Astronomía estelar

2024

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Clase 12

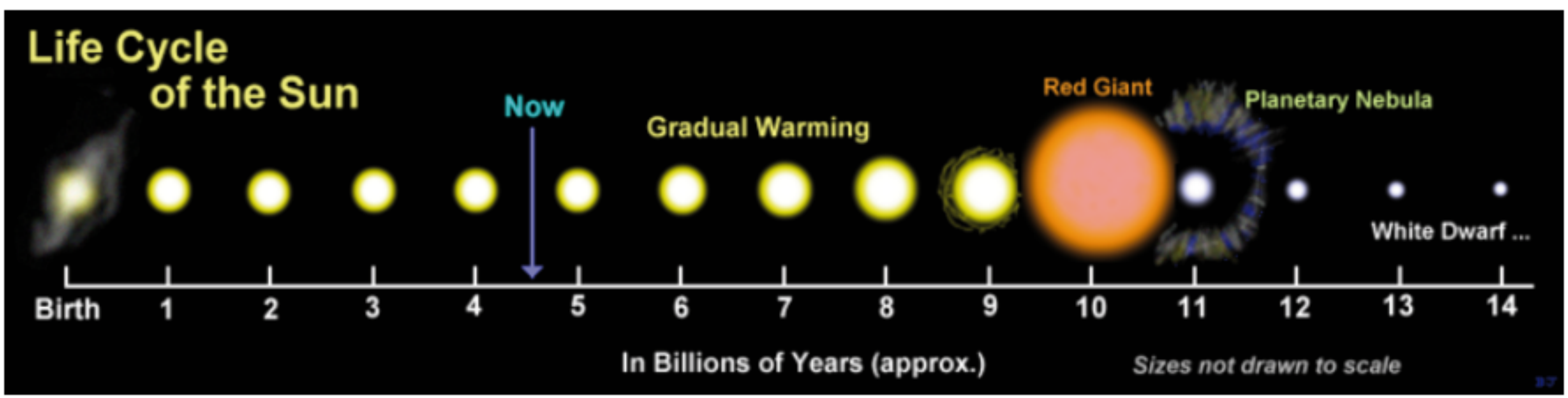
Evolución sobre la Secuencia principal (MS)
y post-Secuencia principal (post-MS)

Chapter 13: Stellar Evolution

Main Sequence and Post-Main-Sequence Stellar Evolution

By definition, a main sequence star is one that is fusing hydrogen into helium to maintain hydrostatic equilibrium. Every second, the Sun burns more than 4 million tons of hydrogen.

When a star burns most of the hydrogen in the core, it begins post-main-sequence evolution. The path that the star takes depends on it's mass.



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Main Sequence and Post-Main-Sequence Stellar Evolution

Pre-main-sequence evolution characterized by free-fall and Kelvin-helmholtz times (10^7 yrs)

Main-sequence evolution is characterized by nuclear reaction timescales (10^{10} yrs)

Recall:

In stars with $M > 1.2\ M_{SUN}$ the cores are convective (CNO chain and strong temperature gradient)

Stars with $0.3 < M < 1.2\ M_{SUN}$ have radiative cores

Stars with $M < 0.3\ M_{SUN}$ are fully convective

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Main Sequence and Post-Main-Sequence Stellar Evolution

As the sun evolves, the mean molecular weight of the core increases. With fewer H-fusion reactions taking place, the core is compressed. Half of the gravitational potential energy is radiated away and half goes into heating the gas, increasing the temperature.

A consequence of the increase in temperature is that the region of the star that is hot enough to burn hydrogen increases.

Since the p-p rxn rate goes as $\rho X^2 T_6^4$ the increase in density and temperature more than offset the decrease in the mass fraction of hydrogen - the remaining hydrogen burns faster and the luminosity of the star (along with the radius and temperature) increase.

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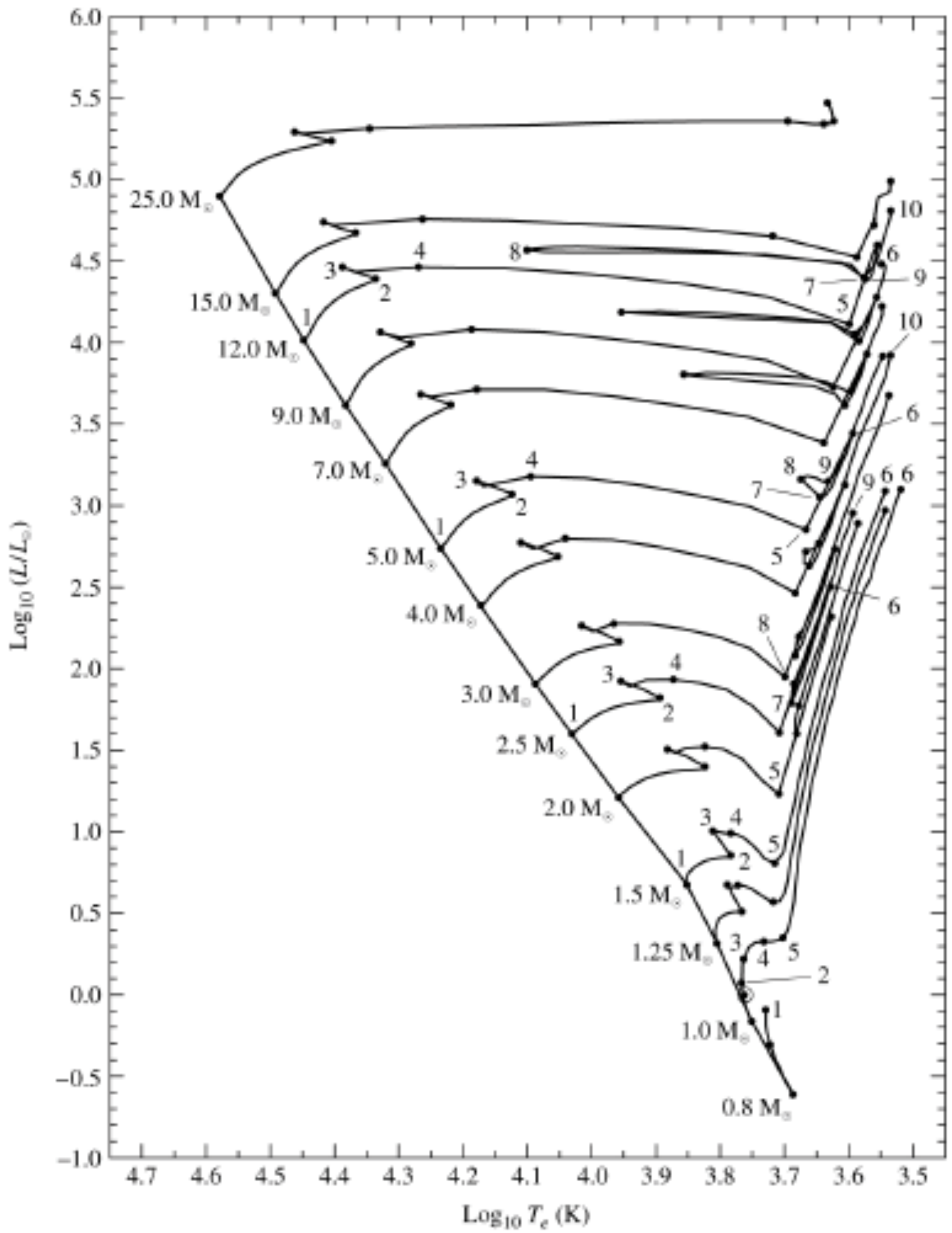
Main Sequence and Post-Main-Sequence Stellar Evolution

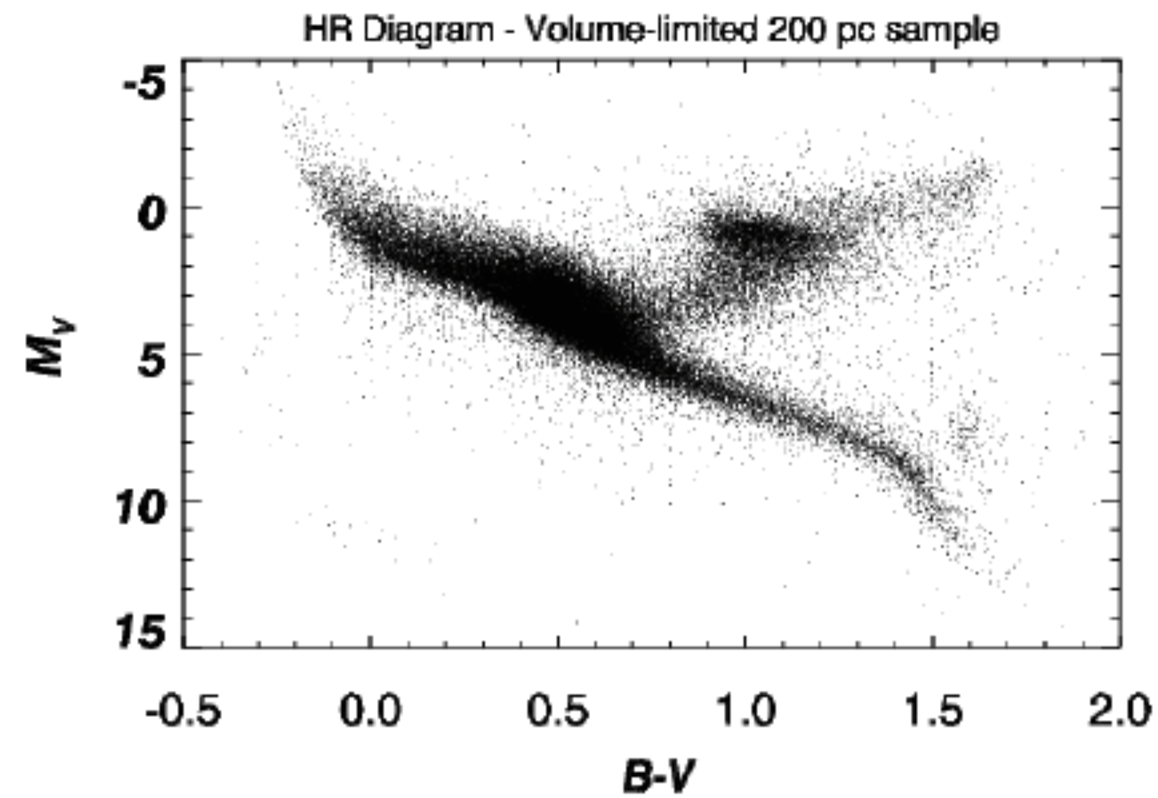


Stellar evolution tracks:

Main sequence

Subgiant branch

Giant branch



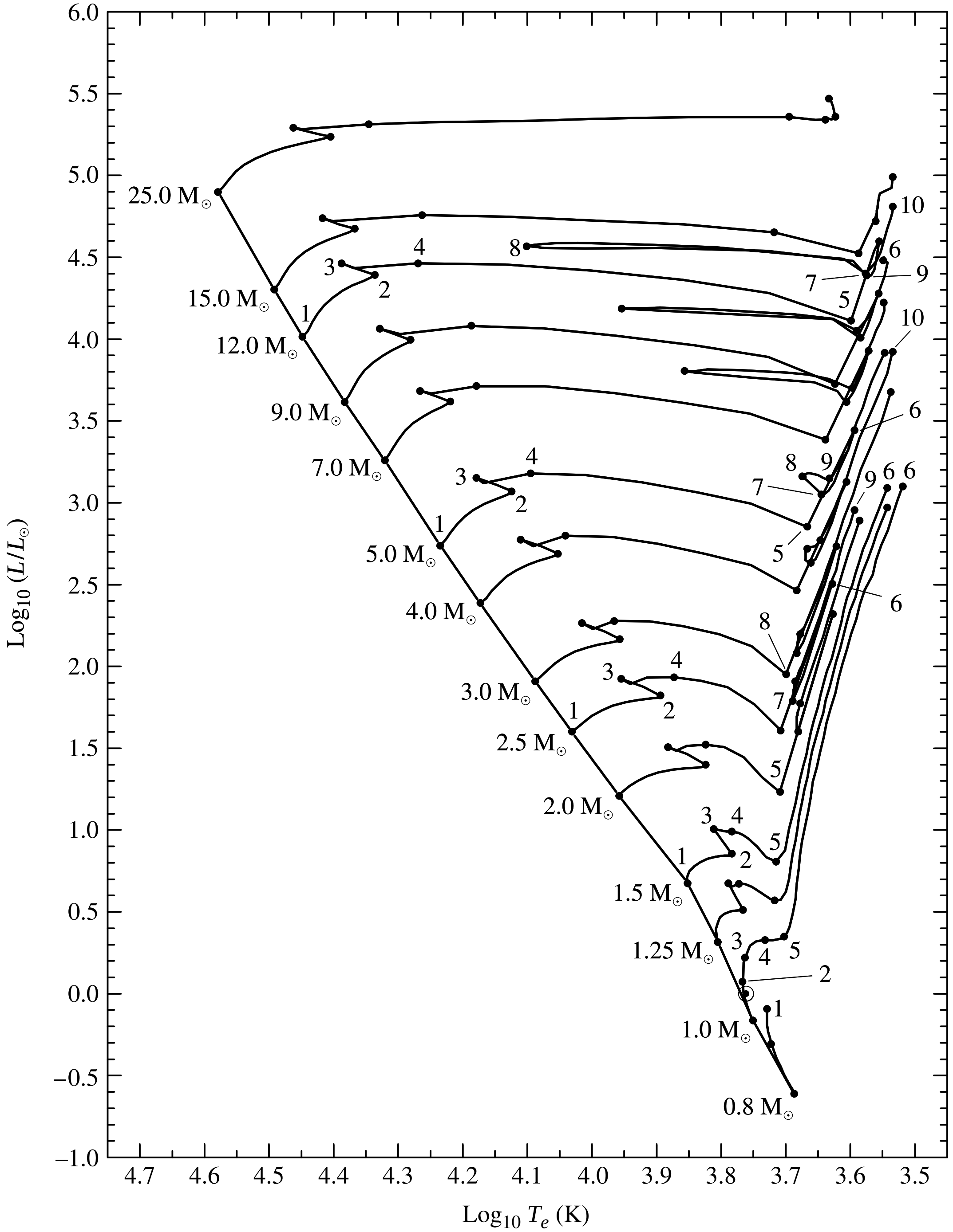
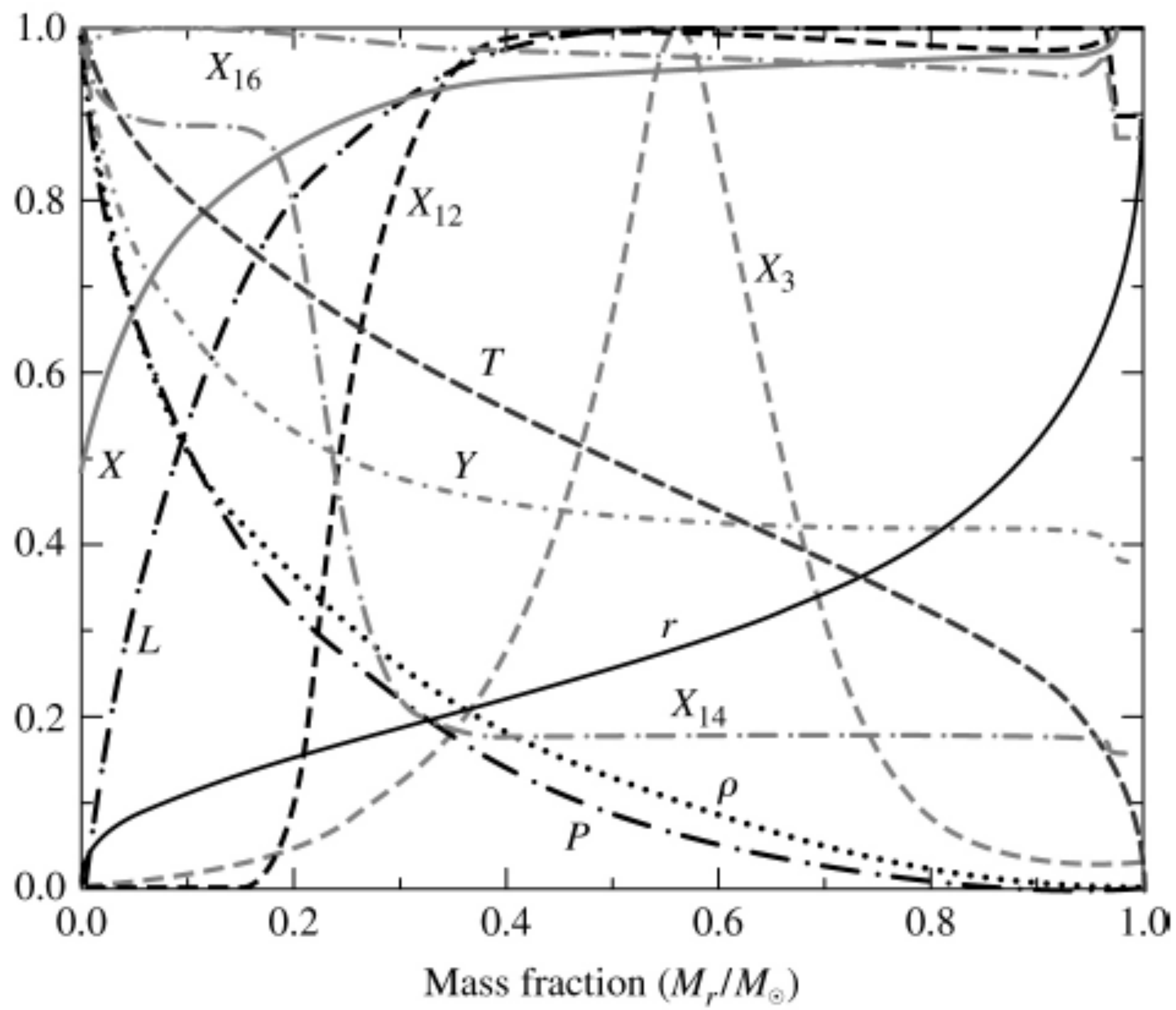


FIGURE 1 Main-sequence and post-main-sequence evolutionary tracks of stars with an initial composition of $X = 0.68, Y = 0.30$, and $Z = 0.02$. The location of the present-day Sun (see Fig. 2) is depicted by the solar symbol ($\odot$) between points 1 and 2 on the 1 M$_\odot$ track. The elapsed times to points indicated on the diagram are given in Table 1. To enhance readability, only the points on the evolutionary tracks for 0.8, 1.0, 1.5, 2.5, 5.0, and 12.0 M$_\odot$ are labeled. The model calculations include mass loss and convective overshooting. The diagonal line connecting the locus of points 1 is the zero-age main sequence. For complete, and annotated, evolutionary tracks of 1 M$_\odot$ and 5 M$_\odot$ stars, see Figs. 4 and 5, respectively. (Data from Schaller et al., *Astron. Astrophys. Suppl.*, *96*, 269, 1992.)

TABLE 1 The elapsed times since reaching the zero-age main sequence to the indicated points in Fig. 1, measured in millions of years (Myr). (Data from Schaller et al., *Astron. Astrophys. Suppl.*, *96*, 269, 1992.)

Initial Mass (M$_\odot$)	1 6	2 7	3 8	4 9	5 10
25	0	6.33044	6.40774	6.41337	6.43767
	6.51783	7.04971	7.0591		
15	0	11.4099	11.5842	11.5986	11.6118
	11.6135	11.6991	12.7554		
12	0	15.7149	16.0176	16.0337	16.0555
	16.1150	16.4230	16.7120	17.5847	17.6749
9	0	25.9376	26.3886	26.4198	26.4580
	26.5019	27.6446	28.1330	28.9618	29.2294
7	0	42.4607	43.1880	43.2291	43.3388
	43.4304	45.3175	46.1810	47.9727	48.3916
5	0	92.9357	94.4591	94.5735	94.9218
	95.2108	99.3835	100.888	107.208	108.454
4	0	162.043	164.734	164.916	165.701
	166.362	172.38	185.435	192.198	194.284
3	0	346.240	352.503	352.792	355.018
	357.310	366.880	420.502	440.536	
2.5	0	574.337	584.916	586.165	589.786
	595.476	607.356	710.235	757.056	
2	0	1094.08	1115.94	1117.74	1129.12
	1148.10	1160.96	1379.94	1411.25	
1.5	0	2632.52	2690.39	2699.52	2756.73
	2910.76				
1.25	0	4703.20	4910.11	4933.83	5114.83
	5588.92				
1	0	7048.40	9844.57	11386.0	11635.8
	12269.8				
0.8	0	18828.9	25027.9		

Main Sequence and Post-Main-Sequence Stellar Evolution



The interior structure of the Sun - between points 1 and 2 on the previous plot.

Maximum ordinate values: r = 1.0 R_{SUN}

L = 1.0 L_{SUN}

T = 15 x 10^6 K

ρ = 1.5 x 10^5 kg m^{-3}

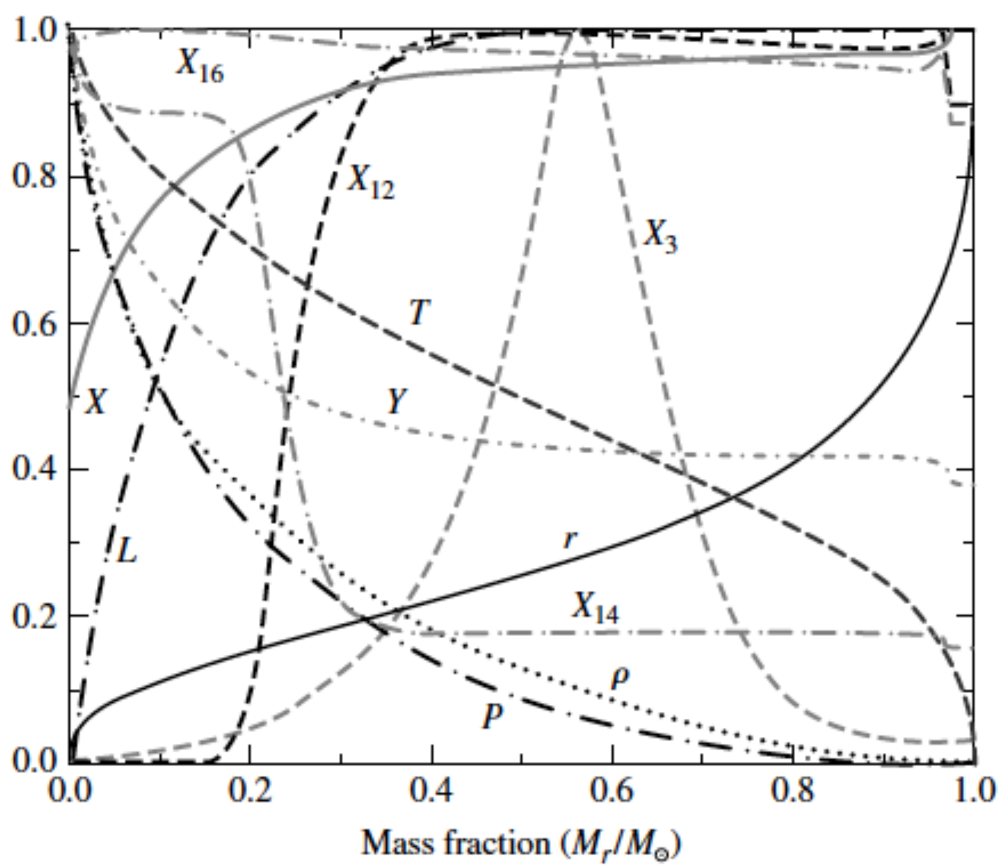
P = 2.34 x 10^{16} N m^{-2}

mass fractions of the species ${}^1_1$H, ${}^3_2$He, ${}^{12}_6$C, ${}^{14}_7$N, and ${}^{16}_8$O.

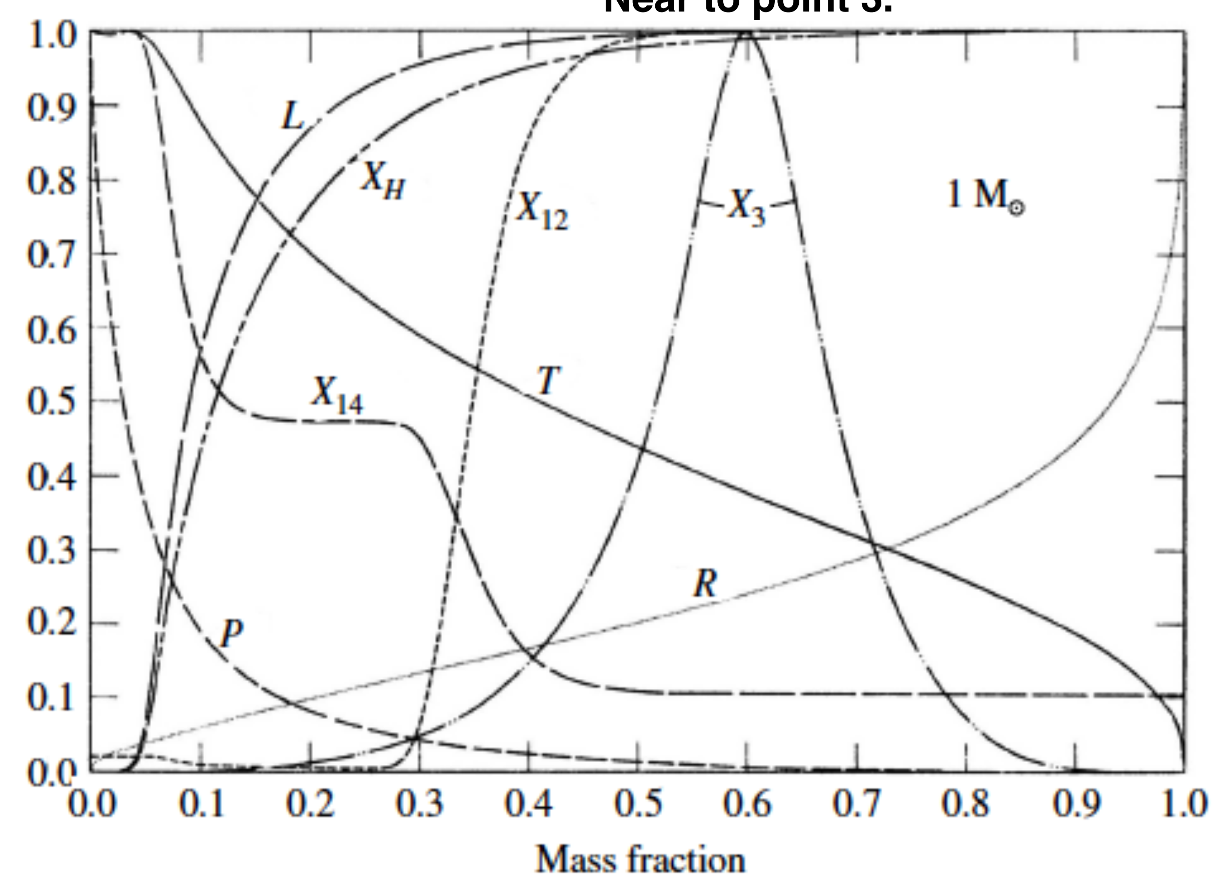
When hydrogen is depleted in the core, p-p chain reactions must stop, however the core temperature has increased to the point that nuclear fusion continues in a shell around the small, predominately helium core. *The luminosity in this thick shell exceeds the luminosity from the core during the earlier phase and the* evolutionary track rises.

Some energy goes into heating and expanding the star causing the radius to increase and resulting in cooling in the star and the evolutionary track bends to the right.

Since the helium core is not giving off energy at this stage, it is isothermal. In order to maintain support against gravity, there must be a pressure gradient in the core that is a result of a continuous increase in density.



Near to point 3.



Schoenberg-Chandrasekhar limit

When the mass in the isothermal core becomes to great, it is not efficient at maintaining support against gravity. The maximum fraction of a star's mass that can exist in an isothermal core and still support it against upper layers is given by:

$$\left(\frac{M_{i,c}}{M}\right)_{SC} \sim 0.37\left(\frac{\mu_{env}}{\mu_{i,c}}\right)^2$$

As the mean molecular weight of the core increases, the maximum fraction of mass that can be in the core decreases.

When the mass of the isothermal helium core exceeds this limit, the core collapses. This occurs when the mass fraction in the core is about 8% of the stellar mass.

Example 1.1. If a star is formed with the initial composition $X = 0.68$, $Y = 0.30$, and $Z = 0.02$, and if complete ionization is assumed at the core–envelope boundary, we find that $\mu_{\rm env} \simeq 0.63$. Assuming that all of the hydrogen has been converted into helium in the isothermal core, $\mu_{ic} \simeq 1.34$. Therefore, from Eq. (1), the Schönberg–Chandrasekhar limit is

$$\left(\frac{M_{ic}}{M}\right)_{\rm SC} \simeq 0.08.$$

The isothermal core will collapse if its mass exceeds 8% of the star's total mass.

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Degenerate Electron Gas

The mass of an isothermal core can exceed the Schoenberg-Chandrasekhar limit if the electrons in the gas provide extra electron degenerate pressure.

$$P_e = K\rho^{5/3}$$

Pressure of a non-relativistic, completely degenerate electron gas

Isothermal cores generally have partial degeneracy, raising the typical mass fraction that can reside in the isothermal core to about 13% of the stellar mass.

Less massive stars exhibit even higher levels of degeneracy on the main sequence and may not exceed the Schönberg–Chandrasekhar limit at all before the next stage of nuclear burning commences.

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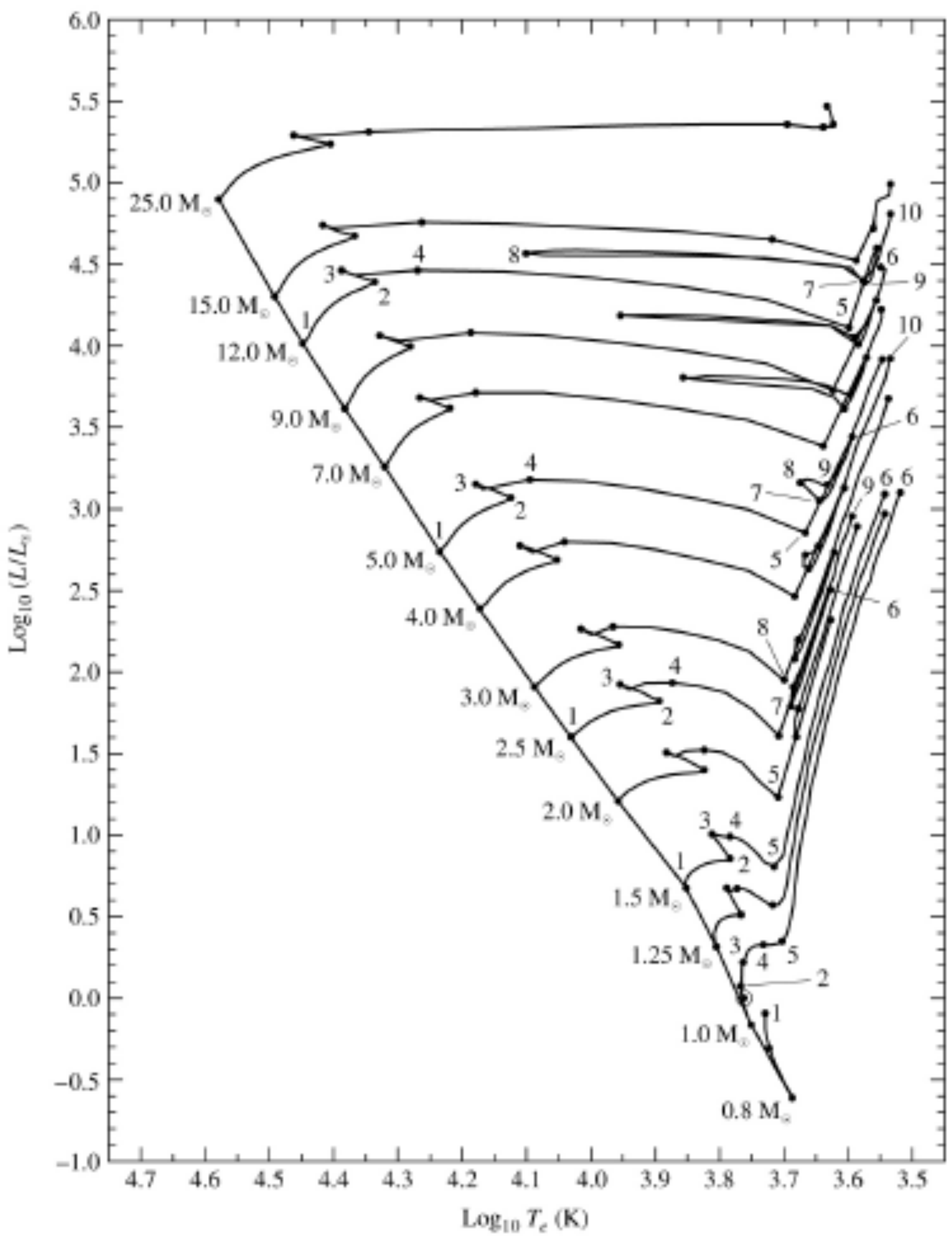
Main sequence evolution of massive stars



In massive stars, the key difference is that the core is convective. Convective timescales are very short, and this serves to keep material well-mixed. As the star evolves, the CZ retreats - this is a sensitive function of stellar mass.

When the mass fraction reaches about X = 0.05 in the core of a 5 MSUN star the entire star begins to contract. The luminosity increases slightly with the release of G.P.E. Since the radius decreases, the temperature increases and the star evolves rapidly

CZ - convection zone

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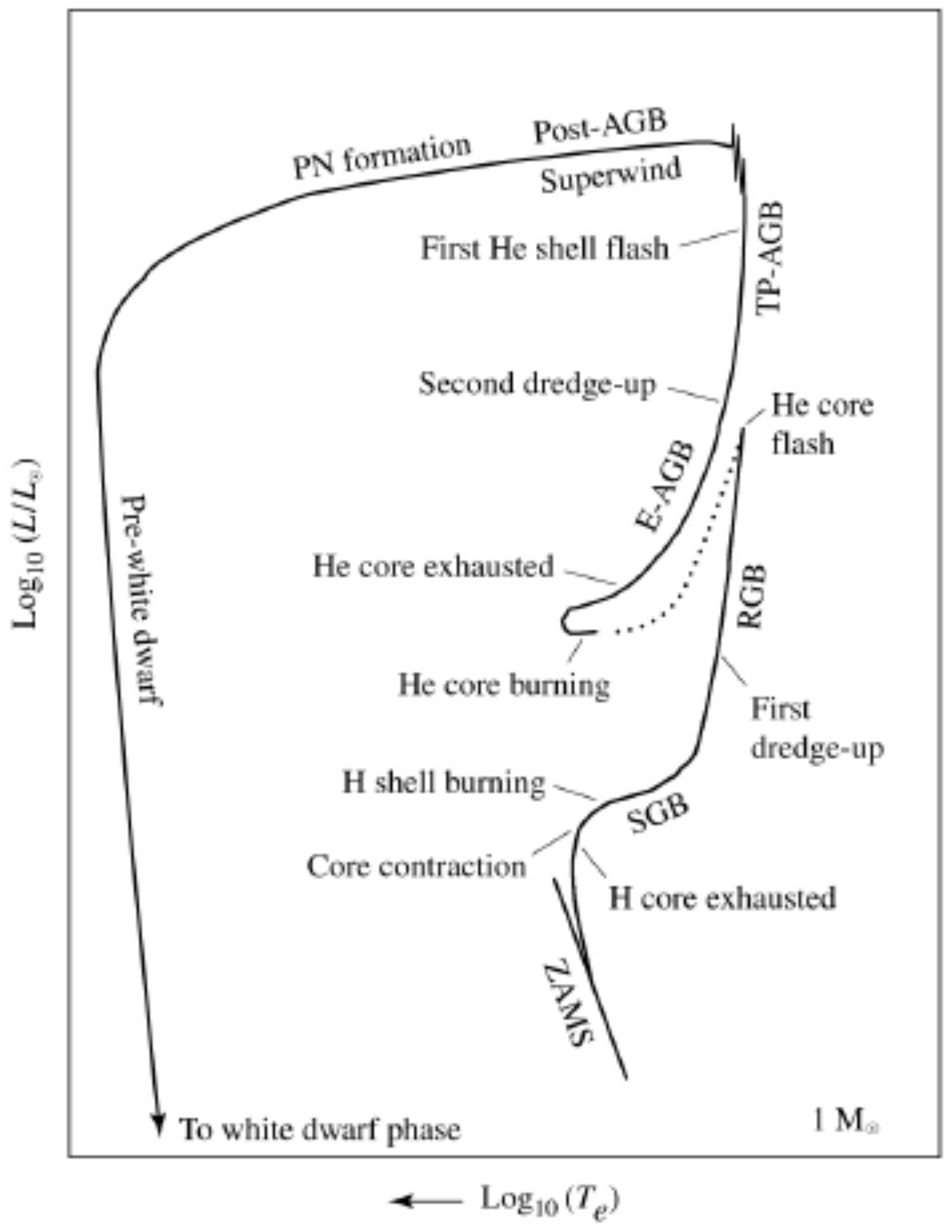
Late stages of stellar evolution: 1 Msun



For a 1 M_{SUN} star, the luminosity increases as the H-burning shells produce more luminosity than the H-burning core.

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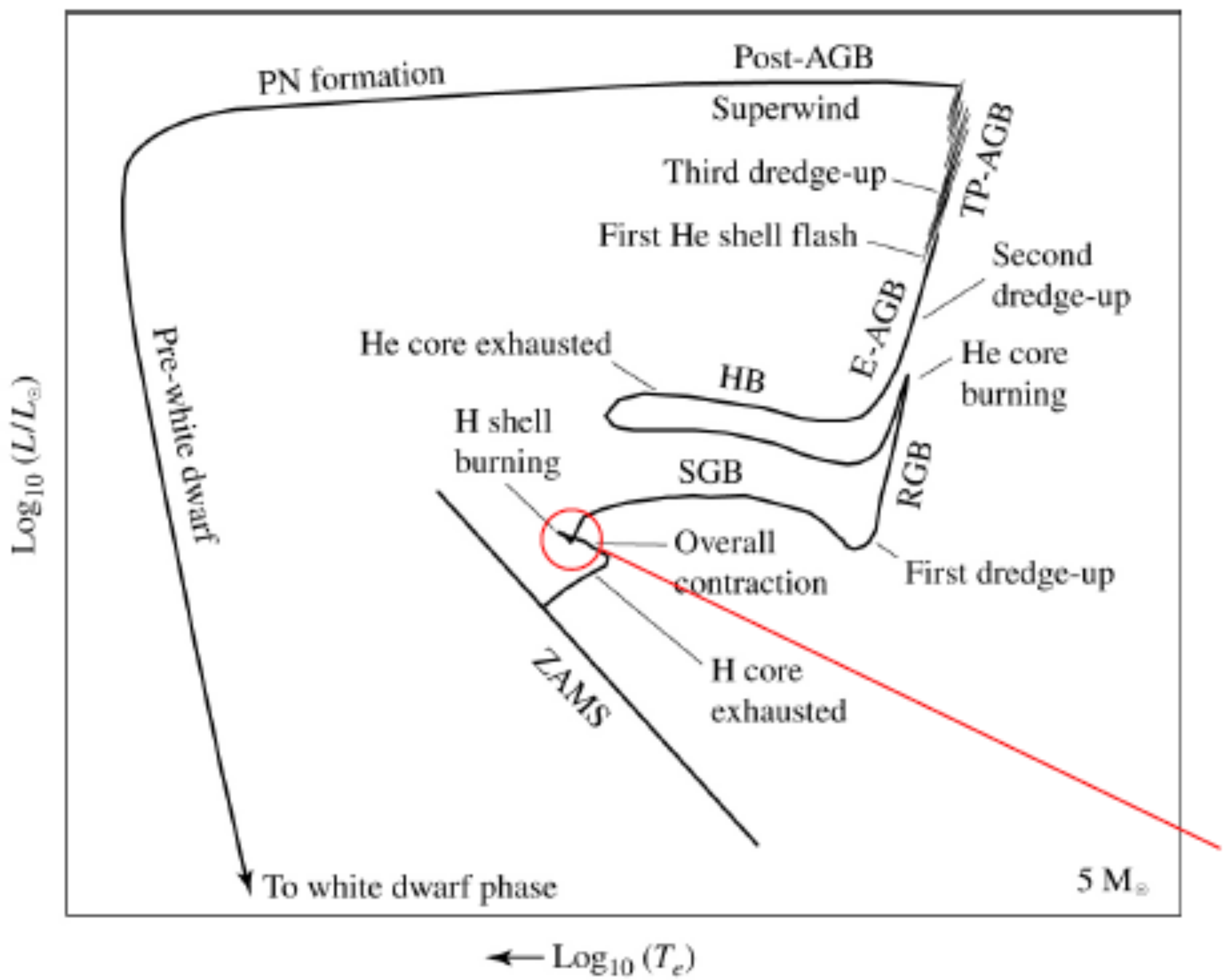
Late stages of stellar evolution: 5 Msun



For a 5 M_{SUN} star, the entire star contracts on a K-H timescale, releasing G.P.E. (increasing luminosity) but decreasing slightly in radius and increasing the effective temperature.

Rapid ignition of the shell causes the outer envelope to expand, absorbing some of the energy. So luminosity takes a dip and the effective temperature drops.

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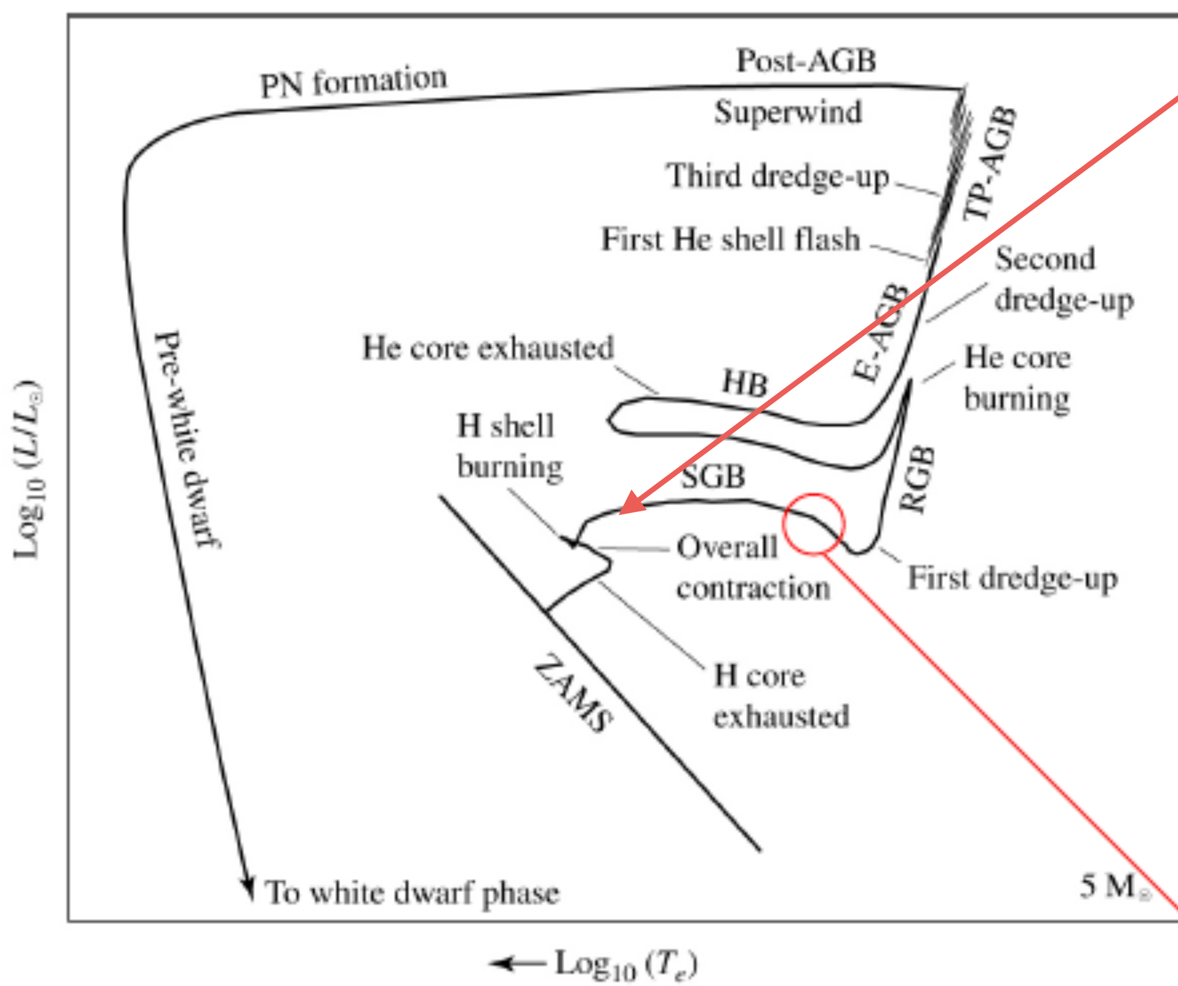
Late stages of stellar evolution: 5 Msun



The Schoenberg-Chandrasekhar limitis reached and the core begins to contract rapidly (K-H timescale). Released G.P.E. causes the envelope of the star to expand and the temperature cools as the star moves across the sub-giant branch.

H-burning begins in a thick shell immediately following overa;l contraction. The expanding envelope absorbs enough energy for a while to cause the luminosity to dip before recovering.

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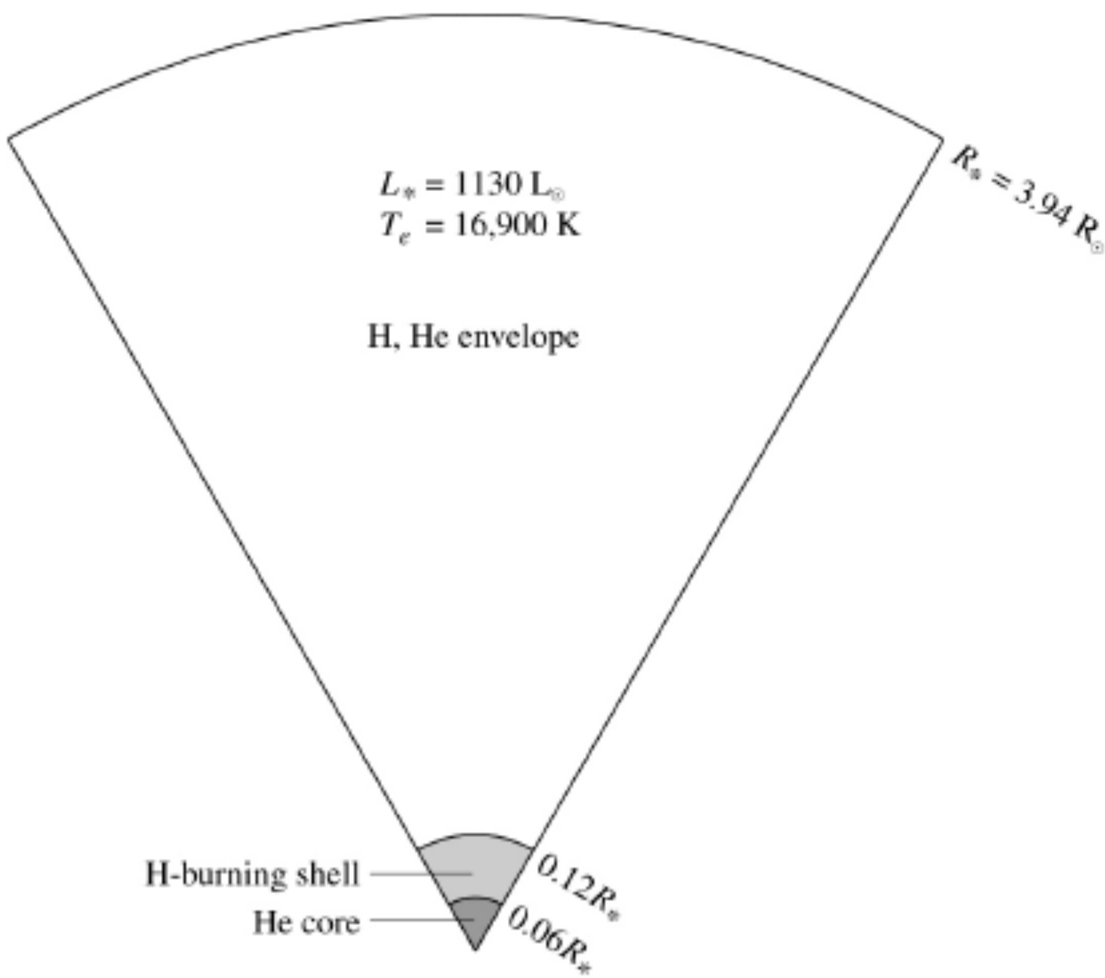
Late stages of stellar evolution



On the SGB, a temperature gradient in the core is re-established and the temperature and density of the shell increases.

The shell begins to narrow, and the energy generation increases.

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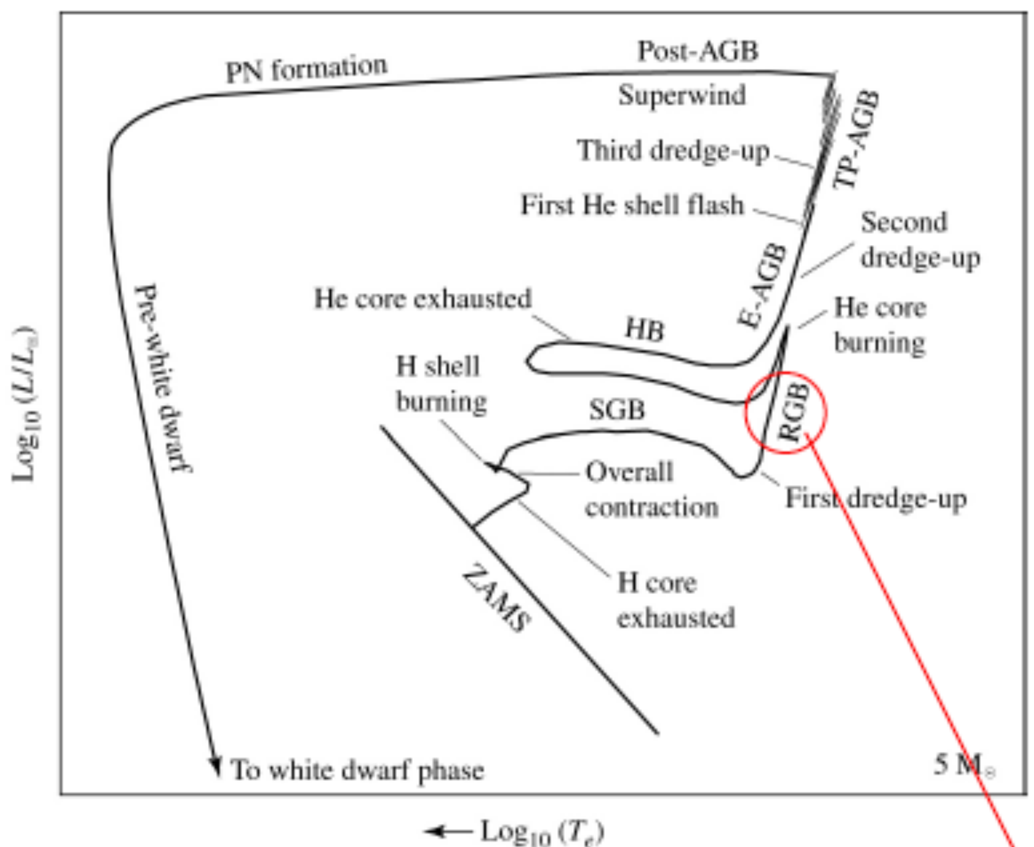
Red Giant Branch



As the stellar envelope expands, there is a decrease in the effective temperature. This changes the opacity of the envelope, increasing it as more H^- is formed. This causes the base of the convective zone to drop inward.

Remember that convective timescales are much shorter than radiative timescales. With energy efficiently transported out, the star begins to rise rapidly upward on the red giant branch (RGB).

CZ continues to deepen until it reaches down to regions where the chemical composition of the star has been modified by nuclear processes. This dredges up heavier elements, transporting ^{12}C inward and ^{14}N outward. This change in abundance ratios has been observed in giants.

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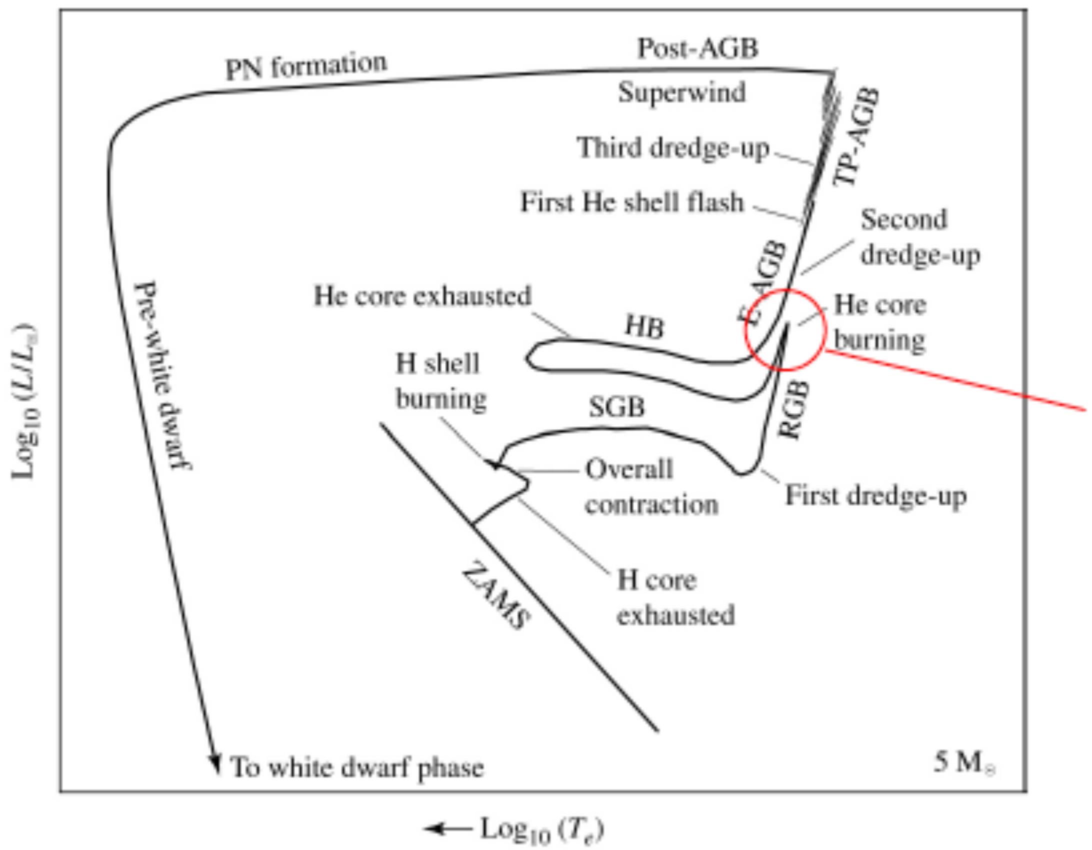
Red Giant Tip



At the tip of the RGB, the central temperature and density (1.3×10^8 K and 7.7×10^6 kg m^{-3}) have become high enough that quantum-mechanical tunneling becomes effective through the Coulomb barrier, and the triple-alpha process begins.

This increase in energy generation causes the core to expand, pushing the h-burning shell outward, cooling it and decreasing the energy output of the shell.

There is an abrupt decrease in the luminosity of the star and the envelope contracts and effective temperature begins to rise.

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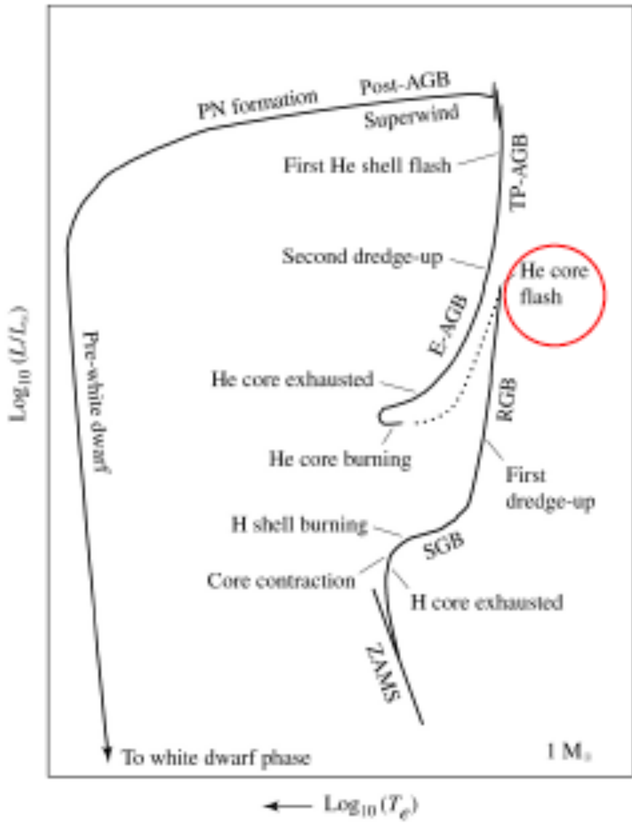
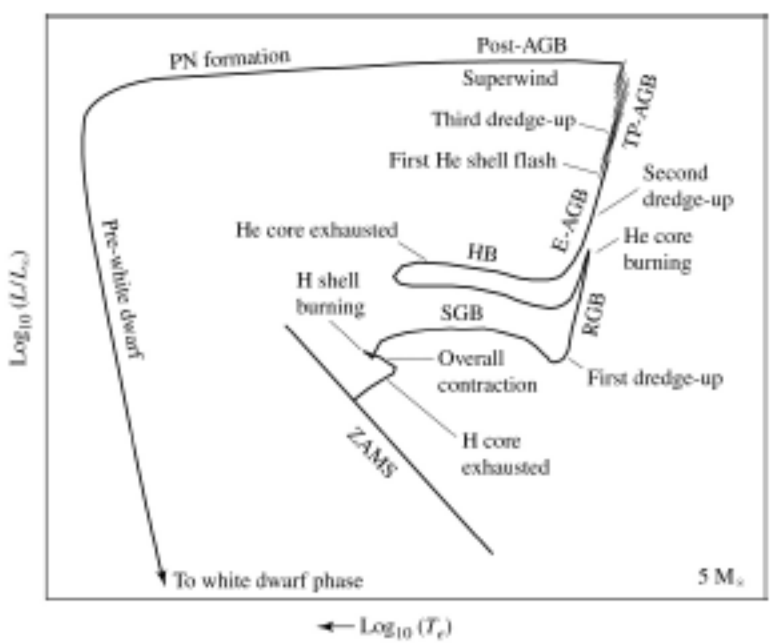


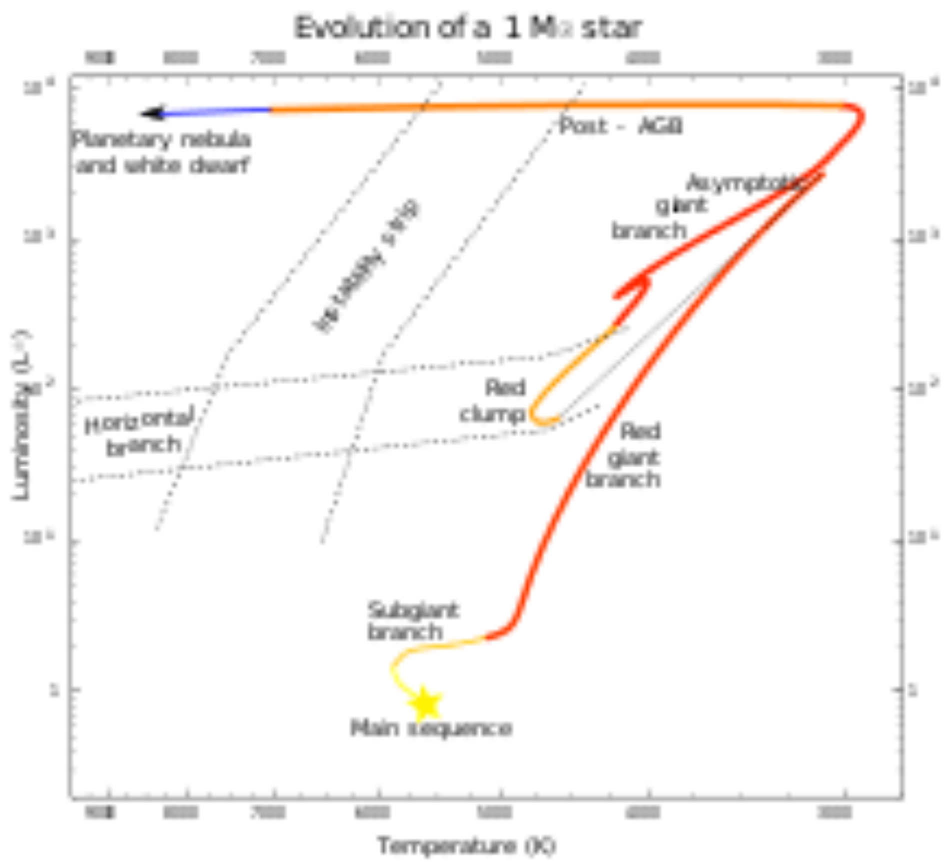


Helium core flash

For stars with mass < 1.8 MSUN, the helium core continues to collapse during evolution up to the tip of the RGB and the He core becomes strongly electron degenerate. Neutrino losses from the core of th star result in a temperature inversion in the core and the core collapses. When the temperature and density reaches He-burning values, there is an enormous flash as the temperature inversion is lifted.

The luminosity generated by the helium-burning core reaches 10^{11} L_{SUN}, comparable luminosities of entire galaxies, but lasts only for a few seconds!

Horizontal Branch



Cycles of expansion of the outer envelope, contraction, increases in temperature, beginning of fusion reactions, thinning of the shell, settling of ash onto inner layers.

When the evolution of the star reaches its most blueward point (point 8 in Fig. 1 for the 5 $M_\odot$ star), the mean molecular weight of the core has increased to the point that the core begins to contract, accompanied by the expansion and cooling of the star's envelope. Shortly after beginning the redward portion of the HB loop, the core helium is exhausted, having been converted to carbon and oxygen. Again the redward evolution proceeds rapidly as the inert CO core contracts, much like the rapid evolution across the SGB following the extinction of core hydrogen burning.

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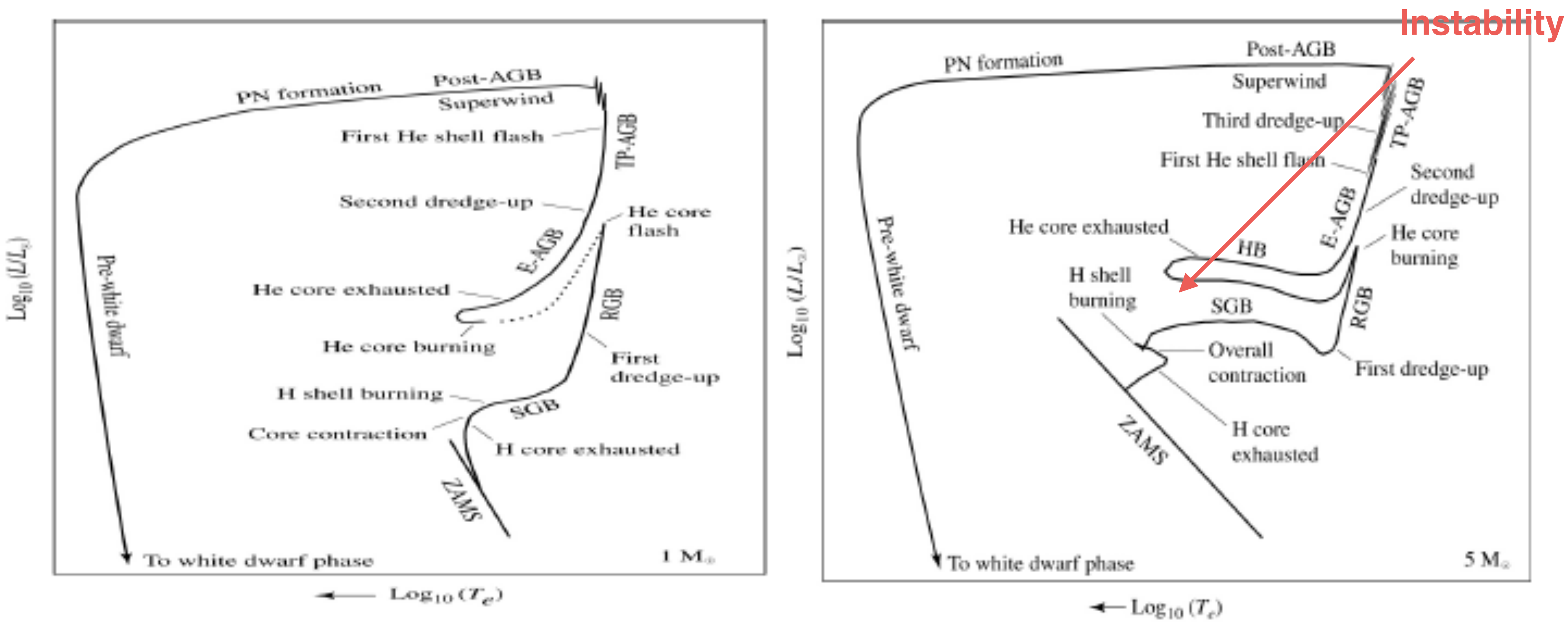
Horizontal Branch



Post RGB-tip, the star contracts, compressing the H-burning shell and increasing the energy output. The CZ becomes more shallow and a convective core develops (high temperature output from triple-alpha burning).

When the star reaches the bluest point on the HB, the mean molecular weight of the core has increased - with the loss of He comes a decrease in energy output and the star contracts.

Looping back evolution mimics the SGB, with contraction of an isothermal CO core, deepening of the CZ, development of instabilities and He shell-burning

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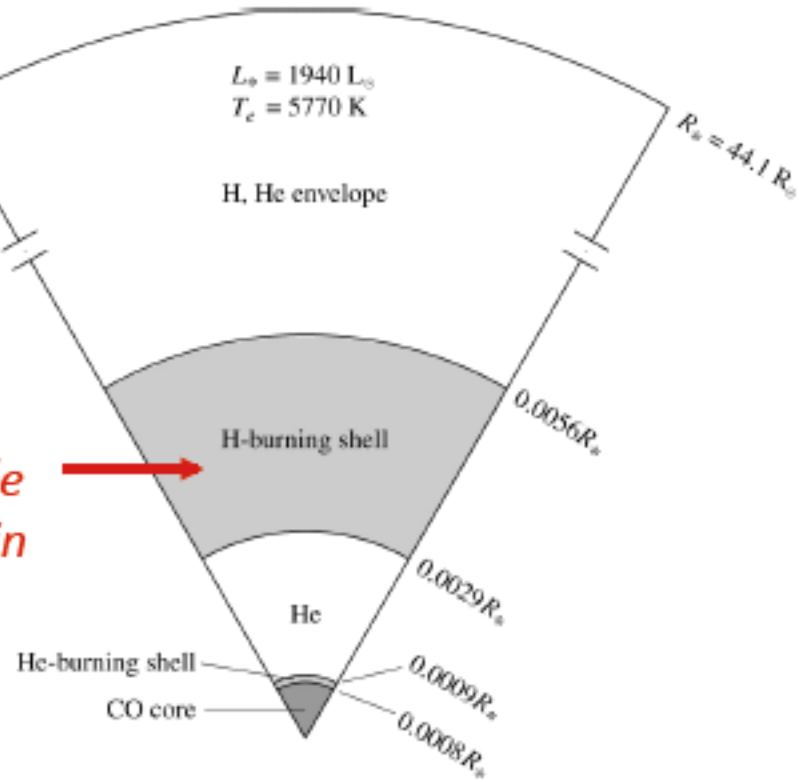
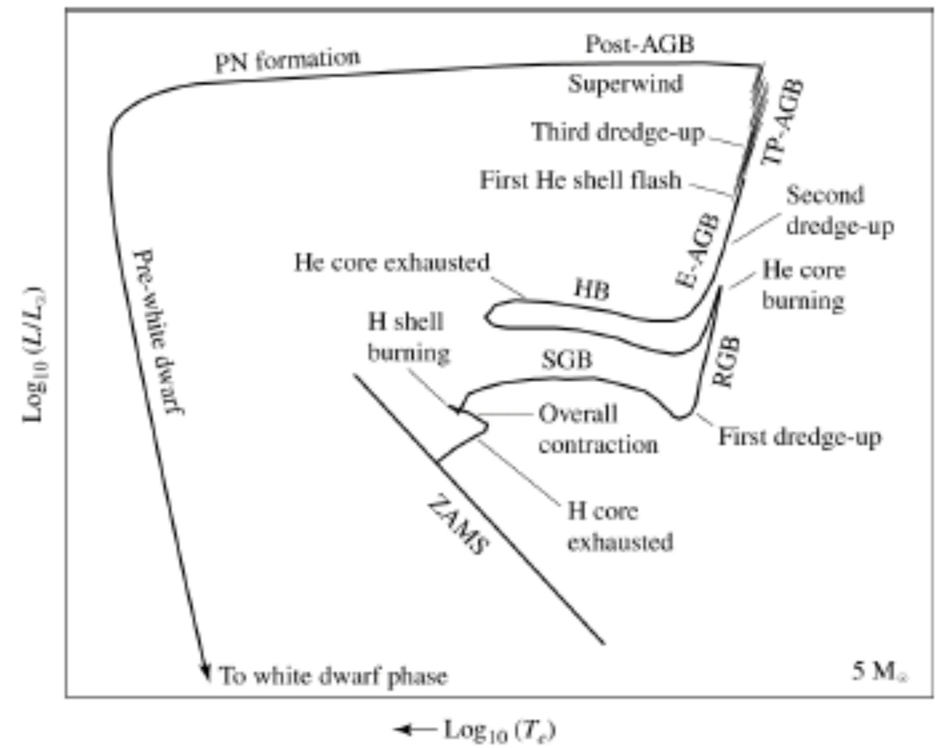
Early Asymptotic Giant Branch



Not to scale this is a thin layer!



the core temperature of the 5 $M_\odot$ star is approximately 2×10^8 K, its density is on the order of $10^9\ \mathrm{kg\ m^{-3}}$.

The evolutionary tracks asymptotically approach the giant branch. Most energy provided by He-burning shell, which expands the stellar envelope.

Again, expansion cools the outer envelope, increasing the opacity, giving rise to instabilities that push the CZ deeper. There is a second dredge-up that increases the He and H content of the envelope.

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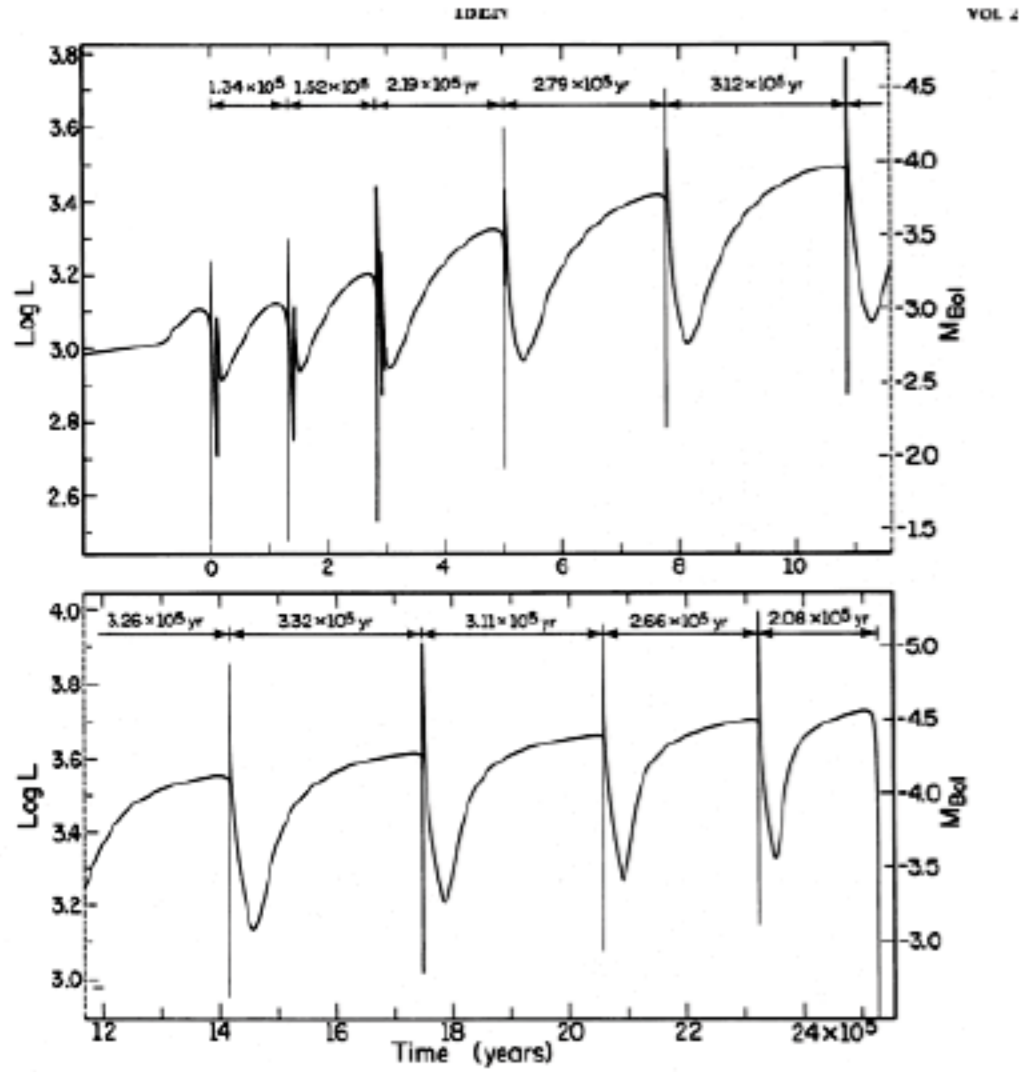
Thermal-Pulse Asymptotic Giant Branch



Iben, 1982, ApJ 260, 821

H-burning shell re-ignites, while the He-shell sputters along, turning on and off. Intermittent He-shell flashes occur as the H-burning shell deposits He ash onto the He-burning layer.

The period between pulses is a function of the stellar mass: 1000's of years for 5 M_{SUN} to 100,000's years for subsolar masses.

Evident in abrupt luminosity changes at the surface of the star: Mira variables

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Third dredge-up and C-type stars

The sudden increase in energy from the He-burning shell sets up a convective region between the H-burning region and the He-shell. The depth of the CZ envelope is also increasing and these convective regions merge, causing a dramatic dredge up of carbon-rich material.

C-type stars are giants with more carbon molecules in their atmospheres than oxygen.

SiC instead of SiO

This occurs if there is more carbon than oxygen. CO is a tightly bound molecule, so if there is an excess of oxygen, SiO forms. If there is an excess of carbon, most oxygen is tied up in CO and SiC forms.

S-type stars

Almost identical carbon and oxygen abundances. Identified by ZrO lines.

${}^{99}_{43}$Tc is an isotope with a 200,000 yr half life, seen in abundance in TP-AGB's - suggests recent dredge-up.

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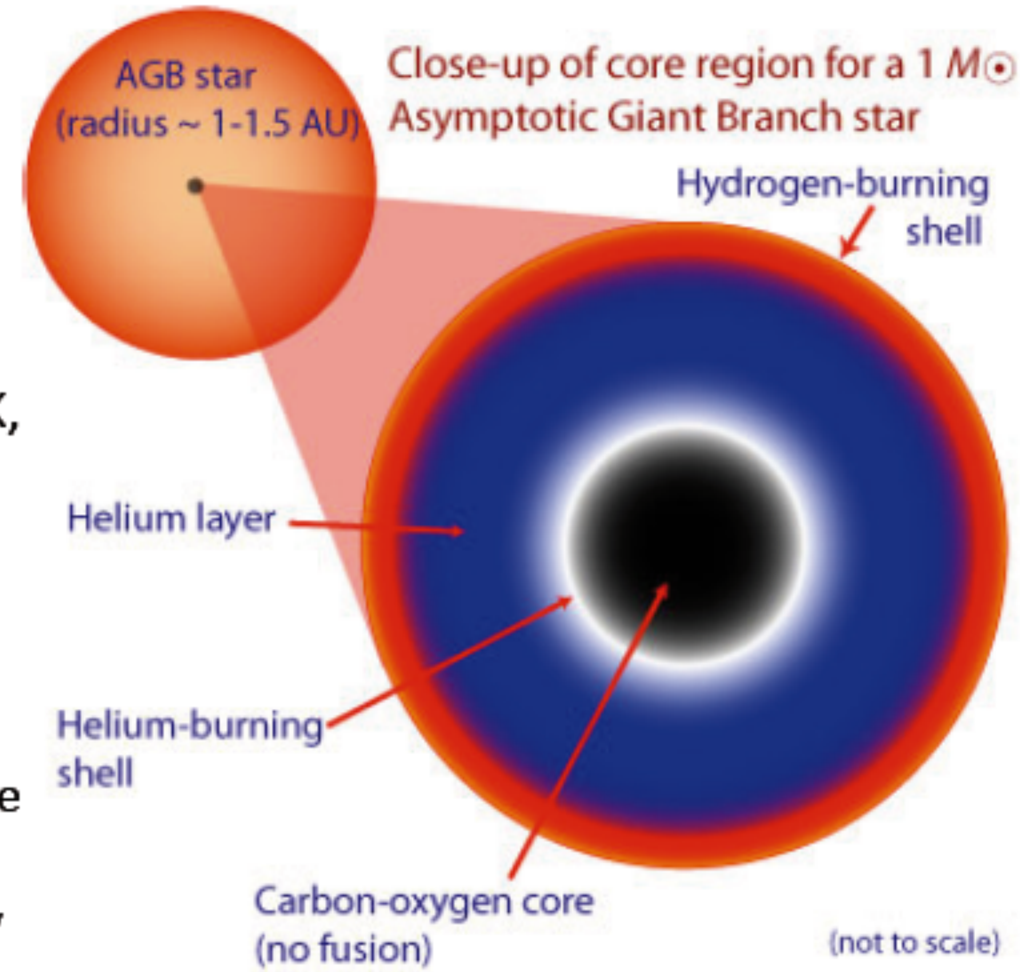
Mass loss and AGB evolution

Mass loss in AGB's is as high as 10^{-4} M_{SUN} per year.

The effective temperatures of these stars is about 3000 K, so the expelled matter is in the form of grains. Silicate grains form in oxygen rich environments and graphite grains form in carbon rich environments.

Two mass regimes of importances, cut at 8 M_{SUN}.

For lower mass stars, the He-burning shell produces more carbon and oxygen, which settles onto the CO core. The core continues to contract, increasing the central density until electron degeneracy begins to dominate.



For stars between 4 - 8 M_{SUN}, mass loss occurs, preventing collapse of the degenerate core. Heavier elements form (O, Ne, Mg).

Rate of mass loss increases with time: luminosity and radius are increasing while the stellar mass is decreasing. In the latest stages, a superwind develops with mass losses of 10^{-4} M_{SUN} per year and the star becomes shrouded with optically thick dust clouds (OH/IR sources).

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M. C. Shepherd, R. J. Cohen, M. J. Gaylard & M. E. West

OH–IR sources as precursors to protoplanetary nebulae

Nature 344, 522 - 524 (05 April 1990)

OH-IR sources are highly evolved red giant stars that have built up massive, cool gaseous envelopes through heavy mass loss, are precursors to planetary nebulae. The two kinds of object share a similar galactic distribution, and their circumstellar envelopes have comparable masses and expansion velocities2,3. Recently, several hybrid objects have been found with the far infrared and OH maser emission characteristic of the OH–IR sources, but also with radio continuum emission from a central H II region4–6. There is strong circumstantial evidence that these objects, of which the prototype is Vy2–2 (refs 4,7), seem to be in a transitional state, but their precise evolutionary status remains unclear.

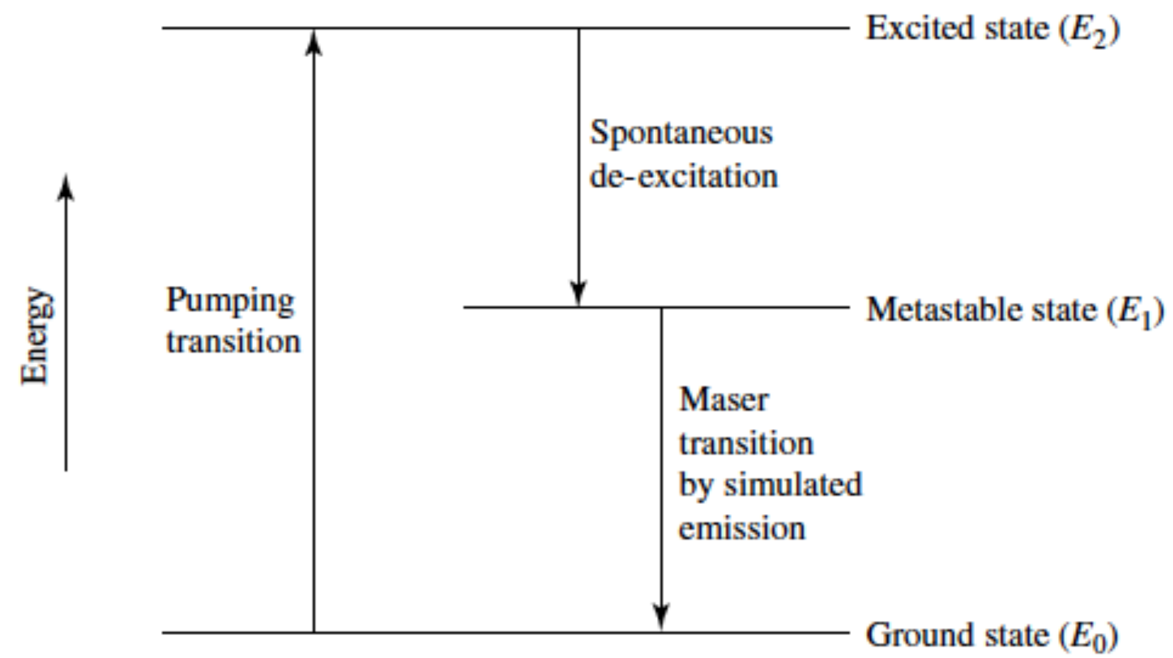

FIGURE 11 A schematic diagram of a hypothetical three-level maser. The intermediate energy level is a relatively long-lived metastable state. A transition from the metastable state to the lowest energy level can occur through stimulated emission by a photon of energy equal to the energy difference between the two states ($E_\gamma = h\nu = E_1 - E_0$).

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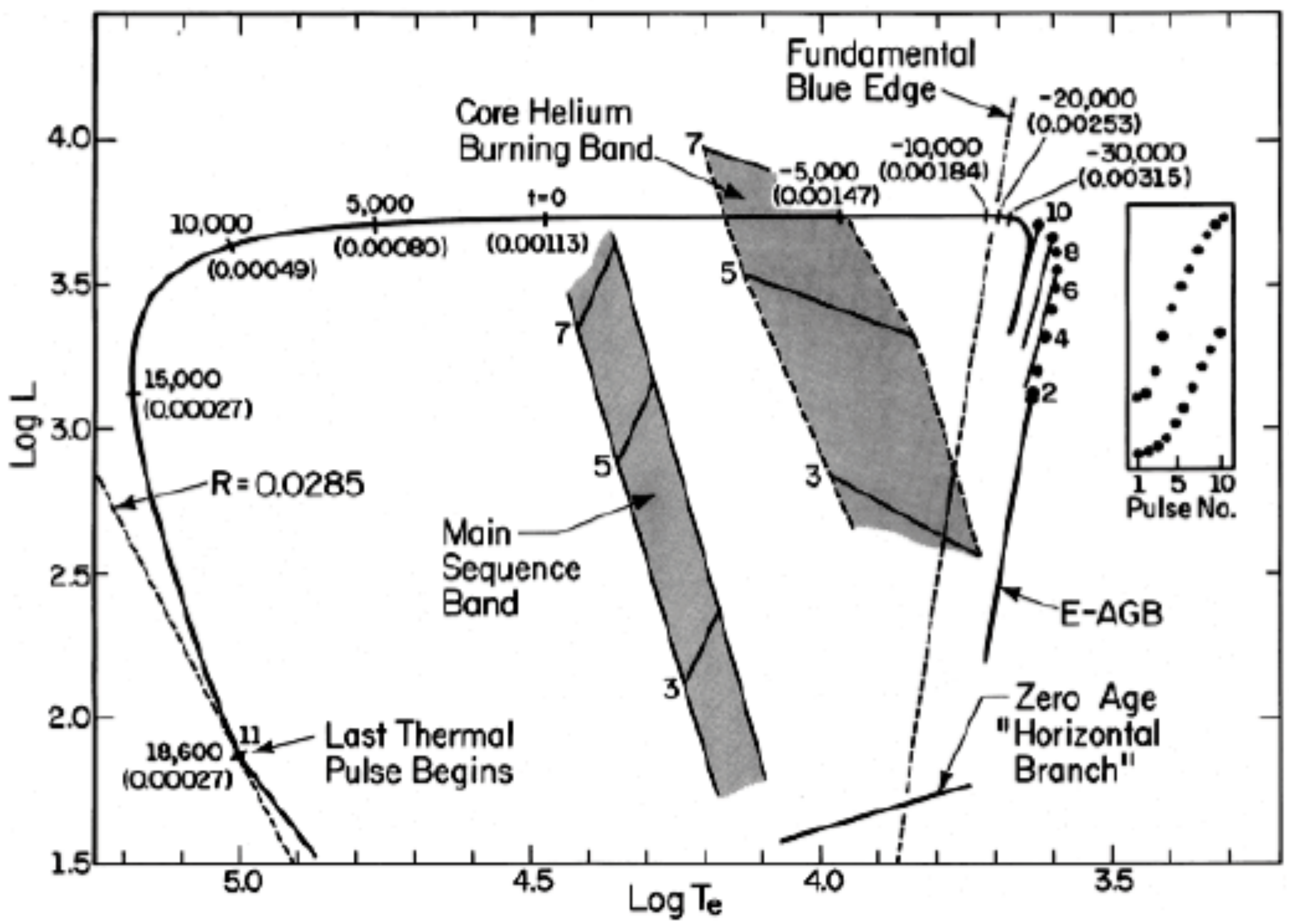
Post-Asymptotic Giant Branch

As the OH-IR cloud expands, it becomes optically thin exposing the star which has a spectral type F or G supergiant. Given that the progenitor was a ~5 M_{SUN} star (B- or A-type), does this make sense?

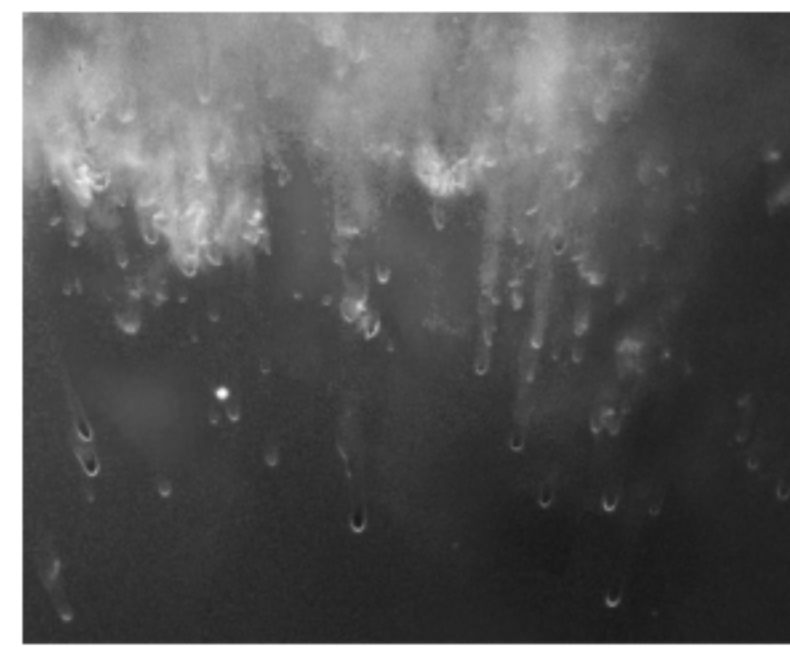
The outer layers are blown off, and the H-burning and He-burning shells have only a thin layer above them. With no more pressure on these layers, fusion ceases and the luminosity of the star decreases rapidly. The hot central object cools to become a white dwarf.

Post-Asymptotic Giant Branch



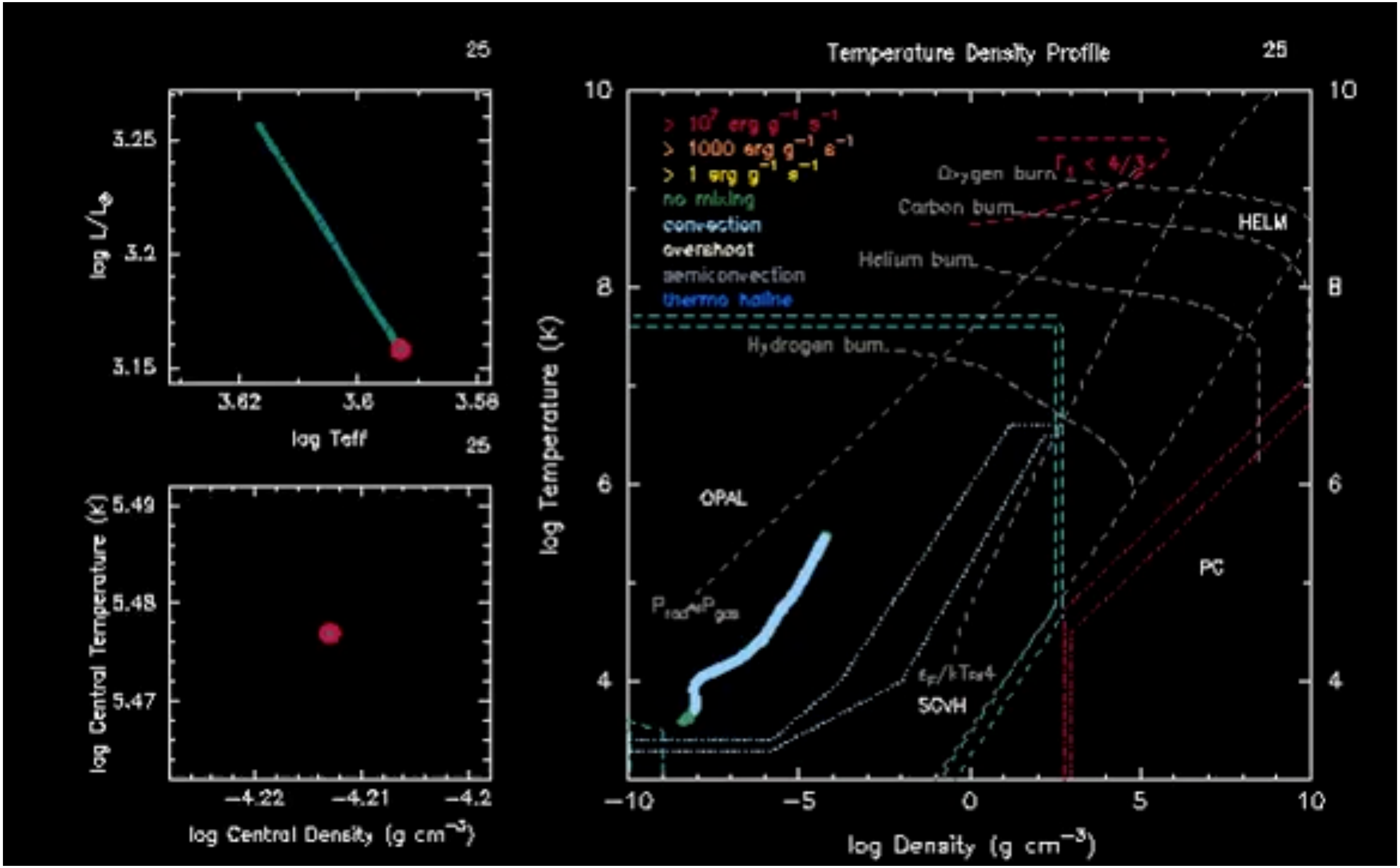
Latest stages for a 0.6 M_{SUN} model undergoing mass loss. The MS and HB of 3, 5, and 7 M_{SUN} stars are shown for reference. The numbered spots are positions where pulses begin. Following the 10th pulse, the model evolves to the WD stage. Times are defined in terms of the time where the surface temperature reaches 30,000K. The mass in the H envelope at these times is given in parentheses in SMU's. Model terminates when the He-burning CZ reaches the H-rich envelope and extends into these layers.

(a)

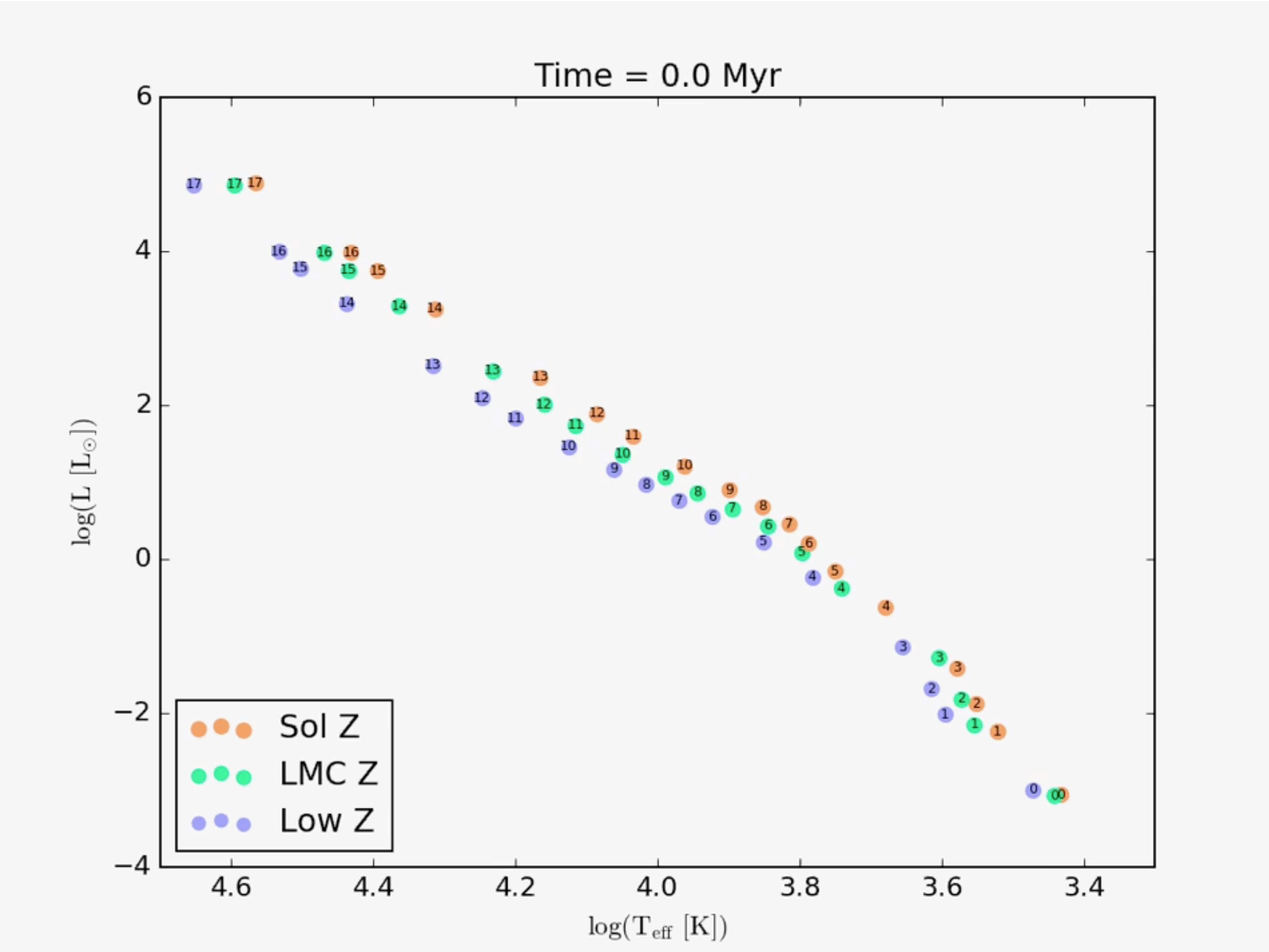


(b)

FIGURE 13 (a) The Helix nebula (NGC 7293) is one of the closest planetary nebulae to Earth, 213 pc away in the constellation of Aquarius. Its angular diameter in the sky is about 16 arcmin, roughly one-half the angular size of the full moon. The pre-white dwarf star is visible at the center of the nebula. [Credit: NASA, ESA, C.R. O'Dell (Vanderbilt University), M. Meixner, and P. McCullough.] (b) A close-up of "cometary knots" in the Helix nebula. The central star is located beyond the bottom of the picture. [Credit: NASA, NOAO, ESA, the Hubble Helix Nebula Team, M. Meixner (STScI), and T. A. Rector (NRAO).]



25
log L/L⊙
3.25
3.2
3.15
3.62
3.6
3.58
log Teff
25
log Central Temperature (K)
5.49
5.48
5.47
−4.22
−4.21
−4.2
log Central Density (g cm−3)
Temperature Density Profile
25
> 10^7 erg g^−1 s^−1
> 1000 erg g^−1 s^−1
> 1 erg g^−1 s^−1
no mixing
convection
overshoot
semiconvection
thermo haline
Oxygen burn
Γ1 < 4/3
Carbon burn
Helium burn
Hydrogen burn
HELM
OPAL
Prad≈Pgas
εF/kT≈4
SCVH
PC
log Temperature (K)
log Density (g cm−3)
10
8
6
4
−10
−5
0
5
10



Time = 0.0 Myr
log(L [L⊙])
log(Teff [K])
6
4
2
0
−2
−4
4.6
4.4
4.2
4.0
3.8
3.6
3.4
Sol Z
LMC Z
Low Z

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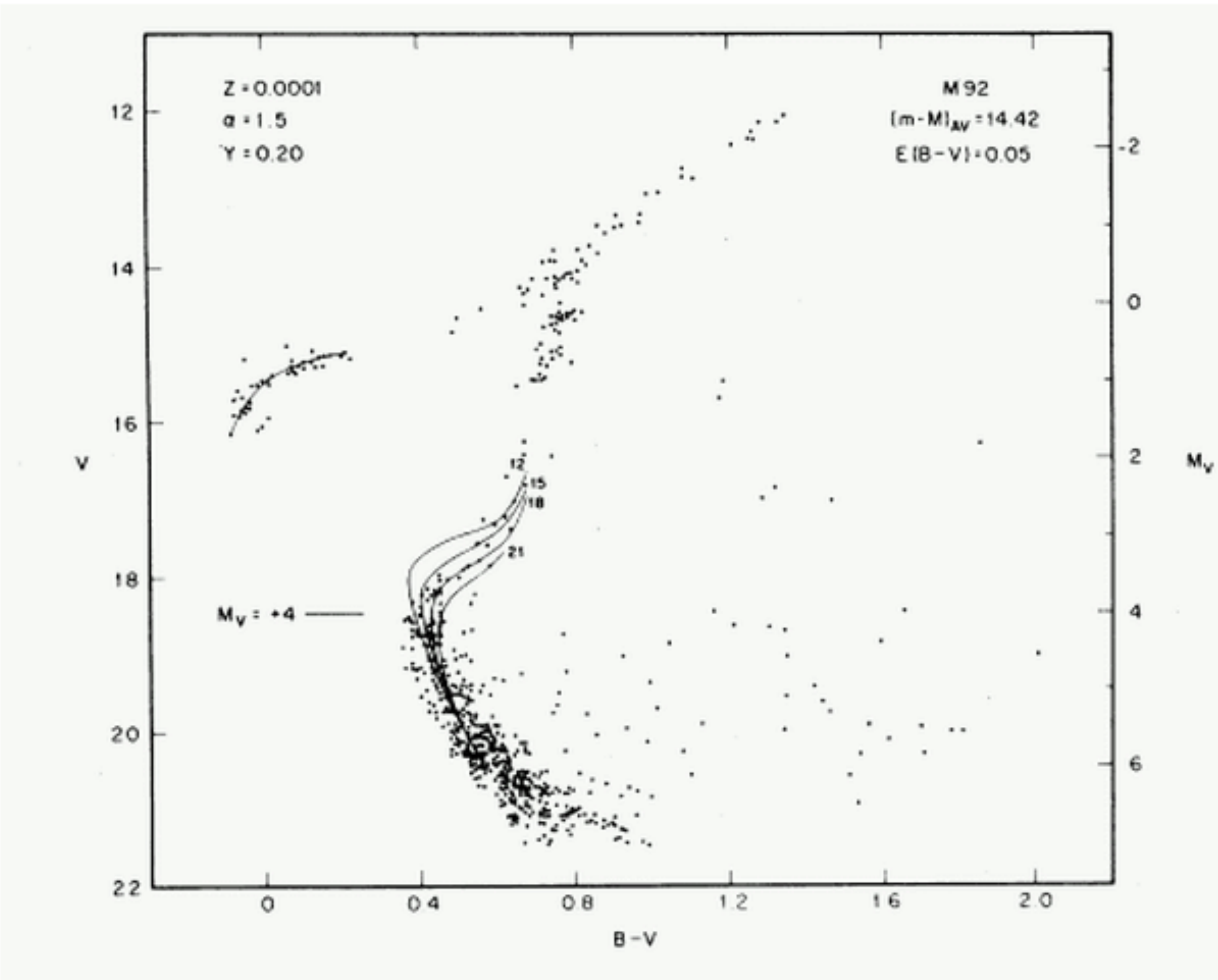
Isochrones and Cluster ages



A thrifty way to estimate the ages of clusters is with a color-magnitude diagram (CMD).

Measure B-V and V

All stars are at the same distance

All stars are the same age

Fit evolutionary tracks to find the “same age track” or isochrone that fits the turn-off point, to derive the age of the cluster

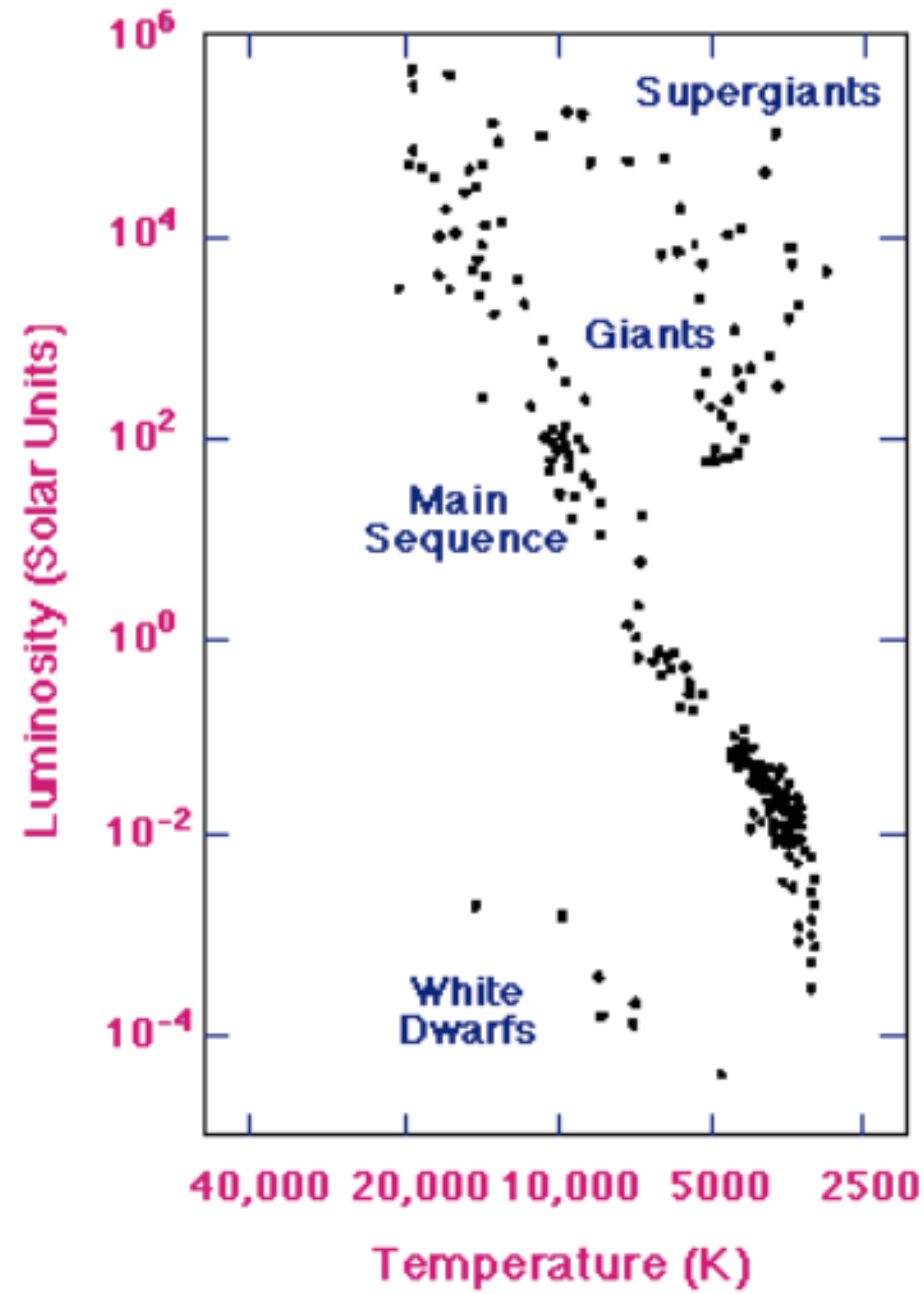
Chapter 13: Stellar Evolution

Hertzsprung Gap

The paucity of stars between the main sequence and giant branch atests to the rapidity of evolution on the SG and HB.

Relatively few stars are found on the AGB - again rapid pace of evolution.

Worth noting that stellar lifetimes are metallicity-dependent. Low metallicity stars evolve more rapidly, so this is included in modeling isochrones.



Chapter 12: Star formation

Review

Stars live on the main sequence for billions of years

-stars are in hydrostatic equilibrium, but not static. Gravity and radiation energy are balanced. If the fusion rate decreases, the star contracts, heating up the core and increasing the reaction rates

-stars with $M > 1.2\ M_{SUN}$ have convective cores (CNO chain and strong temperature gradient)

-stars with $0.3 < M < 1.2\ M_{SUN}$ have radiative cores

-stars with $M < 0.3\ M_{SUN}$ are fully convective

Chapter 13: Stellar Evolution

Review

Stars begin evolution when the H-fusion rate in the core can no longer support the star against gravity.

- Mean molecular weight in core increases. H-fusion slows. Star compresses, increasing the temperature. H-fusion begins in shell around the core - more material here, more energy output, so subgiants are more luminous.

- Schoenberg-Chandrasekhar limit gives the maximum mass that can be supported by an isothermal He core. This works out to be 8% of the mass fraction, or 13% of the mass fraction accounting for extra support by electron degeneracy.

-convection in the core of massive stars decreases the Schoenberg-Chandrasekhar limit to about 5% and accelerates evolution

-On the subgiant branch, a temperature gradient is re-established in the core (no longer isothermal) and density in the H-burning shells increase. Some energy goes into expanding the shell - as it cools, the outer envelope increases opacity and instabilities cause the CZ to dip deeper into the star

-Density and temperature increase, triple-alpha process begins