Structure and Evolution of Stars

Lecture 17: Post-Main Sequence Evolution of Intermediate Mass Stars ~0.7-2M_{sun}

- Exhaustion of core Hydrogen fuel on main sequence
- Shell Hydrogen-burning source
- Ascent of the red giant branch
- Ignition of Helium burning in core - Helium flash
- Horizontal Branch – Helium core-burning main sequence
- Ascent of the asymptotic giant branch
- Mass Loss
- Planetary Nebulae
- White Dwarfs

Post-Main Sequence Evolution

- Zero age main sequence (ZAMS) populated according to the initial mass function (IMF). Location on ZAMS depends only on the mass and composition of the star

- Energy source from nuclear burning:
  - p-p chain dominant for stars with $M<1.5M_{sun}$
  - CNO cycle dominant at increasingly higher masses

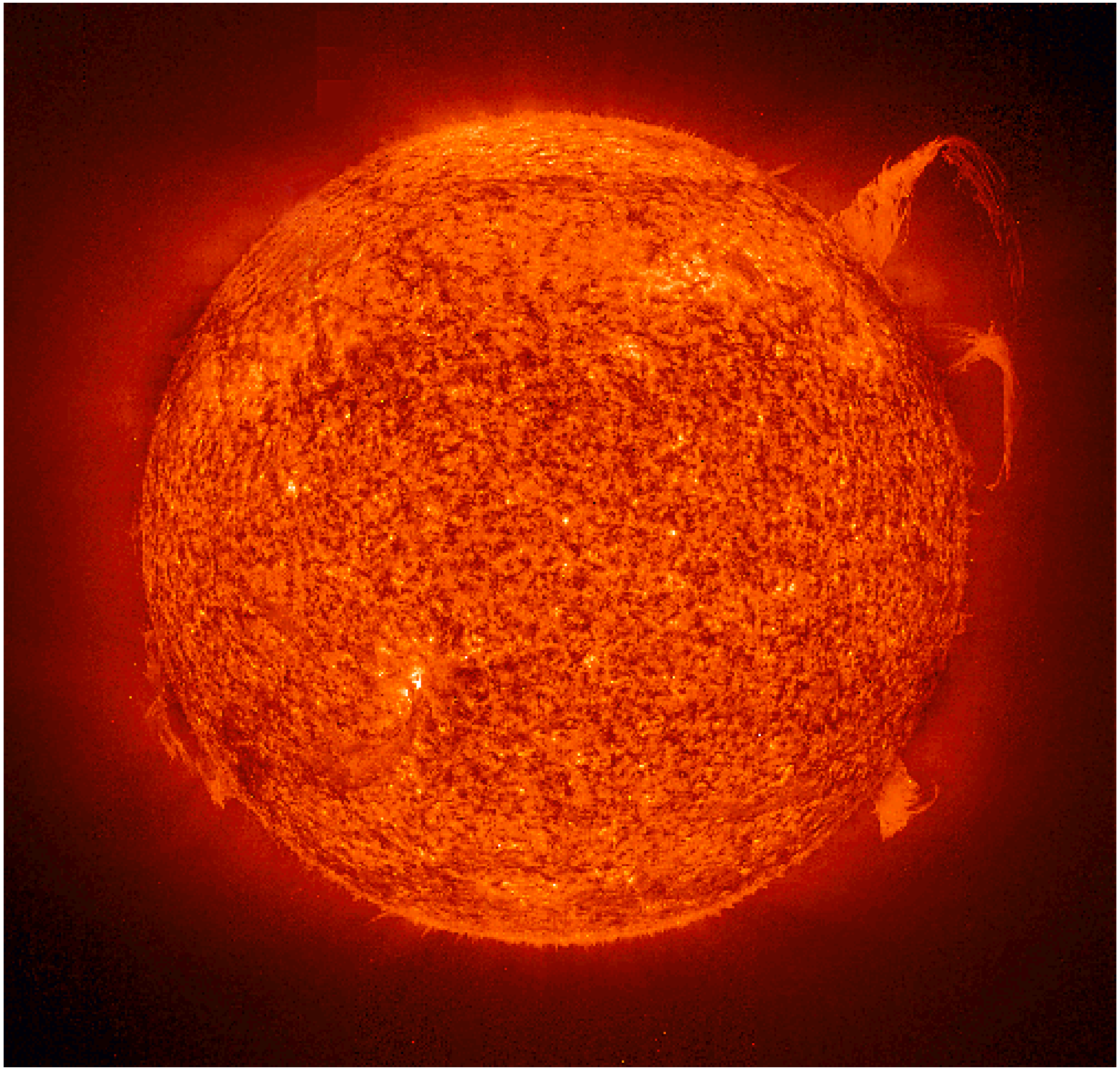
- Consider evolution of a $\sim 1M_{sun}$ star – similar behaviour for mass range ~ 0.7-$2M_{sun}$

- As core hydrogen burning procedes, mass fractions, $X \rightarrow 0$ and $Y \rightarrow 1$ in the core

- For stars of mass $< 2M_{sun}$, the central temperature is not high enough to initiate helium burning and an inert He core of increasing mass grows

Sun

Mass = 2×10^{30}kg
Radius = 7×10^{8}m
$L = 3.9 \times 10^{26}$W
$T = 5800$K



SOHO image at 304A


radiative zone
convective zone
core

Post-Main Sequence Evolution: ~1M_{sun} Star

- Lifetime from consideration of energy released via fusion of H to He (Lecture 11) and core mass of ~10% of total gives $\tau_{ms} \approx 10^{10}$yr

- Devoid of energy source the core contracts with ρ and T increasing as gravity winning without a source of energy

- T and ρ in shell surrounding the He-core increases and H-burning begins in the shell - **shell-burning phase**. Fusion in shell via p-p chain and CNO cycle becomes the new energy source for the star

- Density in core becomes sufficiently high that electrons packed so close that degeneracy pressure dominates over the gas pressure and holds the core up against gravity. No dependence on T (Lecture 7)

$$P \propto \rho^{5/3}$$

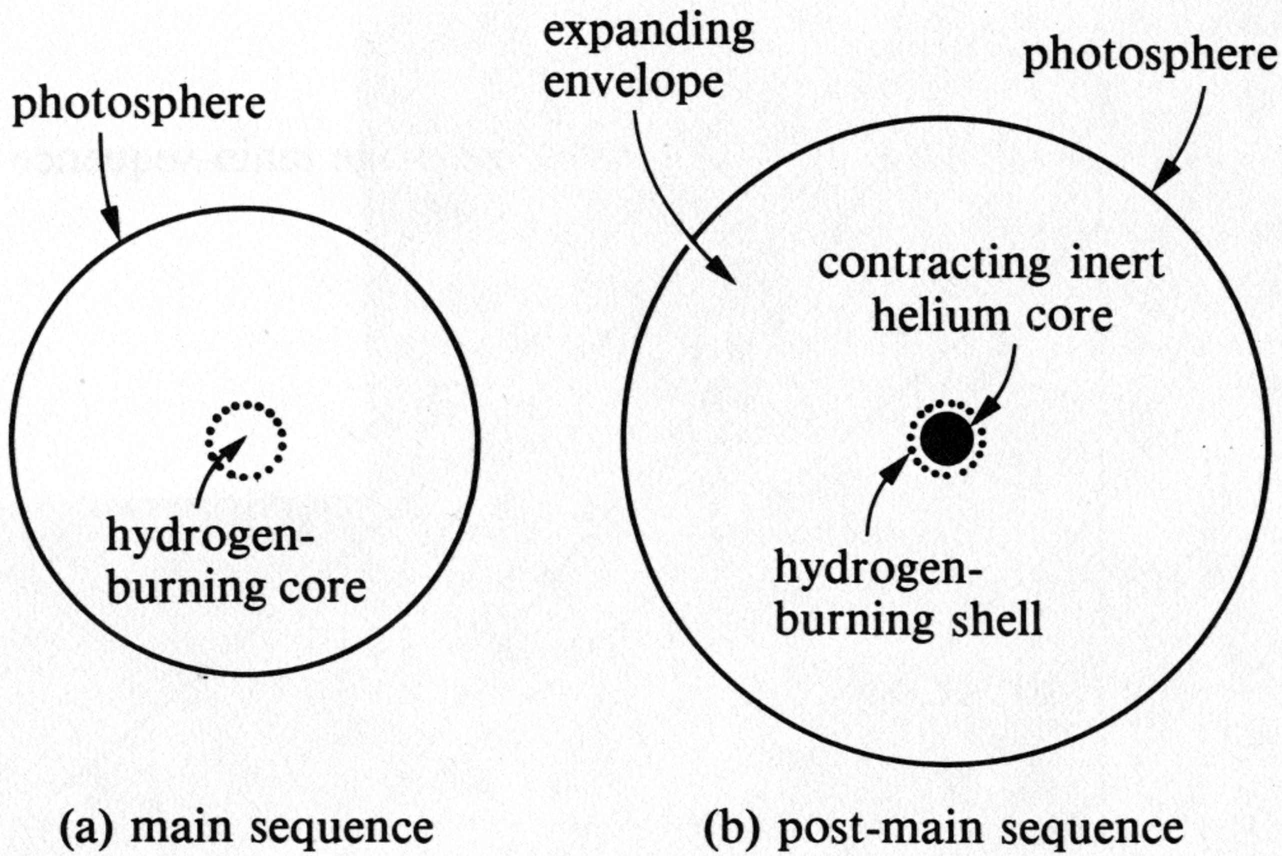


Figure 8.3. The structure of a star (a) on the main sequence and (b) as it begins to leave the main sequence because of core-hydrogen exhaustion.

Post-Main Sequence Evolution: ~1M_{sun} Star

- Contraction of the He-core has a significant impact on the structure of the star
- Core contraction occurs on a timescale $\tau_{contract} >> \tau_{dyn}$ and can be treated as quasi-static with the Virial Theorem holding
- Providing that the release of gravitational potential $E_{grav} << E_{tot}$ then thermal equilibrium can also be taken to hold
- Under such conditions the gravitational potential energy and thermal energy are both conserved
- As the core has contracted and heated up the stellar envelope must therefore expand and cool down
- Expansion of envelope at approximately constant $L = 4\pi R^2 \sigma T_{eff}^4$ results in a drop in the effective temperature
- Star moves to the right in the HR-diagram to reach base of the **red-giant branch**

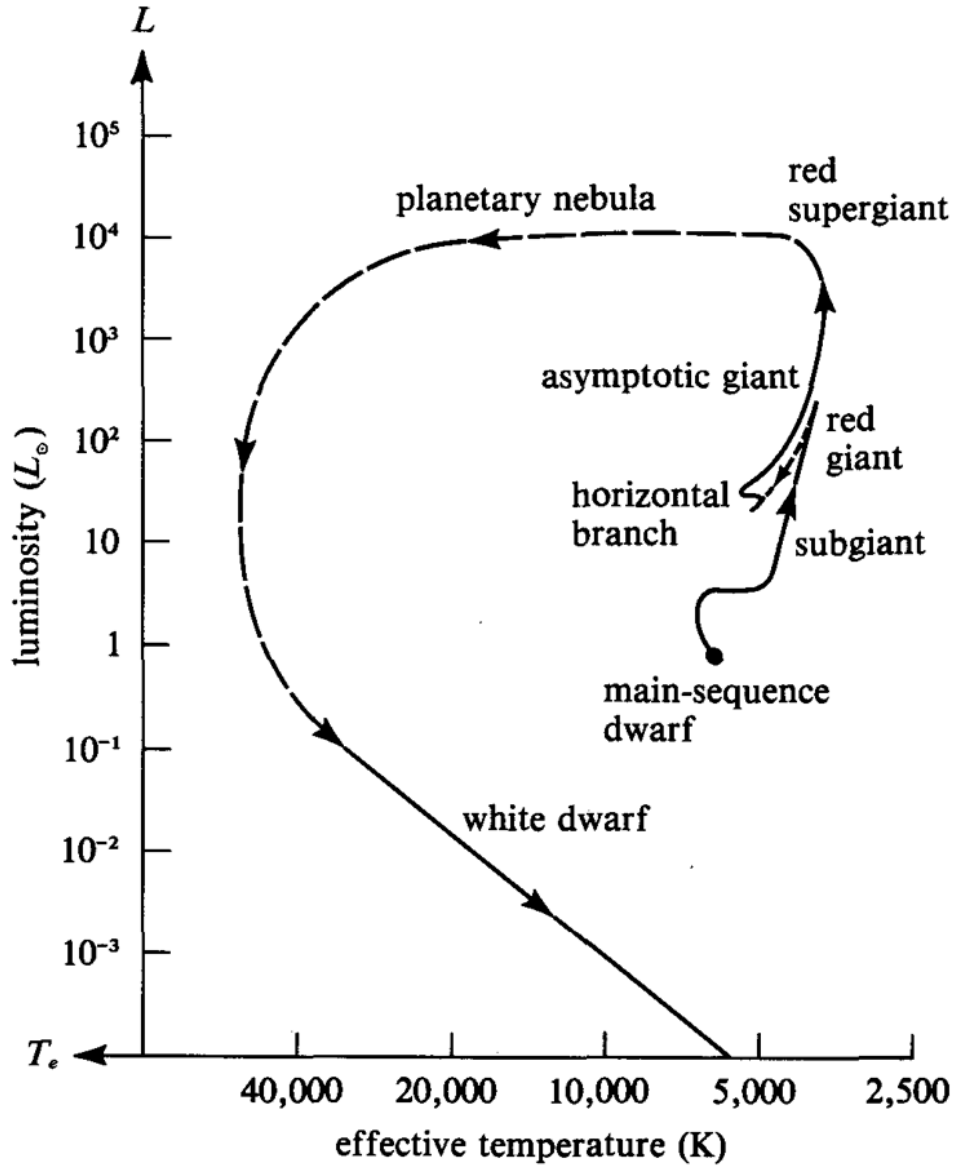


Figure 8.10. The complete evolution of a low-mass star from the main sequence to a white dwarf. The track from the asymptotic giant branch to a white dwarf (via a planetary nebula) is uncertain and is shown as a dashed curve.

Post-Main Sequence Evolution: ~1M_{sun} Star

• In fact, the relatively large volume of the H-burning shell, combined with the high T and ρ at the boundary of the He-core, results in an increase in L and the move away from the MS is also characterised by a vertical displacement in the HR-diagram
- star becomes a sub-giant (Luminosity Class IV)

• L increases as T and ρ at the boundary of the He-core increases – radius of the degenerate He-core decreases as core mass increases:
$R \propto M^{-1/3}$ (see Lecture 19)

• Envelope is fully convective as radiative diffusion incapable of transporting energy to surface. Star ascends the **giant branch** following (in reverse) an almost vertical track in the HR-diagram that has a similar form to the Hayashi Track that we deduced applied to the behaviour of a fully-convective contracting protostar (Lecture 15)

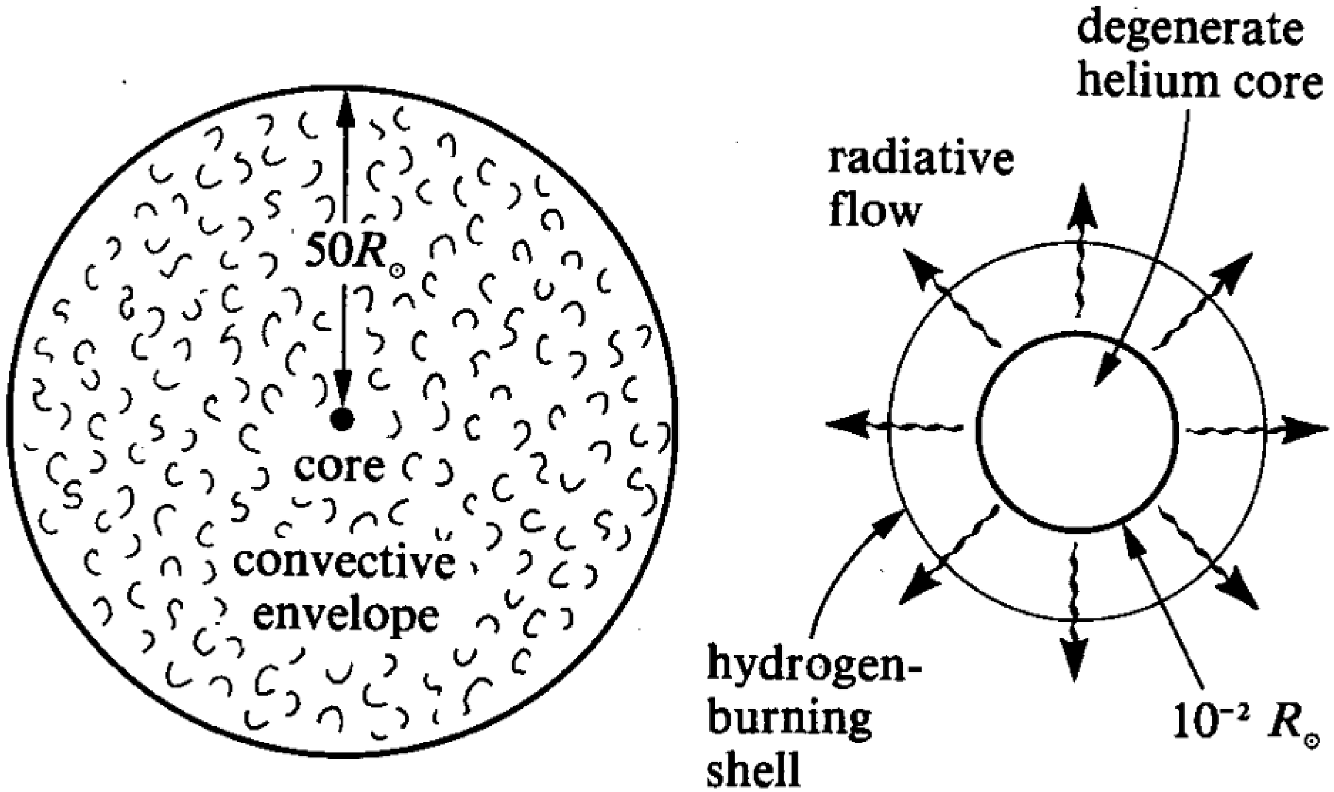


Figure 8.5. The structure of a red giant. The left figure shows the entire star from core to photosphere. The right figure shows an enlarged picture of the region near the core. Notice that the core, which may contain about half the total mass of a low-mass star at this point, occupies only one ten-billionth of the total volume.

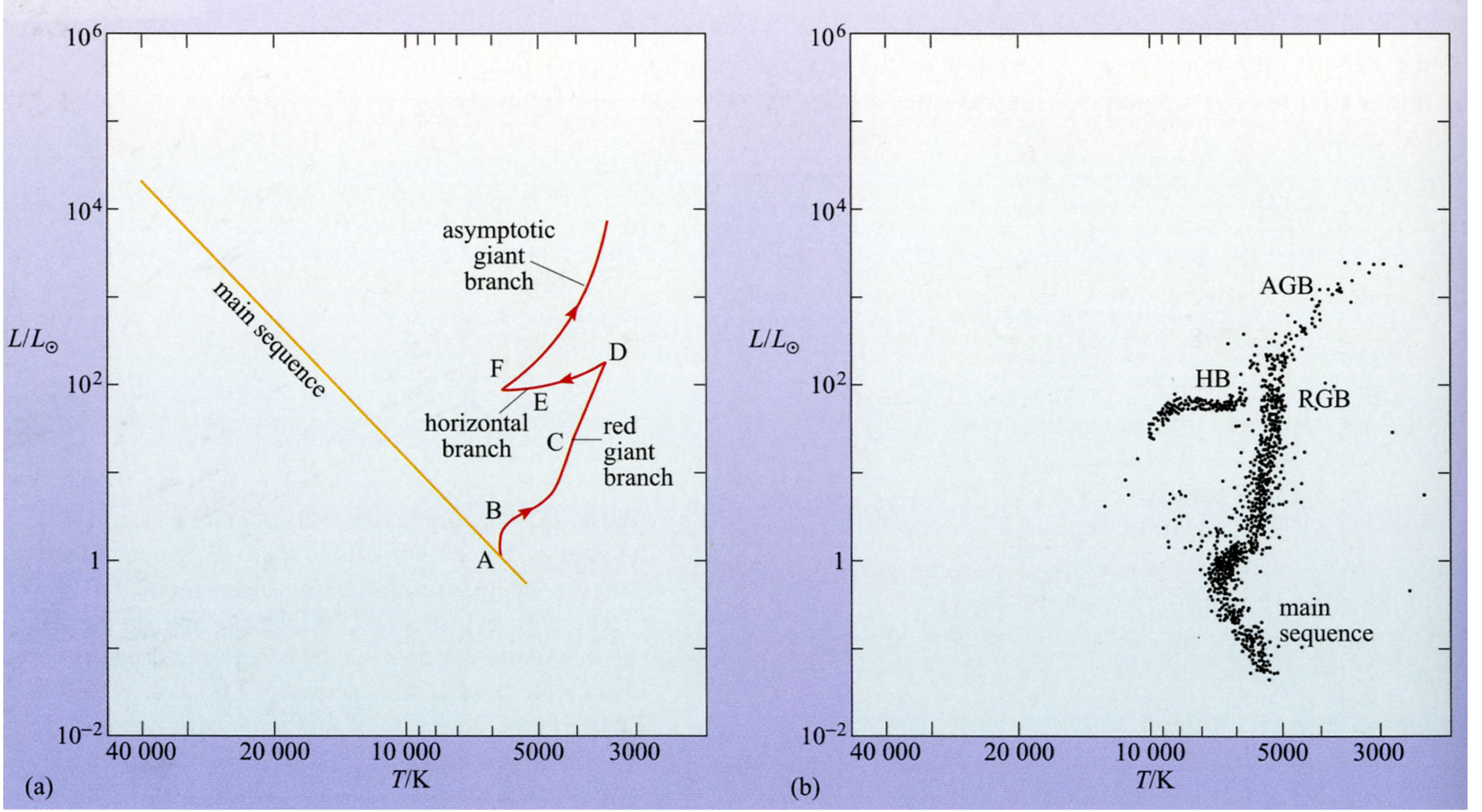


Figure 7.3 (a) The predicted path of a $1M_\odot$ star, plotted on the same scale with the same labels as Figure 7.2, (A) hydrogen core fusion; (B) onset of hydrogen shell fusion; (C) hydrogen shell fusion continues; (D) helium core fusion starts; (E) helium core fusion continues; (F) helium shell fusion starts. (b) The H–R diagram of a globular cluster which illustrates how stars tend to concentrate in these regions.

Post-Main Sequence Evolution: $1M_{sun}$ star

• Rapid ascent up the giant branch necessary as the energy generation in the H-burning shell continues to increase

• Important to realise that while the pressure in the degenerate He-core, which continues to increase in mass and shrink, derives almost exclusively from the electrons, the temperature in the core continues to rise and the He-nuclei attain increasingly high energies as *T* increases

• When the core mass has reached $\sim 0.5M_{sun}$ and $T \sim 10^8$K the He-nuclei can burn via the triple-α process. The $\sim T^{40}$ temperature sensitivity of the He-burning results in rapid energy generation

• Most importantly, because the equation of state has no *T*-dependence, there is no thermostatic control operating

Post-Main Sequence Evolution: ~1M_{sun} Star

• The core does not respond to the rapid increase in energy generation, *T* keeps increasing at essentially constant density, the situation is thermally unstable and the entire core undergoes a *runaway* with the energy generation rate reaching ~$10^{11}L_{sun}$ for a few seconds! The **helium flash –** initiation of He-burning under degenerate conditions

• The overlying, energy absorbing, stellar envelope prevents the star from blowing itself apart (c.f. Type Ia supernovae) and there is no direct observational manifestation of the occurrence of the helium flash in the core

• The thermal runaway results in such high *T* that the degeneracy in the core is lifted, $P=nkT$, and the core expands, lowering *T* both in the He-core and in the surrounding H-burning shell

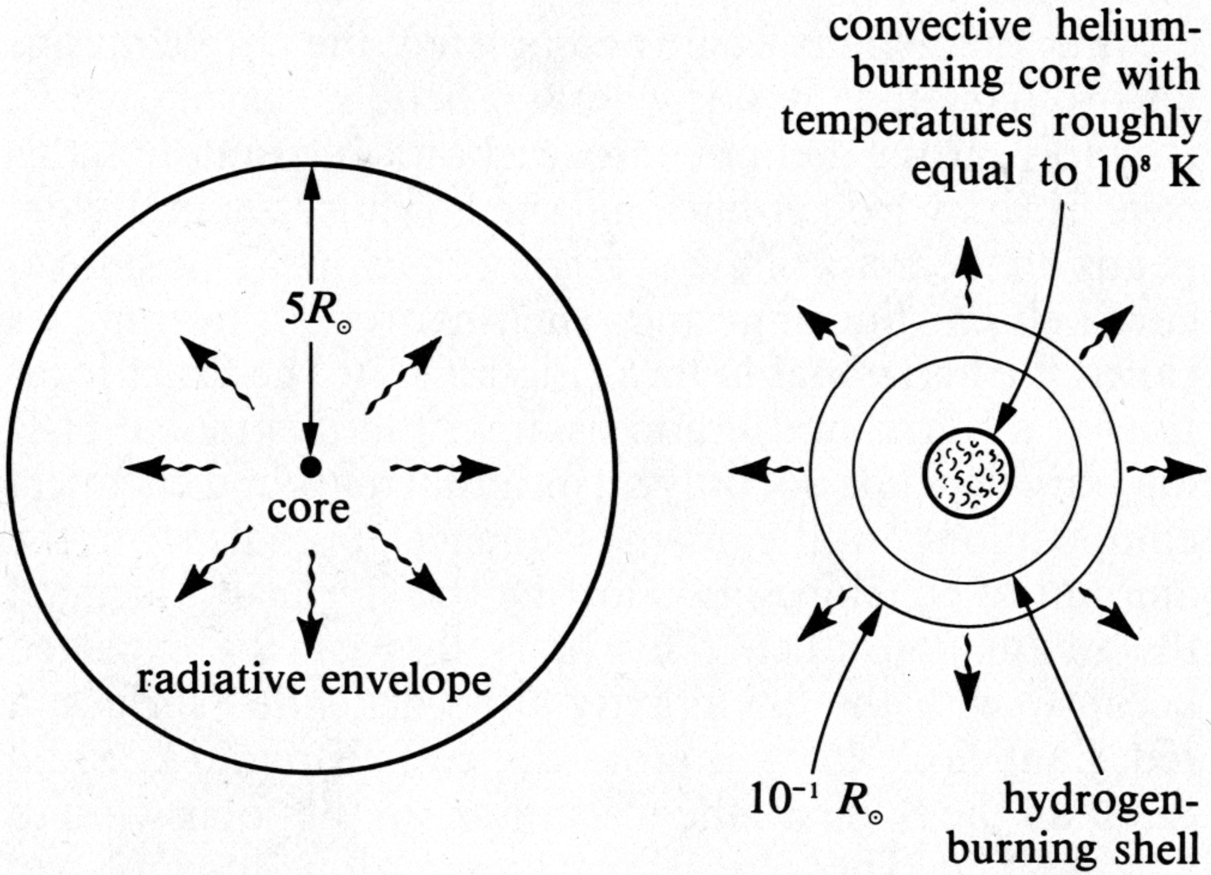


Figure 8.7. The structure of a horizontal-branch star. The left figure shows the entire star from core to photosphere. The right figure shows an enlarged picture of the region near the core.

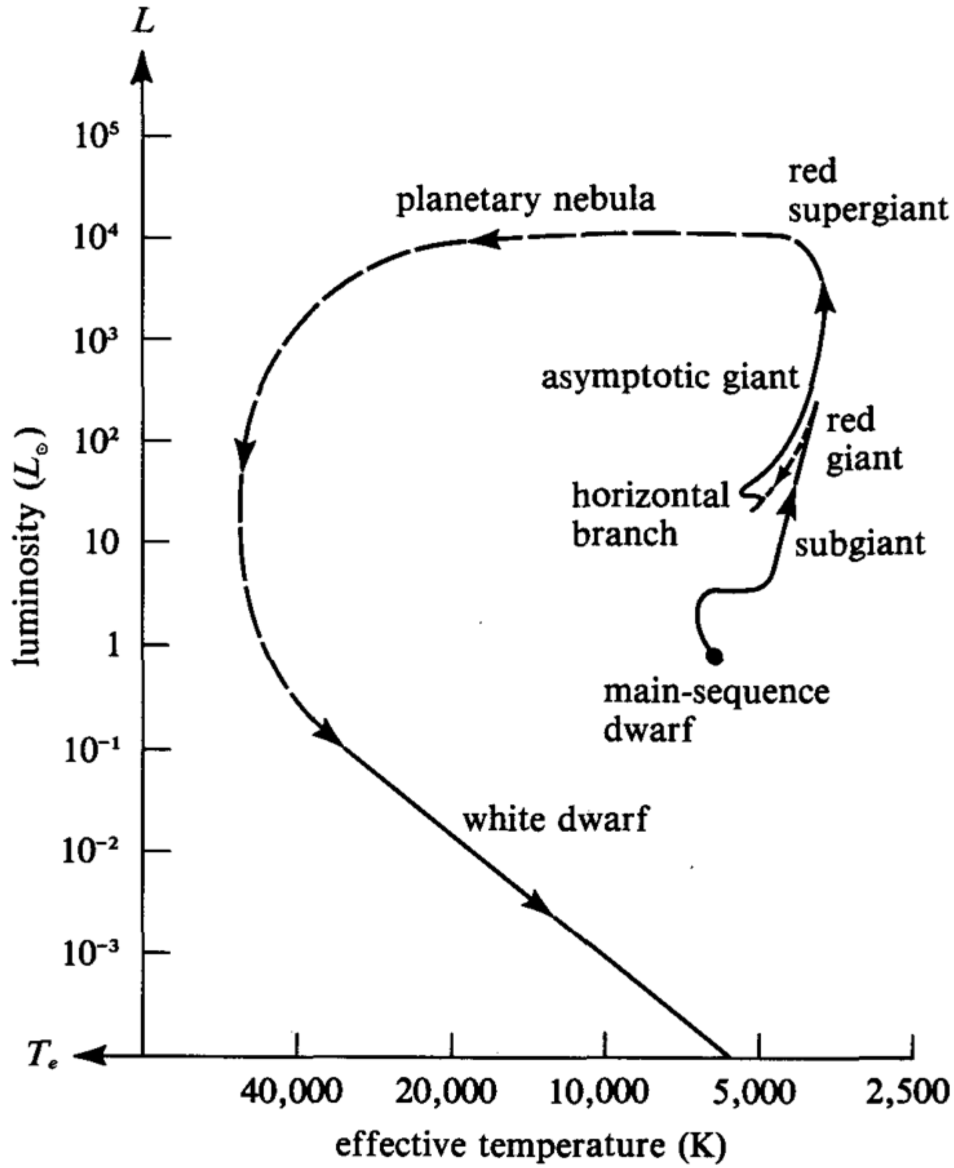


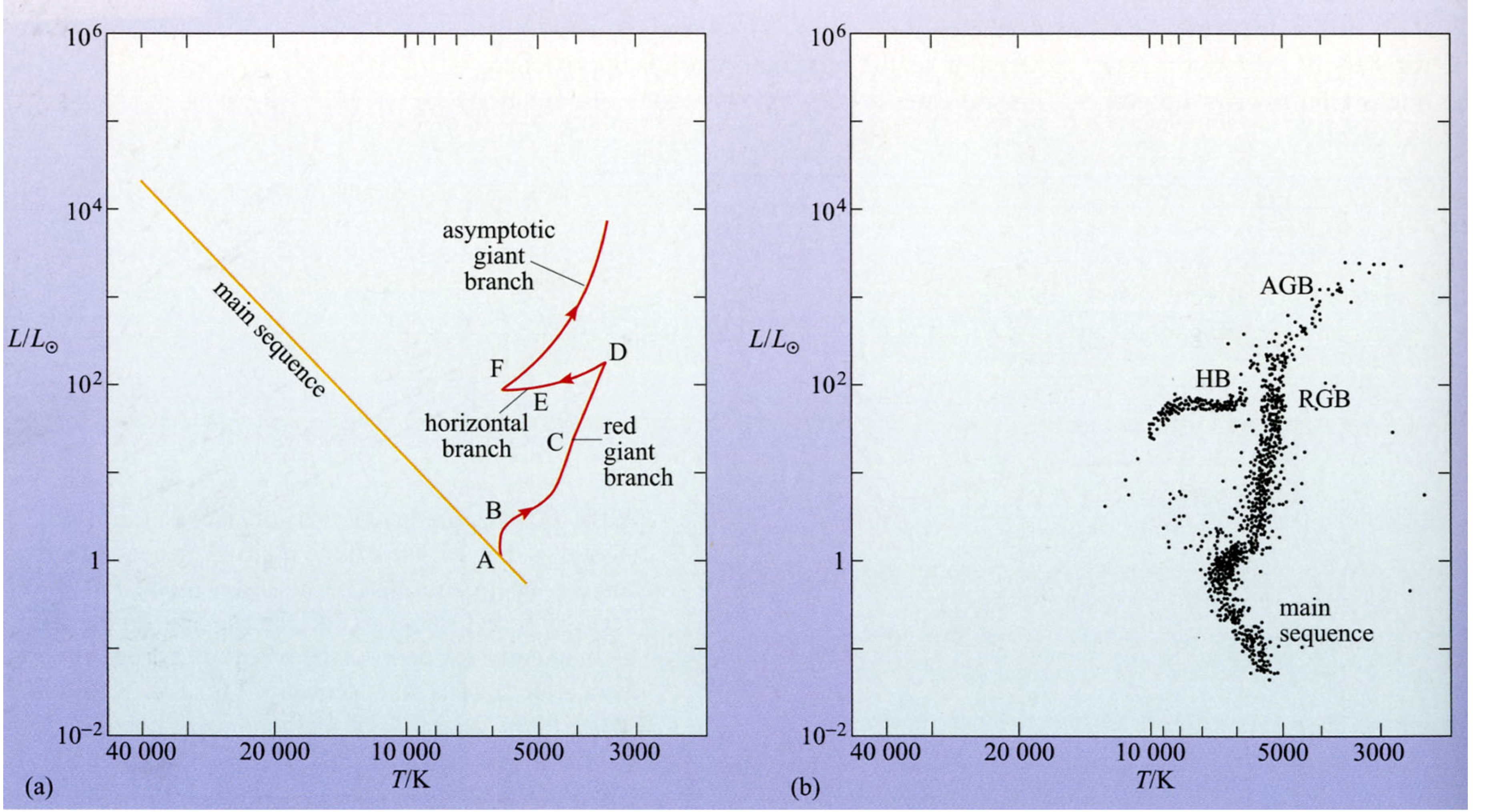
Figure 8.10. The complete evolution of a low-mass star from the main sequence to a white dwarf. The track from the asymptotic giant branch to a white dwarf (via a planetary nebula) is uncertain and is shown as a dashed curve.

Post-Main Sequence Evolution: ~1M_{sun} Star

• Although the star has now acquired a second energy generation source the expansion of the core has lowered *T* to such a degree that the total energy generation rate is much reduced. The luminosity declines, the convective energy transport in the envelope gives way to radiative diffusion and the star moves down and to the left in the HR-diagram onto the **horizontal branch**

• The horizontal branch can be thought of as the core-Helium burning main sequence (c.f. the core-H burning main-sequence), although the H-burning shell source is also important $L \approx 50$-$100 L_{sun}$. Lifetime on horizontal branch ~10^8yr

• The location of stars on the horizontal branch depends significantly on the importance of mass-loss during the rise of the star up the red giant branch and the remaining envelope mass



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Post-Main Sequence Evolution: ~1M_{sun} Star

• At one extreme, maximum degree of mass loss produces star with low-mass envelope and reduced or no H-burning shell – star appears relatively blue and has relatively small radius

• Less mass loss results in more massive envelope with well-developed H-burning shell, leading to higher luminosity and somewhat larger radii for the radiative envelopes

• Least mass loss leads to most extended envelopes with stars appearing increasingly red – lower T_{eff} and larger R

• Result is a horizontal distribution of stars in the HR-diagram, hence horizontal branch, extending from close to the giant branch blueward to a turndown point (lower L) where the H-burning shell becomes less important (*Star(s) of the Week #1*)

Post-Main Sequence Evolution: ~1M_{sun} Star

• As on the H-burning MS the stars on the horizontal branch run out of fuel in the core. In this case the core consists of C and O and again the temperatures are not high enough to initiate C-burning

• Core contracts, ρ and T rise both in the core and in the immediately surrounding region

• T and ρ in the surrounding shell become high enough that He-burning via the triple-α process begins. The H-burning shell still exists, with high rate of energy generation due to increased T and ρ – have the **double shell-burning phase**

• Inert core continues to contract, reaching densities where degeneracy pressure again dominates. Energy generation from the twin shells is enormous

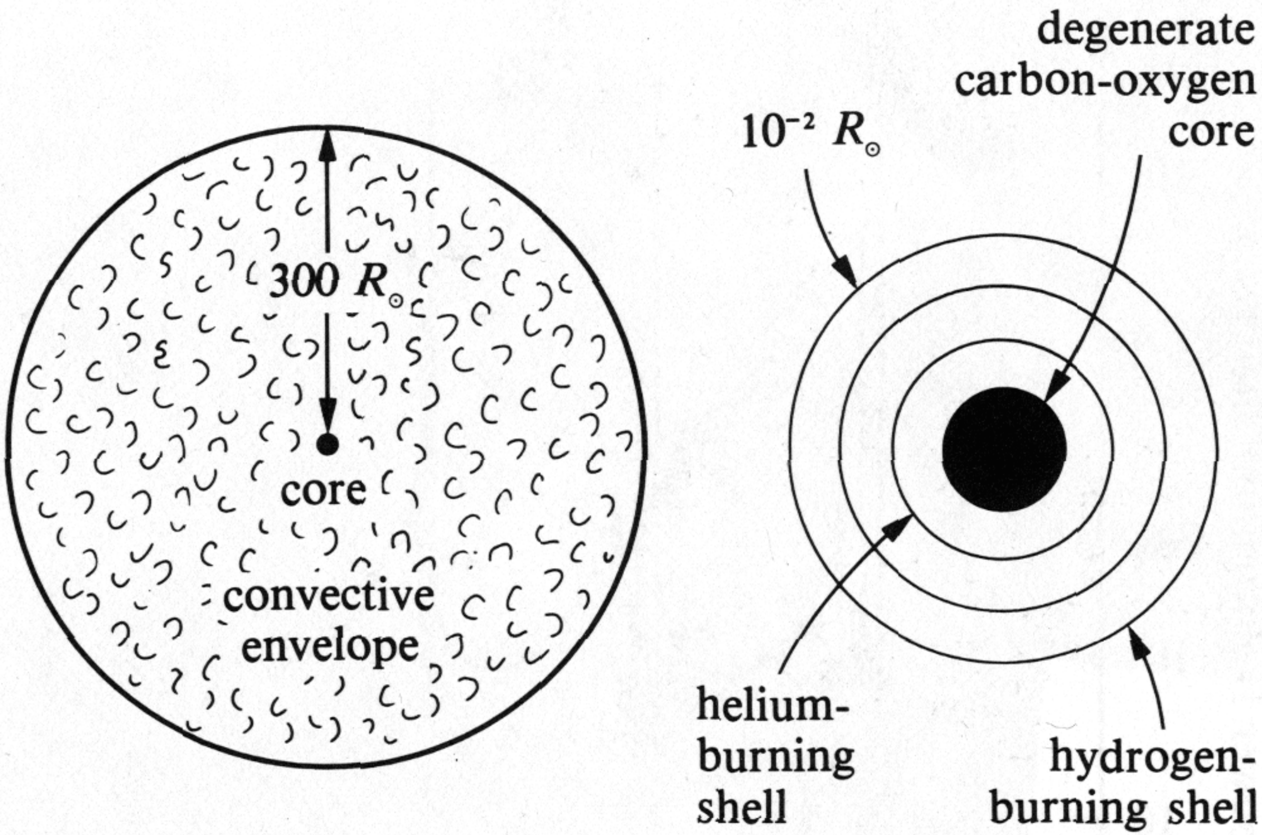


Figure 8.8. The structure of an asymptotic giant. The figure on the left shows the entire star from core to photosphere. The figure on the right shows an enlarged picture of the region near the core.

Post-Main Sequence Evolution: ~1M_{sun} Star

• Contraction of the core, combined with the enormous increase in the energy generation produces same behaviour as for a shell-burning star ascending the giant branch. Stellar envelope expands and energy transport is via convection – ascends the **asymptotic giant branch.** Luminosity is now even higher, so further up in the HR-diagram in the supergiant (Luminosity Class II) regime.

• Now in phase of evolution that is extremely short (L is enormous and little fuel available) and star is finding increasing difficulty in maintaining equilibrium with energy generation very sensitive to T taking place in narrow shells. Instability is evident from evidence of stellar pulsations

• Mass loss, with $L > L_{Edd}$, is critical but the details are poorly understood (*Star of the Week #4*: VY Canis Majoris)

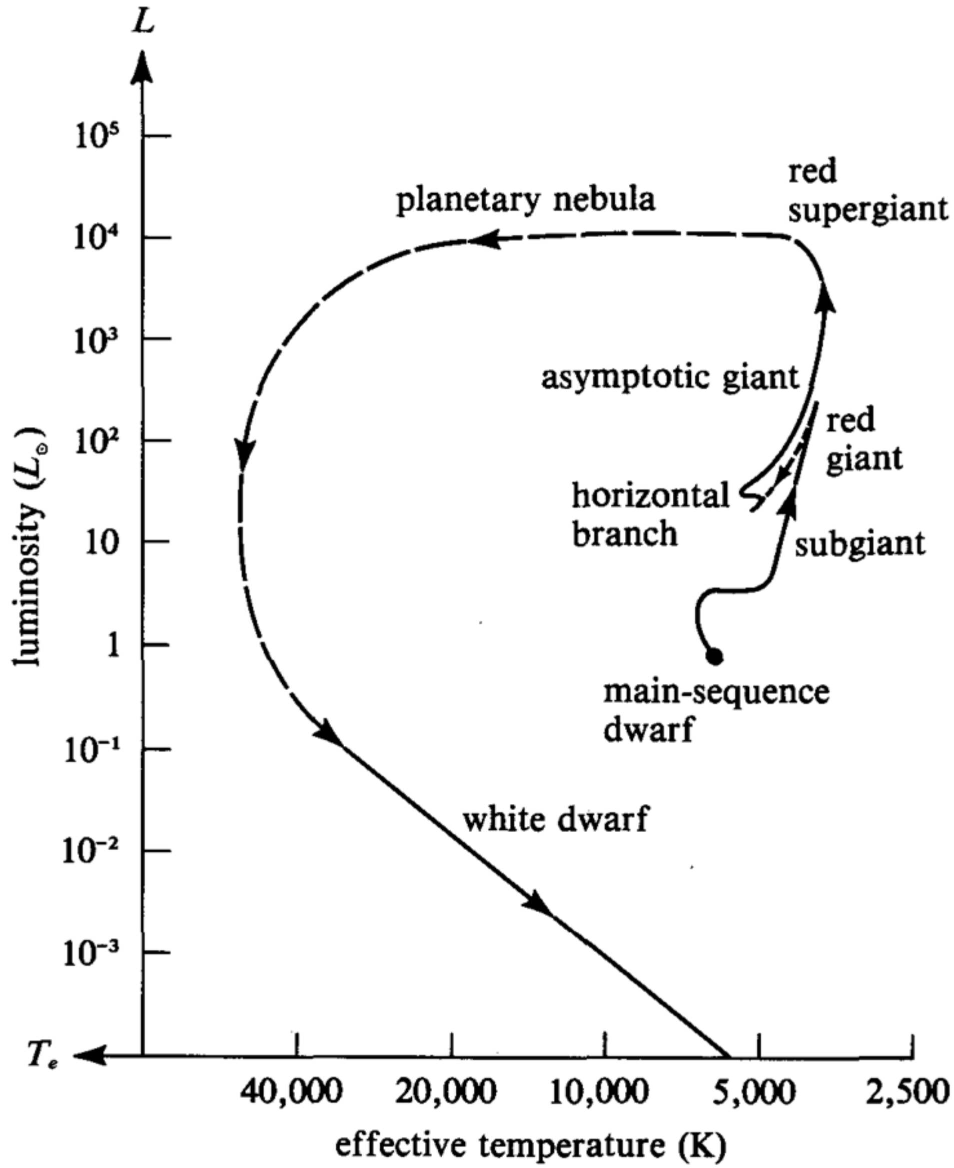


Figure 8.10. The complete evolution of a low-mass star from the main sequence to a white dwarf. The track from the asymptotic giant branch to a white dwarf (via a planetary nebula) is uncertain and is shown as a dashed curve.

Post-Main Sequence Evolution: ~1M_{sun} Star

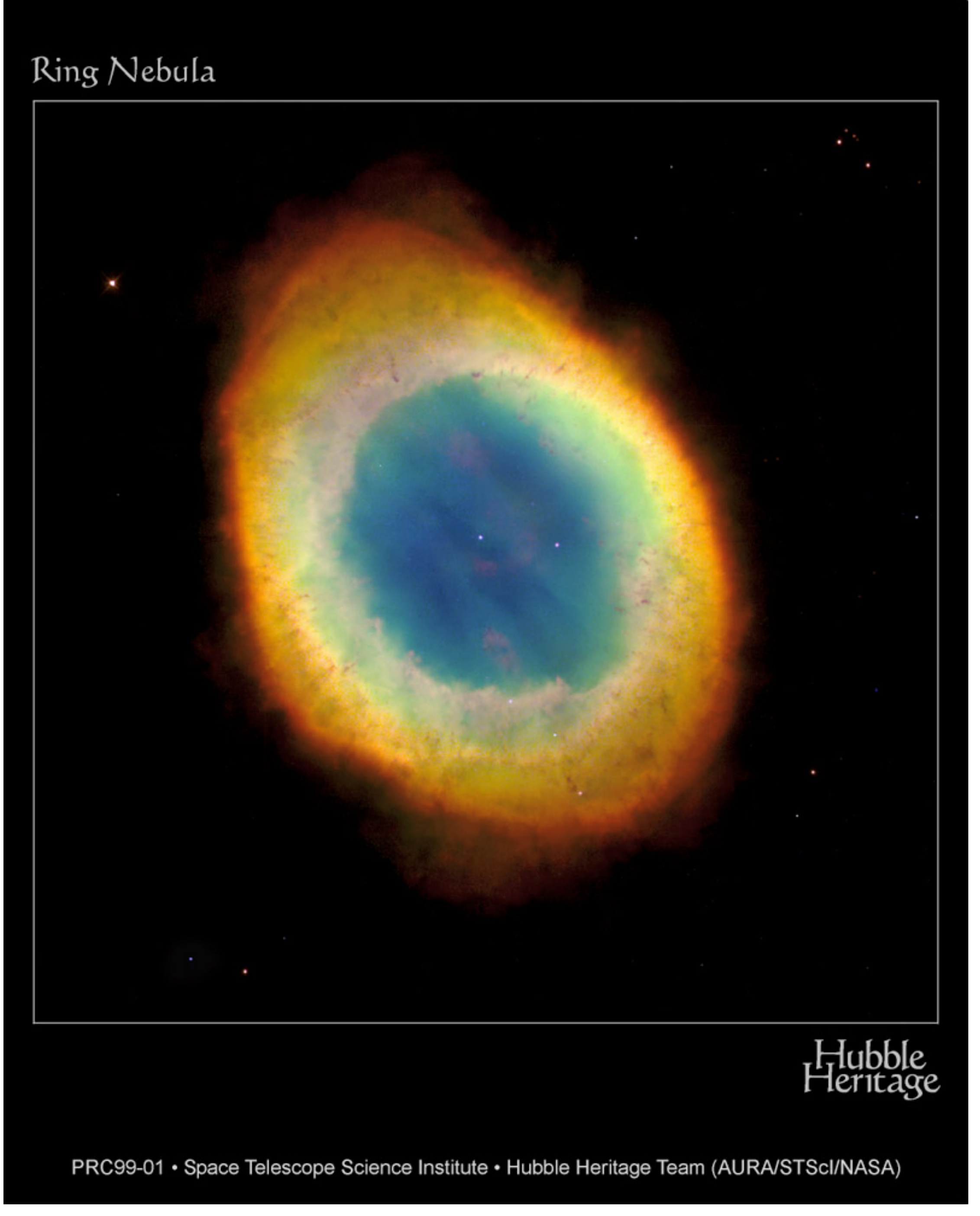
• Significant mass loss takes place on the giant branch (GB) and asymptotic giant branch (AGB). Winds, producing extended periods of loss of material, are undoubtedly important but discrete mass-loss events may be most important (VY Canis Majoris again)

• The final and most dramatic phase of the mass-loss process results in the creation of a **planetary nebula –** again, many planetary nebulae show evidence for short phases of enhanced mass loss

• Temperature and luminosities of central stars of planetary nebulae establish statistical connection between stars at tip of AGB and revealing of bare degenerate C-O stellar core as a white dwarf. Masses typically ~0.6M_{sun} and rarely exceed 1M_{sun} – confirming importance of mass loss.

• Completes the evolution of intermediate mass stars from the ZAMS to fate as a degenerate remnant devoid of any energy source


Cat's Eye Nebula • NGC 6543
Hubble Heritage
NASA, ESA, HEIC and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope ACS • STScI-PRC04-27


Ring Nebula
Hubble Heritage
PRC99-01 • Space Telescope Science Institute • Hubble Heritage Team (AURA/STScI/NASA)

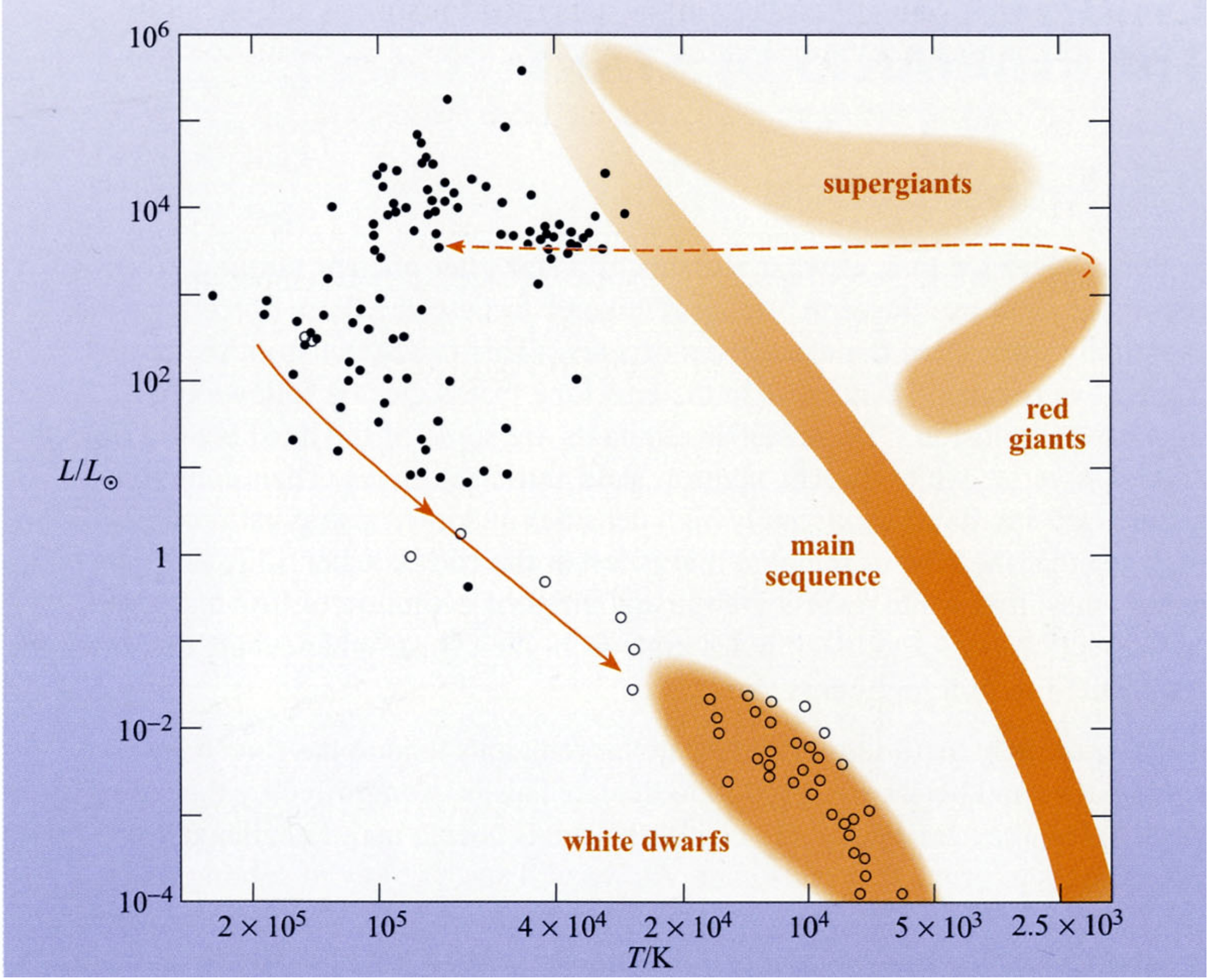


Figure 9.1 The positions of central stars associated with planetary nebulae (dots) and of white dwarfs (open circles) on the H–R diagram. Also shown (solid line) is the evolutionary track that would be followed by a star of constant radius as it cools and (dashed line) a schematic evolutionary track between the regions occupied by AGB stars (Section 8.2.1) and by the central stars of planetary nebulae.

Lecture 17: Summary

- Post-MS evolution commences after exhaustion of core Hydrogen
- For intermediate mass stars, contraction of core results in initiation of shell Hydrogen-burning source. Luminosity increases and star moves to the right in the HR-diagram
- Increasing luminosity and very extended convective envelope leads to ascent of the red giant branch
- For masses 0.7-2M_{sun}, ignition of Helium burning in core under degenerate conditions at tip of giant branch - Helium flash
- Star descends onto the Horizontal Branch – Helium core-burning main sequence – blueward of the giant branch
- Exhaustion of He in core results in similar behaviour following move from the main sequence, except there are 2 shell burning sources – inner He-burning shell and outer H-burning. Star ascends the asymptotic giant branch achieving very high luminosity
- Mass Loss key on both the giant- and asymptotic giant-branch
- Star unstable and finally, planetary nebulae phase, revealing hot bare white dwarf

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