_e^{1/3}$

Fermi energy: $E_F = \frac{1}{2} m_e v_F^2 = \frac{1}{2} \frac{p_F^2}{m_e} \propto n_e^{2/3}$

Pressure: $P \propto n_e E_F \propto n_e^{5/3} \propto \rho^{5/3}$

$\rightarrow R \propto M^{-1/3}$

(compare with MS: $P = n k T$ *plus* $T \sim$ *constant* $\rightarrow R \propto M$ *)*

Can $M \rightarrow \infty$*? No, would need* $v > c \rightarrow$ *Chandrasekhar limit:* $M < 1.4\, M_o$