The Early Asymptotic Giant Branch (E-AGB)

• Because of mass loss during their evolution, stars with initial mass $\mathcal{M} < 8\mathcal{M}_\odot$ will end up with degenerate carbon-oxygen cores that are under the Chandrasekhar mass limit. These stars will evolve up the asymptotic giant branch and eventually become planetary nebulae and white dwarfs. More massive stars will undergo heavy element nucleosynthesis and a different evolutionary track.

• When a star begins ascending the asymptotic giant branch, the luminosity of the star will again become a function solely of the mass of the helium core. Stars with high initial masses will have higher mass cores and, consequently, higher helium shell luminosities. Similarly, since the luminosity of the helium shell drives envelope expansion, higher (core) mass stars will evolve to larger radii.

• As was the case for giant branch stars, the envelope expansion of asymptotic giant branch stars causes the opacity in the envelope to increase. This drives envelope convection. In stars with initial masses $\mathcal{M} \gtrsim 3\mathcal{M}_\odot$, the convective envelope reaches all the way down to the dormant hydrogen burning shell. Products of hydrogen burning are then convected to the surface, enhancing the abundance of ^{4}He, ^{14}N and ^{13}C at the expense of ^{12}C and ^{16}O. **This is the second dredge-up phase; it only occurs in intermediate mass stars.** In lower (initial) mass stars, where the shell luminosity is less, the convective envelope stops short of the hydrogen discontinuity, hence this second dredge-up does not occur.

• The change in surface abundance for stars undergoing the second dredge-up depends on the initial mass of the star. The most massive asymptotic giant branch stars (initial mass $\mathcal{M} \sim 8\mathcal{M}_\odot$) will have their surface abundance changed from a main-sequence CNO abundance ratio of $0.5 : 0.2 : 1.0$ to $\sim 0.3 : 0.5 : 0.9$.

• Again, as was the case on the giant branch, the luminosity of an AGB star with (initial) mass $\mathcal{M} \gtrsim 6\mathcal{M}_\odot$ decreases slightly when the envelope reaches the hydrogen discontinuity, due to the abrupt change in mean molecular weight and opacity. In lower mass stars, the luminosity decrease is more than offset by the steading increasing rate of shell burning.

• The contracting carbon core reaches densities and temperatures that facilitate neutrino pair production from $e^- - e^-$ interactions. The escaping neutrinos cool the core to such an extent that the degenerate carbon cannot fuse (unless the Chandrasekhar limit is reached). A corollary of this cooling is that the hottest point is no longer in the center; instead, it is just inside the helium burning shell. The center of the star therefore undergoes a luminosity inversion.

Note that the core is stable to neutrino losses. Recall that if you perturb the energy conservation equation, you get

$$\mathcal{M} d\epsilon - d\mathcal{L} = \mathcal{M}\frac{dq}{dt} = \mathcal{M} c^* \frac{dT}{dt} \qquad (20.3.1)$$

where

$$c^* = c_P \left(1 - \nabla_{\rm ad} \frac{4\delta}{4\alpha - 3}\right) \qquad (20.2.6)$$

In the case of neutrinos, $d\epsilon$ will always be negative, and the perturbation on the energy flux, due to the neutrinos will be small. Thus

$$d\epsilon = c_P \left(1 - \nabla_{\rm ad} \frac{4\delta}{4\alpha - 3}\right) \frac{dT}{dt}$$

Under degenerate conditions, c^* is positive. Thus, a positive temperature excursion that creates more neutrinos will cool the core, thereby decreasing neutrino emission. There will not be a neutrino flash.

• As the star ascends the asymptotic giant branch, the luminosity of the star rapidly increases, in accordance with the core mass-luminosity relation. As this occurs, the helium shell becomes thinner, and moves outward in mass. In low mass stars, the helium shell can even reach to the hydrogen shell discontinuity. Towards the end of the Early Asymptotic Giant Branch phase, hydrogen is reignited in a very thin shell.

• If strong mass loss has occurred in the star, it is possible that the mass in the hydrogen envelope will become too small for fusion. Such stars will then abort their progress up the asymptotic branch. As the helium burning zone approaches the surface, the stars will move to the left in the HR diagram. These are Post-Early-Asymptotic Branch (PEAGB) stars. They are very similar to AGB manqué objects, except that they have evolved slightly further before ending their evolution.

AGB Thermal Pulses

Although shell helium burning takes place under non-degenerate conditions, the extreme temperature dependence of the reaction, coupled with the thinness of the shell, causes thermal runaways to occur periodically. These can effect the observable evolution of the star (though not the core).

• Since helium shell burning occurs non-degenerately, the energy of the thermal pulse goes directly into heating the local area. This raises the pressure and causes rapid expansion of the shell. Eventually, after a few years, cooling sets in, and the helium burning begins to die down. However, during the pulse, the luminosity is raised to such an extent that convection occurs, and matter is circulated out to, and beyond, the hydrogen discontinuity. The expansion lowers the density and temperature so much that hydrogen shell burning is effective shut off.

• As the helium burning dies out, some of the matter that was propelled outward falls back towards the core. This compresses the hydrogen layer and re-ignites the hydrogen burning shell. The luminosity from hydrogen burning grows and, in a short period of time, it is once again the dominant source of energy in the star. This state continues for quite a while, with helium shell burning almost dormant, and the hydrogen shell providing the star's luminosity. After a critical amount of helium has been built up, the process will repeat. Models suggest that, very roughly, the timescale between pulses is

$$\log \tau_p \approx 3.05 + 4.50(1 - \mathcal{M}_c)$$

where the core mass $\mathcal{M}_c$ is in solar masses, and τ_p is in years. For $\mathcal{M}_c \sim 0.5\mathcal{M}_\odot$, $\tau_p \sim 10^5$ years; for $\mathcal{M}_c \sim 1.4\mathcal{M}_\odot$, $\tau_p \sim 10$ years. An AGB star may undergo thousands of thermal pulses before the outer hydrogen shell runs out of mass (*i.e.*, $\mathcal{M}_c \approx \mathcal{M}_T - 0.001\mathcal{M}_\odot$).

• For most stars, the thermal pulse has very little effect on the star's radius, effective temperature, and luminosity. This is simply because the event occurs well inside the star, and is damped out by the large surrounding envelope; most of the energy just goes into internal expansion. However, in low mass AGB stars ($\mathcal{M} \lesssim 0.6\mathcal{M}_\odot$), the pulse can occur near the surface, and the effects of the pulses can be seen. The star will brighten and fade over a timescale of months (or years) as the helium pulse first adds luminosity, then causes the star to fade (as the hydrogen shell burning is extinguished). Concurrently, as the hydrogen shell stops, the envelope contracts, moving the star to the left in the HR diagram. When the hydrogen shell re-ignites, the star moves back to the Hayashi line. (The star FG Sagittae is doing this.)

• During the thermal pulse, the convective envelope temporarily retreats towards the surface. Once the pulse ends, however, convection again returns to the edge of the hydrogen burning shell. Because the thermal pulse convected the products of helium burning out past the hydrogen burning shell, the surface abundances will be affected. **This is the third dredge-up.** Unlike the second dredge-up, it occurs in all AGB stars.

• The nature of the processed material convected to the surface during the third dredge-up depends on many uncertain parameters. The thermal pulse itself synthesizes ^{12}C and ^{16}O. However, some (most?) of this material will be reprocessed in the hydrogen burning shell to ^{14}N, and during the next thermal pulse, ^{14}N can be fused to ^{18}O and then to ^{22}Ne. The most massive AGB stars may further fuse ^{22}Ne to ^{25}Mg in their later pulses. This reaction liberates a neutron, which can then be captured in the *s*-process. Additionally, the reaction $^{13}C(\alpha, n)^{16}O$ is also one that produces a free neutron.

• If the surface abundance of carbon in an AGB star is moderately low, all the carbon will get locked up in the CO molecule. However, if the number of carbon atoms exceeds the number of oxygen atoms (which frequently occurs during dredge-up), the carbon will be quite visible, both through its molecular line blanketing and via the presence of graphite grains. These are *Carbon Stars.*

• For stars with initial masses $\mathcal{M} \gtrsim 3\mathcal{M}_\odot$, the luminosity of the hydrogen burning shell during the interpulse phase may be high enough to support convection. In this case, material from the entire envelope can be cycled through the hydrogen burning shell, thereby enhancing the surface abundance of ^{14}N and ^{4}He even more. This dredge-up is called **hot bottom burning.**

• When studying the giant branch, we used the ideal gas law and the equations of stellar structure (21.2.1) - (21.2.5) to show through homology that the luminosity of a hydrogen burning shell is related to the core mass by

$$\mathcal{L} \propto \mathcal{M}_c^z \tag{21.2.11}$$

where $z \sim 8$. (There was also a weak dependence on the core radius.) For hydrogen shell burning on the asymptotic branch, the luminosity is such that radiation pressure can no longer be neglected in the equation of state, *i.e.,*

$$P = \frac{\rho}{\mu m_a} kT + \frac{a}{3} T^4 = \frac{\rho}{\beta \mu m_a} kT$$

where $\beta = P_{\rm gas}/P$. This changes the homology relations so that in the limit where $\beta \longrightarrow 0$, $\mathcal{L} \propto \mathcal{M}_c$, (*i.e.,* $z \sim 1$). Numerical modeling confirms this and gives,

$$\mathcal{L}_{\max} \approx 5.925 \times 10^4 (\mathcal{M}_c - 0.52)$$

for the maximum interpulse luminosity of the hydrogen burning shell.

• Asymptotic Giant Branch stars continue to brighten, until their hydrogen shell approaches the stellar surface. Thus, the maximum brightness the star will achieve is a sensitive function of the star's initial mass and how much mass was lost throughout the star's history. Since the details of mass loss are poorly understood, the maximum brightness of an AGB star is not well known.

• Near the tip of the AGB, the mass loss rate from the star can be quite large, $\sim 10^{-5} \mathcal{M}_\odot$ yr^{-1} or greater. This "superwind" comes off at a velocity of ~ 10 km s^{-1}, and forms a thick dusty envelope around the star. (This envelope will probably *not* be spherically symmetric!) Since the envelope is bright in the IR and contains OH masers, the star is classified at this time as an OH-IR star.

• Bright AGB stars can also become unstable to radial pulsations, which take place with periods of the order of hundreds of days. Although these pulsations are poorly understood, the driving mechanism is undoubtably the partial ionization (and recombination) of *hydrogen* in the star's outer layers. (Note that these *Mira variables* do *not* lie in the classical instability strip with Cepheids and RR Lyr stars; they are supergiant AGB stars!) Mira pulsations are moderately small (a factor of ~ 2 in radius and ~ 1 mag in bolometric luminosity over a period of ~ 400 days), but the pulsations may be enough to enhance the rate of mass loss from their envelope, possibly to $10^{-3} \mathcal{M}_\odot$ yr^{-1}.

(Mira itself has a low mass loss rate, $\dot{\mathcal{M}} \sim 10^{-6}\mathcal{M}_\odot$ yr^{-1}, but some OH-IR sources appear to have extremely high values of $\dot{\mathcal{M}}$. Note also that, in the optical, Mira (*o* Ceti) varies from $m_V \sim 3$ to $m_V \sim 10$, but most of this change is due to a rapidly varying bolometric correction.)

(Note: Mira pulsations are *not* strictly periodic. Typically, these stars have radii of $R \sim 300R_\odot$, and luminosities of $\mathcal{L} \sim 10^4\ \mathcal{L}_\odot$. Thus, their thermal timescales ($\sim$ 10 years) are comparable to their dynamical timescale ($\sim$ 0.25 year). Thus the star is never in hydrostatic or thermal equilibrium, and the structure of the star is different from pulse to pulse.

• When the hydrogen shell approaches the stellar surface, the photosphere of the star begins to heat up. This moves the star to the left in the HR diagram and the surface can attain a temperature of $\sim 10^5$ K. The far UV photons emitted from the photosphere ionize the hydrogen which has been lost in early phases of mass loss. The star becomes a planetary nebulae.

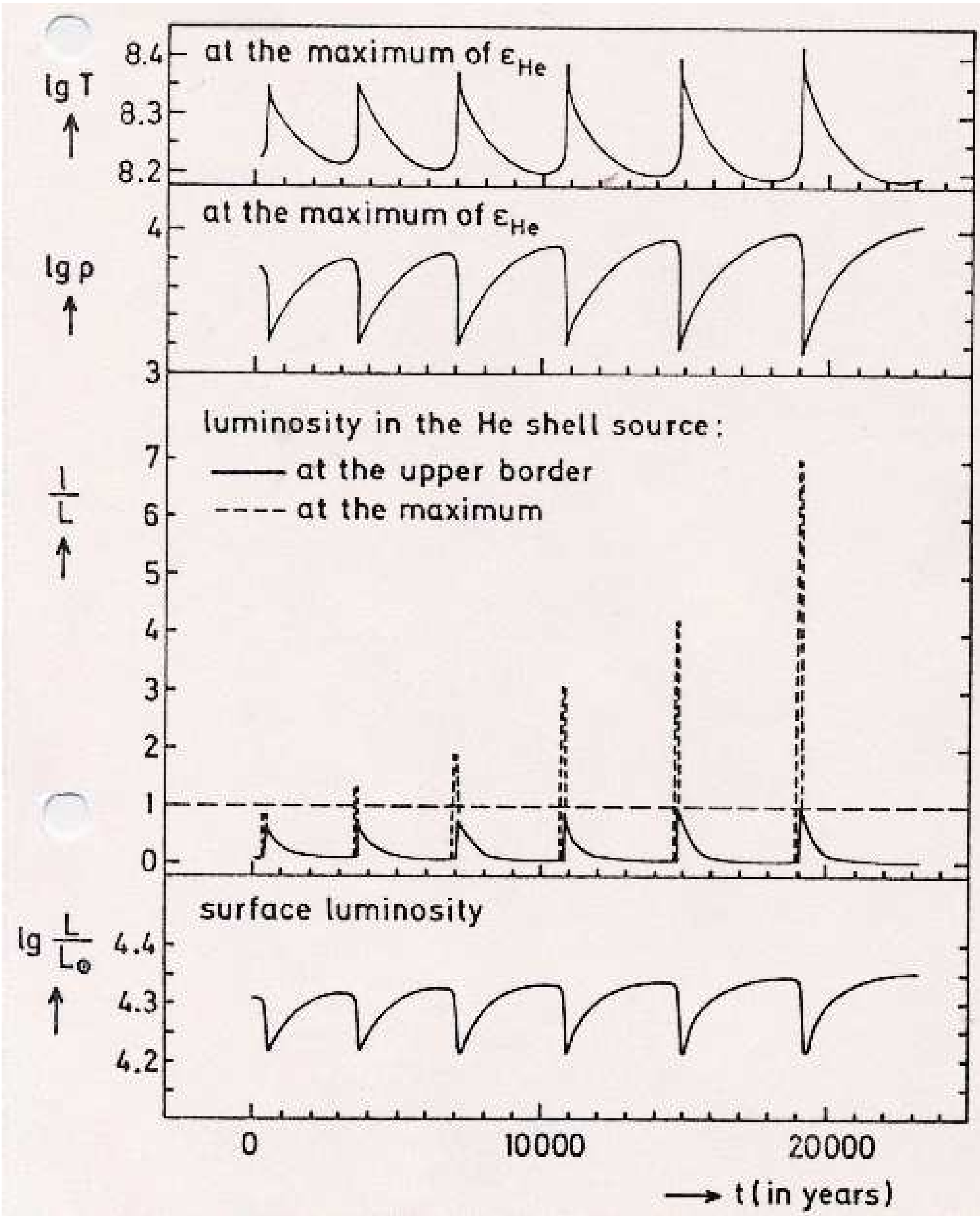
• As we have seen, stars spend most of their lives on the main sequence, and, to first-order, the main-sequence lifetime (and therefore the total lifetime) can be approximated by

$$\tau_{\rm nuc} = \frac{Q\mathcal{M}}{\mathcal{L}} \tag{10.2.3}$$

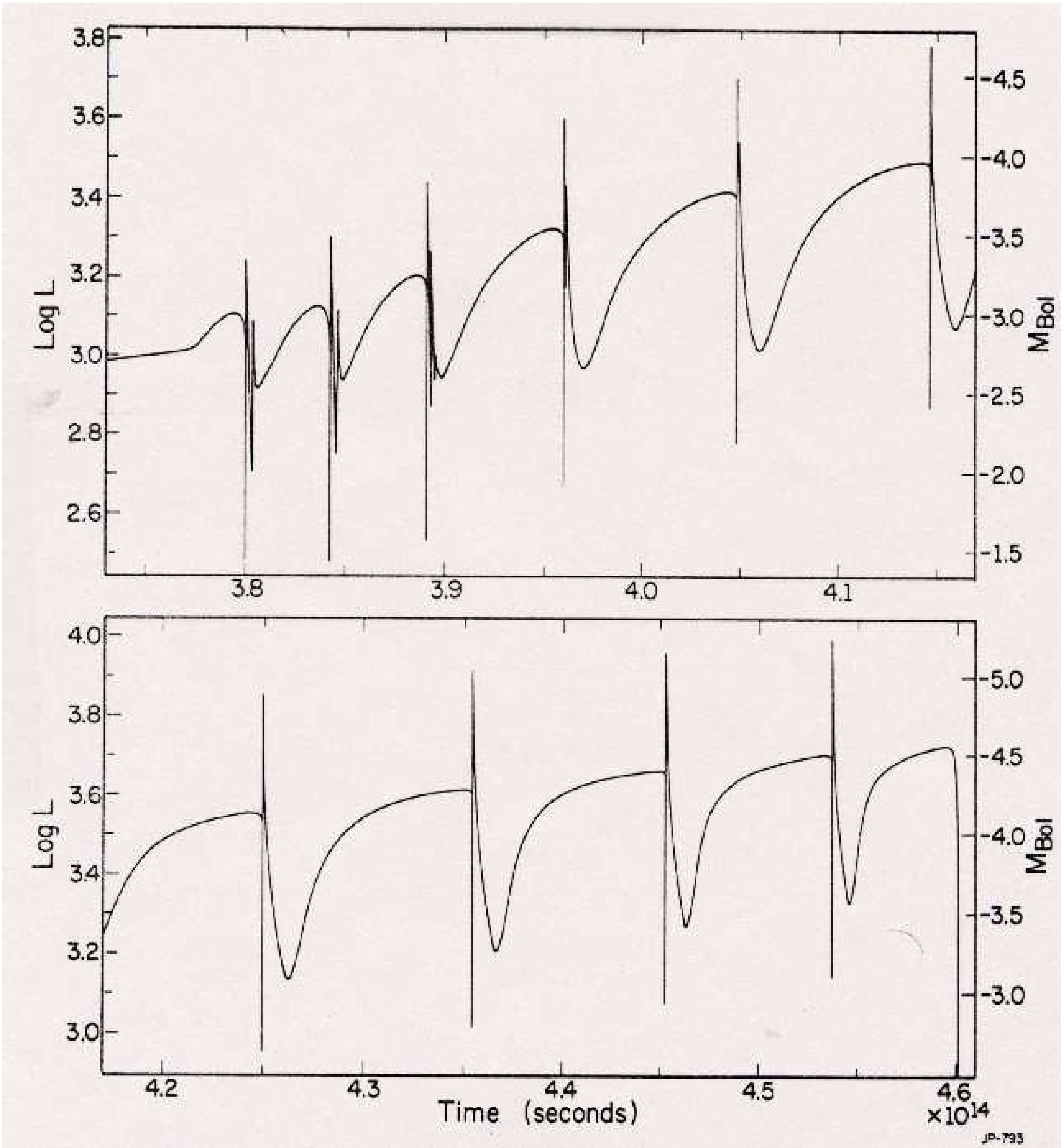
The next level of approximation requires knowledge of the mass loss rates on the RGB and AGB, since these determine when the fuel (*i.e.,* the envelope mass) runs out. According to Iben & Laughlin (1989), the total evolution time from the zero age main sequence to the end of the AGB phase (for stars with masses $0.6 \lesssim \mathcal{M}/\mathcal{M}_\odot \lesssim 10$) can be approximated with a polynomial in log mass:

$$\log t_{\rm evol} = 9.921 - 3.6648\,(\log\mathcal{M}) + 1.9697\,(\log\mathcal{M})^2 - 0.9369\,(\log\mathcal{M})^3 \tag{24.1}$$

where $\mathcal{M}$ is given in solar masses.



Thermal pulses in the helium shell in a $5\mathcal{M}_\odot$ star after helium burning.



Surface luminosity (in solar units) of a $0.6\mathcal{M}_{\odot}$ star underdoing helium pulses.

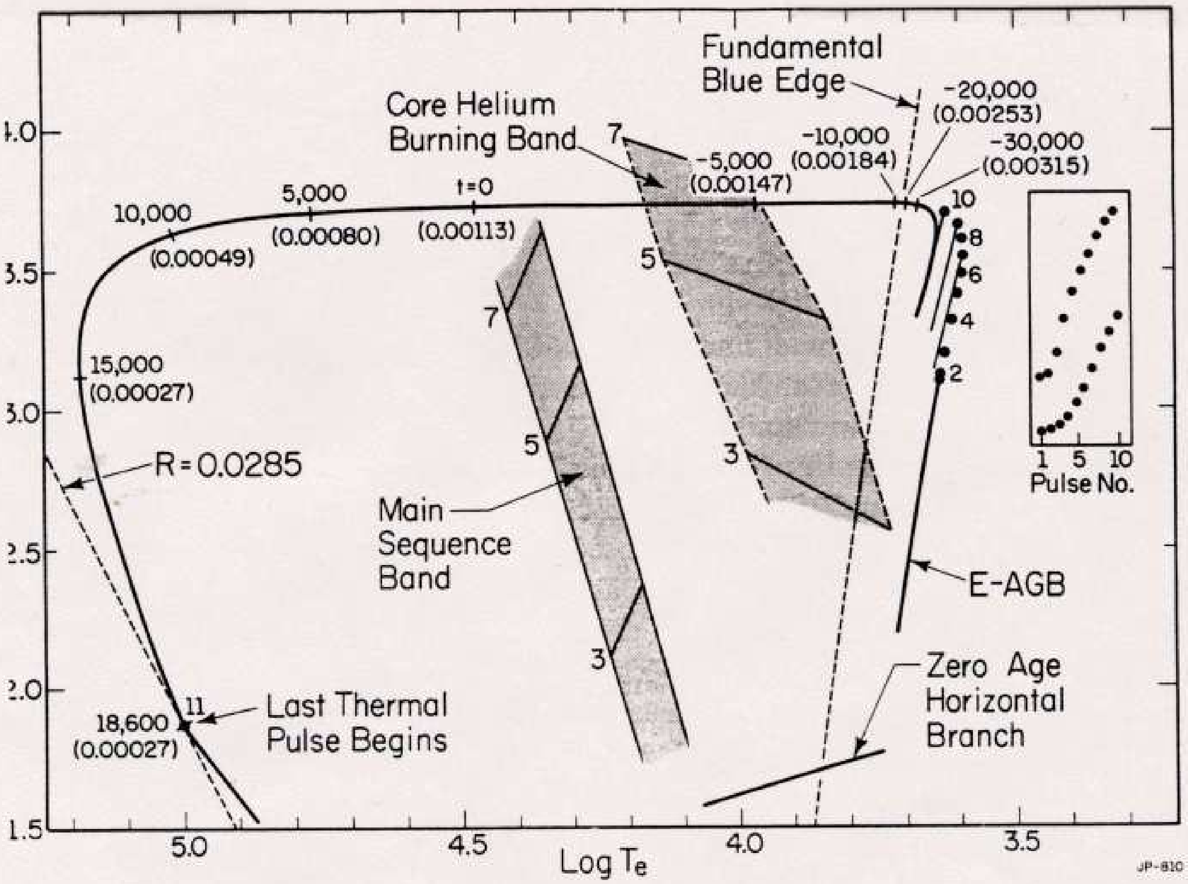


Figure 5 Evolutionary track in the H-R diagram of an AGB model of mass $0.6M_{\odot}$, initial composition $(Y, Z) = (0.25, 0.001)$. After burning helium in its core on the horizontal branch, the model arrives on the E-AGB to burn helium in a shell; the hydrogen-burning shell is extinguished. The E-AGB phase is terminated when hydrogen reignites and thermal pulsing begins. The location of the model at the start of each pulse is indicated by heavy dots. Excursions in the H-R diagram during the extended postflash dip and recovery period are shown for pulses 7, 9, and 10. Dots in the panel in the extreme right-hand portion of the diagram describe the excursion in luminosity during extended dips for all pulses that occur on the AGB. Evolution time ($t = 0$ when $T_e = 30{,}000$ K) and mass in the hydrogen-rich envelope (in parentheses) are shown at various points along the track leaving the AGB after the tenth pulse. Time is in yr, and M_e and R are in solar units. A line of constant radius passes through the location of the beginning of the eleventh pulse when the model has become a hot white dwarf. The dashed line is a blue edge for pulsation in the fundamental mode for a model of mass $0.6M_{\odot}$ and $(Y, Z) = (0.25, 0.001)$. Shown for orientation purposes are rough evolutionary tracks during core hydrogen- and core helium-burning phases for $(Y, Z) = (0.28, 0.001)$ and masses 3, 5, and $7M_{\odot}$.

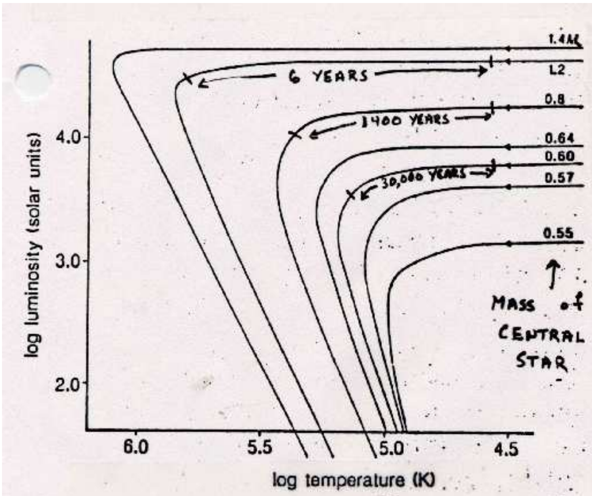
The Planetary Nebula Stage

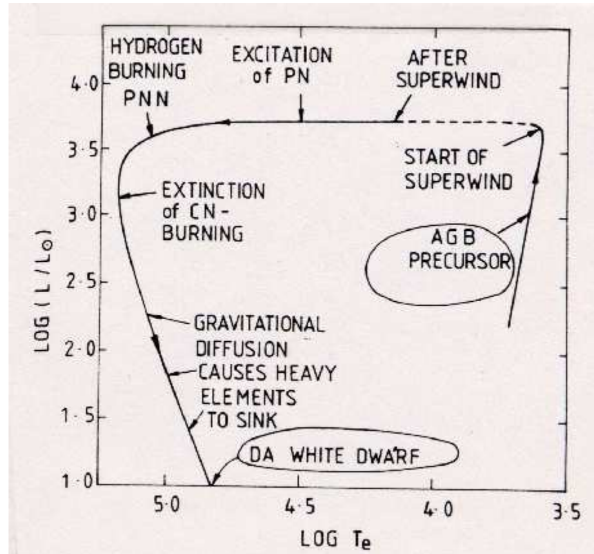
• As the hydrogen burning shell of an AGB approaches the stellar surface, the effective temperature of the star will increase, and the star will move to the left in the HR diagram. The speed at which this occurs depends on the rate of shell burning, which, in turn, depends on the core mass. Low mass cores will evolve slowly and be relatively faint; conversely, high mass cores will be bright, and their evolution will be extremely rapid. Roughly speaking, $\mathcal{L} \propto \mathcal{M}_c^{3.5}$, and $\tau \propto \mathcal{M}_c^{-9.5}$. Note that, in theory, the evolution of a low mass core may be so slow that the surrounding mass may disperse before the core gets hot enough to ionize the material. (This is sometimes called a lazy PN central star.) Similarly, the evolution of a high-mass core may occur so fast, that the star fades before the critical density is reached for forbidden emission lines.

• As the hot core of the planetary nebula is exposed, a very fast ($\sim$ 2000 km s^{-1}) stellar wind appears with a mass loss rate of $\dot{\mathcal{M}} \sim 10^{-7}$ to $10^{-9}\mathcal{M}_\odot$ yr^{-1}. This fast wind runs into the previously ejected shell, and is responsible for some of the ionization structures seen in nebulae. During this time, the spectra of the star is extremely similar to that of a Wolf-Rayet star.

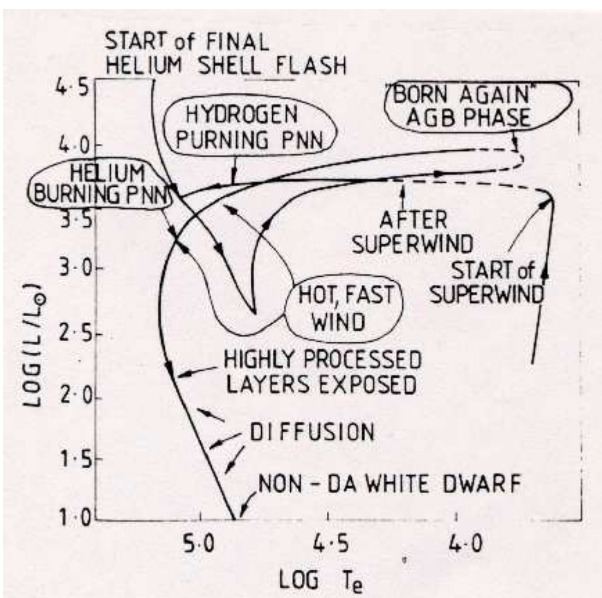
• While shell hydrogen burning is proceeding, some shell helium burning may also exist. The ratio of these two energy sources depends on the progenitor, but typically, hydrogen burning will dominate.

• The lifetime of a planetary nebula is $\sim 25,000$ yr. During the hydrogen burning stage, the star evolves to the left in the HR diagram at constant luminosity. When the envelope becomes too small to support hydrogen burning, this source of energy vanishes, and the star begins to produce energy via gravitational contraction. This is the beginning of the white dwarf phase.

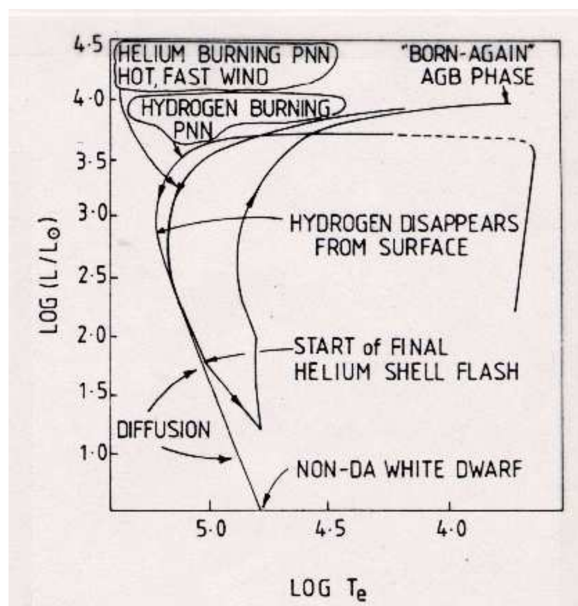




Evolutionary path of $0.6M_\odot$ PN central star with He-shell pulse phase $0.15 < \phi < 0.75$



Evolutionary path of $0.6M_\odot$ PN central star which undergoes a final He-shell flash while it is still burning hydrogen ($0.85 < \phi < 1.0$).



Evolutionary path of $0.6M_\odot$ PN central star which undergoes a final He-shell flash after CNO cycle burning has ceased ($0.75 < \phi < 0.85$).

Born Again Stars

During post-AGB star's excursion away from the Hayashi line, the hydrogen burning shell is still depositing material onto the helium core below it. Thus, it is possible that the star will experience one, final thermal pulse after it has left the AGB. (By some calculations, $\sim$ 10% of all stars should do this.) When this occurs, the helium shell mixes directly with the hydrogen rich envelope. (Because the envelope mass is small and already hot, the energy of the pulse is not absorbed by the cool matter surrounding the shell.) Consequently,

• A thermal runaway will ensue, due to fresh hydrogen being cycled into the helium shell.

• All the remaining hydrogen will be destroyed through the reaction sequence

$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{1}\mathrm{H} &\longrightarrow {}^{13}\mathrm{N} + \gamma \\
{}^{13}\mathrm{N} &\longrightarrow {}^{13}\mathrm{C} + \mathrm{e}^{+} + \nu_e \\
{}^{13}\mathrm{C} + {}^{4}\mathrm{He} &\longrightarrow {}^{16}\mathrm{O} + n
\end{aligned}
$$

Since the sequence also liberates a neutron, s- and possibly r-process elements will also be formed. After the pulse, the surface of the star will contain no hydrogen.

• The energy liberated in the pulse will cause the intershell region expand. As the expansion proceeds, the temperature of the envelope will cool; this will increase the local opacity. The higher opacity will then cause the envelope to better absorb the input energy, further fueling the expansion. As a result, the photosphere will expand, and the star will (briefly) return on the Hayashi track.

- After the pulse, the helium shell will return to its pre-pulse luminosity, and the star will repeat its journey across the HR diagram.

This *Born Again* scenario is thought to be responsible for the origin of a number of hydrogen deficient stars, including R Cr B stars, some helium stars, and hydrogen-deficient planetary nebulae nuclei and white dwarfs.