Homologous Stellar Models and Polytropes

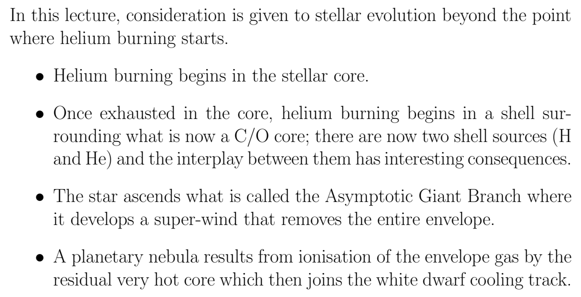
Main Sequence Stars

Post-Main Sequence Hydrogen-Shell Burning

Post-Main Sequence Helium-Core Burning
- Core Helium Burning
- Asymptotic Giant Branch
- Post-Asymptotic Giant Branch

White Dwarfs, Massive and Neutron Stars

Introduction



In this lecture, consideration is given to stellar evolution beyond the point where helium burning starts.

- Helium burning begins in the stellar core.
- Once exhausted in the core, helium burning begins in a shell surrounding what is now a C/O core; there are now two shell sources (H and He) and the interplay between them has interesting consequences.
- The star ascends what is called the Asymptotic Giant Branch where it develops a super-wind that removes the entire envelope.
- A planetary nebula results from ionisation of the envelope gas by the residual very hot core which then joins the white dwarf cooling track.

Core Helium-Ingition

The onset of the He-burning phase of stellar evolution occurs as He-core temperatures approach $10^8\,\mathrm{K}$ when the 3α reaction starts to produce energy at a significant rate:

- Unlike H-burning, He-burning reactions are the same for stars of all masses in which $T \sim 10^8\,\mathrm{K}$ is achieved.
- However, core conditions at He-ignition are degenerate in low-mass ($M \lesssim 2\,M_\odot$) stars and non-degenerate in intermediate and higher mass ($M \gtrsim 2\,M_\odot$) stars.
- The two cases are therefore discussed separately.

Core Helium-Burning – Intermediate Mass Stars – I

Consider a $5\,M_\odot$ star whose evolution was depicted in diagrams presented earlier:

- The ignition of He takes place at point E.
- Since the core is non-degenerate ($\rho_\mathrm{c} \simeq 10^4\,\mathrm{g/cm^3}$), nuclear burning is thermally stable and helium ignition proceeds quietly (non explosive).
- Owing to the high-sensitivity to T of the 3α reaction, energy production is highly concentrated towards the centre which gives rise to a convective core.
- The mass of the convective core is $0.2\,M_\odot$ initially and grows with time.
- Initially, the dominant reaction is the 3α which converts $^4\mathrm{He} \rightarrow {}^{12}\mathrm{C}$ inside the convective core.
- As the $^{12}\mathrm{C}$ abundance increases, the $^{12}\mathrm{C} + {}^4\,\mathrm{He} \rightarrow {}^{16}\,\mathrm{O} + \gamma$ reaction gradually takes over, so that $^{16}\mathrm{O}$ is produced at a rate which increases with time

Core Helium-Burning – Intermediate Mass Stars – II

- When the central He mass-fraction $X_{\mathrm{HE}} < 0.2$, the mass-fraction of ^{12}C starts decreasing as a result of the diminishing 3α rate (which is $\propto X_{\mathrm{HE}}^3$).
- The final $^{12}\mathrm{C}/^{16}\mathrm{O}$ ratio is ~ 0.3, decreasing somewhat with M.
- This is related to the fact that in more massive stars T_{c} during He-burning is higher.
- Note also that the final $^{12}\mathrm{C}/^{16}\mathrm{O}$ ratio depends on the uncertain rate of the $^{12}\mathrm{C}(^4\mathrm{He}, \gamma)^{16}\mathrm{O}$ reaction.
- The duration (E-H) of central He-burning in the $5\,M_{\odot}$ star is about 22 M yr or about $0.27 \times \tau_{\mathrm{MS}}$.
- This 22 M yr is surprisingly long given that the energy produced per gram of He-burning is only 10% of that for H-burning, while L is on average larger than L on the Main Sequence.
- The reason is that the larger contribution to L comes from the H-burning shell surrounding the He-core, although the He-burning contribution (L_{HE}) increases with time and becomes comparable towards the end of the core He-burning phase.

Core Helium-Burning – Intermediate Mass Stars – III

- Properties of the He-core depend only on M_c and are largely unaffected by the surrounding envelope.

- Because the envelope is very extended the pressure it exerts on the core is negligible when compared with pressure inside the dense He-core.

- In fact L_{HE} is a steep function of M_c analagous to the Main Sequence $M - L$ relation.

- As a result of H-shell burning, M_c grows with time during the He-burning phase and L_{HE} increases accordingly.

- Another consequence is that L_{HE} is higher in models computed with convective overshooting on account of M_c being larger at the end of the Main Sequence.

- The duration of the He-core burning phase is therefore shorter in models with overshooting.

Core Helium-Burning – Intermediate Mass Stars – IV

During core He-burning, intermediate-mass stars describe a loop in the HRD (points E-H):

- After He-ignition at the RGB tip, the envelope contracts (on the nuclear timescale for He-burning) and the stellar radius decreases.
- Initially the luminosity also decreases while the envelope is mostly convective (E-F) and the star is forced to move along its Hayashi line.
- When most of the envelope has become radiative at point F, the star leaves the RGB and $T_{\rm eff}$ increases.
- This is the start of a so-called **blue loop**, the hottest point of which is reached at G when $X_{\rm He} \simeq 0.3$.
- The point G also corresponds to a minimum in the stellar radius, after which the envelope starts expanding and the star approaches the RGB once more with $X_{\rm He} \simeq 0.05$.
- By the end of core He-burning (H), the star is back on the Hayashi line, very close to its starting point (E).

Core Helium-Burning – Intermediate Mass Stars – V

- Considering stars of different masses, the blue extension of the loops in the HRD increases (the loops extending to higher $T_{\rm eff}$ values) for increasing mass, up to $M \simeq 12\,M_\odot$.

- The behaviour of more massive stars can be more complicated; one reason being a high mass-loss rate.

- For $M \lesssim 4\,M_\odot$ stars, the loops always stay close to the RGB and stars do not become "blue".

- Detailed models indicate that the occurence and extension of blue loops depends quite sensitively on a number of factors: the chemical composition (mainly Z), the mass of the He-core relative to the envelope and the shape of the H-abundance profile above the core.

- It therefore also depends on whether convective overshooting was assumed to have taken place during the Main Sequence; this produces a larger $M_{\rm c}$, which in turn has the effect of decreasing the blue-ward extension of the loops while increasing their L.

Core Helium-Burning – Intermediate Mass Stars – VI

Blue loops are important because they correspond to a slow, nuclear timescale phase of evolution.

- The corresponding region of the HRD is therefore expected to be well-populated.
- More precisely, since intermediate-mass stars spend part of their core He-burning phase as red giants and part of it in a blue loop, these stars are expected to fill a wedge-shaped region in the HRD.
- Many stars are found to be in the corresponding region.
- The blue-loop dependence on overshooting also makes observational tests of overshooting using He-burning stars possible.
- Another significant aspect of the blue loops is that they are necessary for explaining Cepheid variables, which are important extragalactic distance indicators.

Core Helium-Burning – Low Mass Stars – I

The core He-burning phase in low-mass ($M \lesssim 2\,M_\odot$) stars is different from that in higher mass stars in two important respects:

- He-ignition occurs under degenerate conditions giving rise to a helium flash.
- All low-mass stars start He-burning with essentially the same $M_\mathrm{c} \simeq 0.45\,M_\odot$

The L of low-mass core helium-burning stars is therefore almost independent of M, giving rise to the **Horizontal Branch** in the HRD.

First consider the Helium Flash:

- Again take a $1\,M_\odot$ star as a typical example.
- He-ignition occurs when $T_\mathrm{c} \simeq 10^8\,\mathrm{K}$ and $\rho_\mathrm{c} \simeq 10^6\,\mathrm{g/cm^3}$, so the He-core is strongly degenerate.
- He-burning under degenerate conditions is thermally unstable; energy generated by the 3α-reaction causes T to increase and He-ignition initiates a thermonuclear runaway.

Core Helium-Burning – Low Mass Stars – II

- The reason is that degenerate P is essentially independent of T, so that energy released by fusion does not increase P and therefore leads to negligible expansion and work done.
- All nuclear energy released therefore raises internal energy.
- Since internal energy of the degenerate electrons is a function of ρ and hence remains almost unchanged, it is the internal energy of non-degenerate ions that increases and thus raises T.
- As a result, evolution is vertically upward in the $\rho_{\rm c} - T_{\rm c}$ diagram.
- Thermonuclear runaway leads to an enormous overproduction of energy. At maximum, the local luminosity ($\boldsymbol{\ell}$) in the He-core is $\boldsymbol{\ell} \sim 10^{10}\,L_\odot$ but lasts only for a few seconds.
- All nuclear energy released is absorbed by expansion of the non-degenerate layers surrounding the core, so none of this luminosity reaches the surface.
- Since the temperature increases at almost constant ρ, degeneracy is eventually lifted when $T \sim 3 \times 10^8\,K$.

Core Helium-Burning – Low Mass Stars – III

- Further energy release increases P when the gas starts behaving like an ideal gas and thus causes expansion and cooling.
- This results in a decrease of the energy generation rate until it balances the energy-loss rate and the core settles into thermal equilibrium at $T_\mathrm{c} \simeq 10^8\,\mathrm{K}$ and $\rho_\mathrm{c} \simeq 2 \times 10^4\,\mathrm{g/cm^3}$.
- Further nuclear burning is thermally stable.
- Detailed numerical calculations of the Helium Flash indicate that the above sequence of events does indeed take place, but He-ignition starts in a spherical shell at $M(r) \simeq 0.1\,M_\odot$ where T has a maximum.
- The off-centre T-maximum (T_max) is due to neutrino loses during the preceding red giant phase.
- At high ρ and T, neutrinos are released by a number of weak interaction processes.
- Since neutrinos thus created escape without interacting with the stellar gas, this leads to effective cooling of the central region of the degenerate He-core.

Core Helium-Burning – Low Mass Stars – IV

- The $M(r)$ at which $T_{\max}$ occurs, and where He-ignition starts, decreases with stellar mass.
- A high $\boldsymbol{\ell}$ causes almost the entire region between the He-ignition point ($M(r) \simeq 0.1\,M_\odot$) up to the bottom of the H-burning shell (at$M(r) \simeq 0.45\,M_\odot$) to become convective.
- Energy released in the Helium Flash is thus transported efficiently to the edge of the core, where it is absorbed by expansion of non-degenerate layers.
- Convection also mixes the Helium Flash product (^{12}C) produced in the 3α reaction throughout the core.
- About 3% of He in the core is converted to C during the flash.
- Because the convective core containing this C never overlaps with the convective envelope surrounding the H-burning shell, this C does not reach the surface.

Core Helium-Burning – Low Mass Stars – V

Evolution on the Horizontal Branch is the next step.

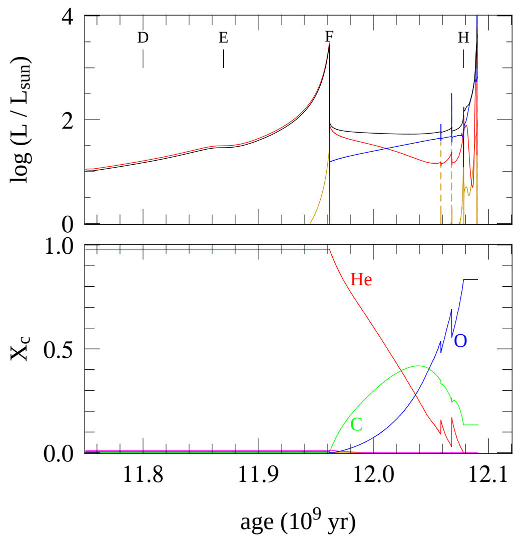
- Evolution through the Helium Flash was not calculated for the $1\,M_\odot$ evolution track shown previously.
- Instead, evolution of the star is resumed at G when the He-core has become non-degenerate and has settled into thermal equilibrium with stable He-burning in the centre and H-shell burning around the core.
- At this stage, L and R have decreased by more than an order of magnitude from values they had just before the Helium Flash.
- Here the "mirror principle" is again seen to operate. The He-core has expanded from a degenerate to a non-degenerate state, and the envelope has simultaneously contracted, with the H-burning shell acting as the "mirror".
- In a $1\,M_\odot$ star of solar composition, core He-burning occurs between G and H.
- The position in the HRD does not change much; the star stays close to but a little to the left of the RGB with $L \simeq 50\,L_\odot$, as determined by M_c but is almost independent of M.

Core Helium-Burning – Low Mass Stars – VI

For core He-burning stars of given composition, for example in a star cluster, only envelope mass may vary from star to star.

- At solar metallicity, all such stars occupy about the same position in the HRD; this gives rise to the so-called red clump in observed colour-magnitude diagrams of low-mass stellar populations.
- $T_{\rm eff}$ and R of core He-burning stars do depend on envelope mass.
- Stars with a small envelope mass, either because of a smaller initial mass or because they suffered a larger amount of mass-loss on the RGB, can be substantially hotter than the one shown in the previous $1\,M_\odot$ evolution track.
- Furthermore, at low metallicity the critical envelope mass below which core He-burning stars become small and hot, is larger.
- Stars with different amounts of mass remaining in their envelopes form a **Horizontal Branch** in the HRD.
- Horizontal branches are found in old stellar populations, especially in globular clusters of low metallicity
- The distribution of stars along the Horizontal Branch varies from cluster to cluster and the origin of this is not fully understood.

Core Helium-Burning – Low Mass Stars – VII



Core Helium-Burning – Low Mass Stars – VIII

The duration of the core He-burning phase is about 120 Myr, again independent of stellar mass ($M \lesssim 2\,M_\odot$). While longer than for higher-mass stars, as a fraction of $\tau_{\rm MS}$ it is much shorter on account of the higher contribution to L of the core He-burning phase.

The evolution of stellar structure, shown in the previous slide, is similar to that of intermediate-mass ($M \gtrsim 2\,M_\odot$) stars; the main differences being:

- The contribution of core He-burning to L is larger, especially towards the end of this phase.
- A substantial semi-convective region develops outside the convective core; this is related to a difference in opacity between the C-rich convective core and the He-rich zone surrounding it, and gives rise to partial (non-homogeneous) mixing in this region.

Asymptotic Giant Branch – I

Core He-burning forms a C/O core which remains when He is exhausted in it. What happens next depends on M as always:

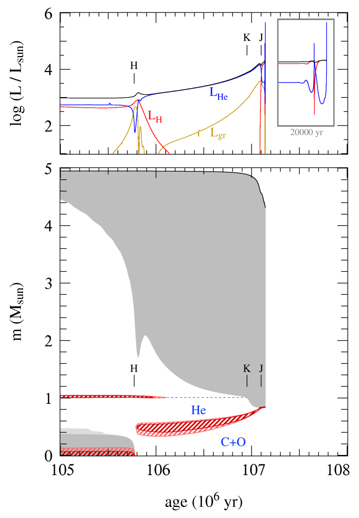
- In massive stars ($M \gtrsim 8\,M_\odot$) the core avoids degeneracy and undergoes further burning cycles.
- In low- and intermediate-mass stars ($M \lesssim 8\,M_\odot$), the C/O core becomes degenerate and stars evolve up the **Asymptotic Giant Branch (AGB)**
- The AGB is a brief but interesting and important phase of evolution because:
  - they are rich nucleosynthesis sites and
  - are the main channel by which material processed in stars is returned to the interstellar medium.
- AGB stars have high mass-loss rates, especially at the end of this evolutionary phase.
- Mass-loss eventually strips an AGB star envelope, leaving a hot remnant with a degenerate C/O core.
- After a brief transition stage as the central star of a planetary nebula, the remnant becomes a long-lived cooling white dwarf.

Asymptotic Giant Branch – II

The AGB phase starts at the exhaustion of He in the core; in the examples of $1\,M_\odot$ and $5\,M_\odot$ stars this is at H in their evolution tracks shown in previous slides.

- The climb along the giant branch, interrupted by core He-ignition and burning, is resumed.
- For stars having $M \lesssim 2.5\,M_\odot$, the AGB lies at similar L but higher $T_{\rm eff}$ than the preceding RGB phase.
- For stars having $M \gtrsim 2.5\,M_\odot$, the AGB lies at higher L.
- As illustrated in the following slide for the $5\,M_\odot$ case ($1\,M_\odot$ is similar), different phases of AGB evolution may be identified.

Asymptotic Giant Branch – III



Asymptotic Giant Branch – IV

The early AGB phase begins after He is exhausted in the core and the resulting C/O core contracts.

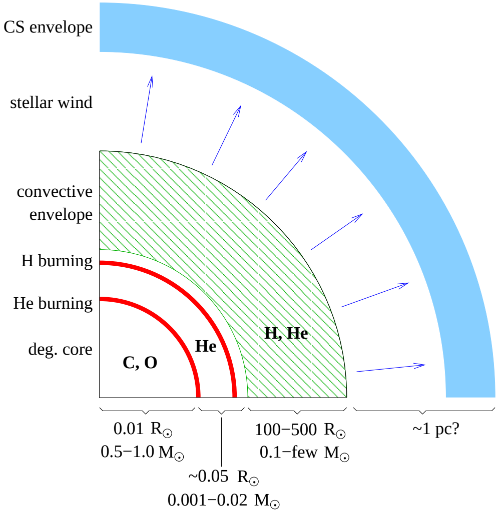
- During a brief transition, all layers below the H-burning shell contract (shortly after H), until He-burning shifts to a shell around the C/O core.
- There are now two active burning shells and a double "mirror effect" operates; the core contracts, the He-rich layers above expand, and the outer envelope starts contracting.
- But due to expansion in the He-rich zone, T in the H-shell decreases and the H-burning shell is extinguished.
- As a result, one "mirror" disappears and the entire envelope (He-rich layer plus H-rich outer envelope) expands in response to core contraction.
- A fairly long-lived phase (H-K) follows in which L is provided almost entirely by He-shell burning.
- He-shell burning gradually adds mass to the growing C/O core, which becomes degenerate due to its increasing density.
- As the envelope expands and cools, the outer convective part penetrates deeper until it reaches the composition discontinuity at K left by the extinct H-shell.

Asymptotic Giant Branch – V

In stars of sufficiently high mass ($M \gtrsim 4\,M_\odot$), depending on initial composition and whether overshooting is included, a convective dredge-up episode can occur, called the **Second Dredge-Up**.

- For lower-mass ($M \lesssim 4\,M_\odot$) stars the H-burning shell remains active at a low level, which prevents the convective envelope from penetrating deeper into the star; consequently the Second Dredge-Up does not occur in these cases.
- In dredged-up material which appears at the surface, $\sim 0.2\,M_\odot$ in a $5\,M_\odot$ star but $\sim 1.0\,M_\odot$ in the most massive AGB stars, H has been completely converted into He while ^{12}C and ^{16}O have been almost completely converted into ^{14}N in the CNO-Cycle.
- Thus the Second Dredge-Up has a qualitatively similar but much more dramatic effect than the First Dredge-Up which occured on the RGB.
- An additional consequence of the Second Dredge-Up is the reduction of the mass of the H-exhausted core, limiting the M of the white dwarf that is eventually formed.
- Effectively, the Second Dredge-Up increases the upper initial mass limit of stars that produce white dwarfs.

Asymptotic Giant Branch – VI



Asymptotic Giant Branch – VII

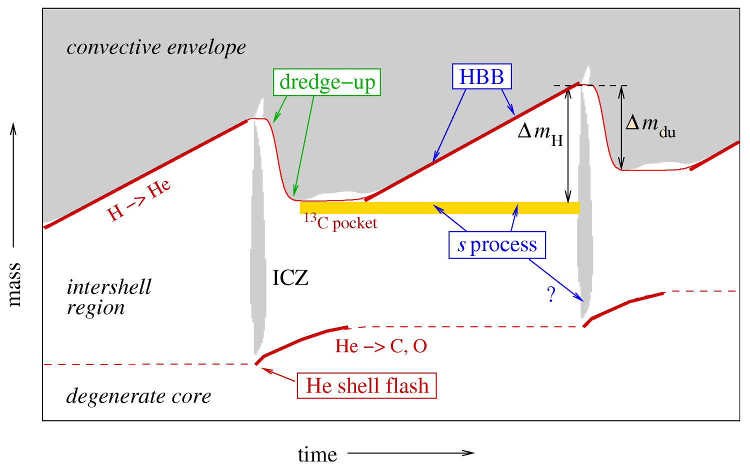
The **Thermally Pulsing AGB** (TP-AGB) begins as the He-burning shell approaches the H-He discontinuity or dormant H-burning shell:

- The He-burning shell begins to run out of fuel and so its contribution to L decreases.
- Layers above then contract in response, heating the extinguished H-burning shell until it is re-ignited.
- Both shells now provide energy and a phase of double shell burning begins.
- Burning in both shells does not occur at the same pace.
- The He-shell becomes thermally unstable and undergoes periodic thermal pulses.
- Salient properties of the TP-AGB are:
  - Periodic thermal pulses alternating with mixing episodes gives a unique nucleosynthesis of (in particular) ^{12}C, ^{14}N and elements heavier than Fe.
  - Stellar properties depend on the size of the degenerate C/O core; there is, for example, a tight core-mass luminosity relation

$$L = 5.9 \times 10^4 \left(\frac{M_c}{M_\odot} - 0.52 \right) L_\odot$$

  - Strong mass-loss ($10^{-7} - 10^{-4}\, M_\odot$/yr), probably driven by pulsation combined with radiation pressure on dust particles formed in the cool atmosphere, gradually removes the envelope.

Asymptotic Giant Branch – VIII



Asymptotic Giant Branch – IX

The previous slide depicts what happens during a thermal pulse cycle:

- For most of the time, the He-burning shell is inactive. The H-burning shell adds mass to the He-rich intershell region which increases T and P at the bottom of this region.
- When the intershell region mass reaches a critical value, He is ignited in an unstable manner giving a thermonuclear runaway as a helium shell flash. Values of $L_{\mathrm{He}} \simeq 10^8\, L_\odot$ are reached during ~ 1 year. The large energy flux drives convection in the whole intershell region, creating the intershell convection zone (ICZ)
- He-burning products then get mixed throughout the intershell region.
- Energy released by the He-shell flash goes into expansion of the intershell region against the gravitational potential. This allows the He-burning shell to expand and cool. As a result, a phase of stable He-shell burning follows and the cooling extinguishes H-shell burning.
- Expansion and cooling of the intershell region can lead to the outer convective envelope penetrating beyond the extinct H-burning shell and mixing intershell material into the outer envelope. The process is called the **Third Dredge-Up**. Helium as well as the products of He-burning, in particular ^{12}C can thus appear at the surface.
- Following a Third Dredge-Up, the H-burning shell is reignited and the He-burning shell becomes inactive again. A long phase of stable H-shell burning then increases the mass of the intershell region and the next thermal pulse occurs.

Asymptotic Giant Branch – X

This thermal pulse cycle can repeat itself many times:

- Pulse amplitude increases with each cycle, which facilitates dredge-up after several cycles.
- For example, in the case of a $3\,M_\odot$ TP-AGB star, third dredge-up begins after the seventh cycle and then follows after every subsequent cycle.
- Dredge-up efficiency (λ) is often measured as the ratio of mass dredged-up ($\Delta\, M_{\rm du}$) to the mass by which the H-exhausted core has grown ($\Delta M_{\rm H}$); that is

$$\lambda = \frac{\Delta\, M_{\rm du}}{\Delta M_{\rm H}}$$

- Apart from its important consequences for relative abundances of elements in gas eventually returned to the interstellar medium, the Third Dredge-Up also limits the growth of the H-exhausted core mass.
- Efficient dredge-up with $\lambda \simeq 1$ means the core mass does not increase in the long run.
- The main effect of thermal pulses and Third Dredge-Up operating in AGB Stars is the appearance of helium-burning products at the surface, in particular ^{12}C.
- For a $3\,M_\odot$ TP-AGB star, the ^{12}C abundance increases after every dredge-up episode and exceeds the ^{16}O abundance after 1.3×10^6 yr; it thus becomes a carbon star.

Asymptotic Giant Branch – XI

In stars with $M \gtrsim 4 - 5\,M_\odot$, T at the base of the convection zone becomes so high ($T_\mathrm{BCE} \gtrsim 3 \times 10^7\,\mathrm{K}$) that H-burning reactions take place:

- The CNO-Cycle operates on material in the convective envelope, a process known as **Hot Bottom Burning** (HBB).
- Most significant consequences of HBB are:
  - an increase in L which breaks the $L - M_\mathrm{c}$ relation and
  - the conversion of dredged-up ^{12}C into ^{14}N.
- HBB thus prevents massive AGB stars from becoming carbon stars, turning such stars into efficient producers of nitrogen.
- Other nuclei produced during HBB are ^{7}Li, ^{23}Na, ^{25}Mg and ^{26}Mg.

Asymptotic Giant Branch – XII

The number of thermal pulses and duration of the TP-AGB phases is limited by

- the decreasing mass of the H-rich envelope and
- the growing mass of the degenerate C/O core.

If the C/O core-mass reaches the Chandrasekhar Mass ($M_{\mathrm{Ch}} \simeq 1.4\,M_\odot$), carbon would be ignited in the centre in the so-called “Carbon Flash” which could potentially disrupt the whole star. But mass-loss becomes so high on the AGB that the entire H-rich envelope can be removed before the core has grown significantly; the lifetime of the TP-AGB phase ($1 - 2 \times 10^6\,\mathrm{yr}$) is therefore determined by the mass-loss rate.

It is clear from spectral energy distributions, which show a large excess flux at infrared wavelengths, that AGB stars have strong stellar winds:

- Many AGB stars (known as OH/IR stars) are completely enshrouded in a dusty circumstellar envelope and their photospheres cannot be seen at optical wavelengths.
- AGB stars are found to undergo strong radial pulsations and are known as Mira variables.
- A correlation is found to exist between pulsation period and mass-loss rate.

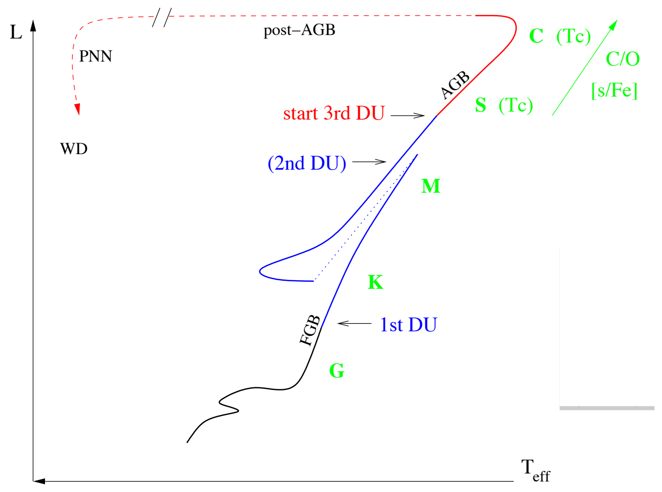
Asymptotic Giant Branch – XIII

The driving of strong mass-loss on the AGB is not fully understood but a combination of dynamical pulsations and radiation pressure on dust particles formed in the atmosphere probably plays an essential role:

- Pulsations induce shock waves in the stellar atmosphere, which bring gas out to larger radii and increase ρ in the outer atmosphere.
- At about $1.5 - 2\,R$, T is low enough ($\sim 1500\,\mathrm{K}$) for dust particles to condense; in the absence of pulsation, ρ would be too low at this distance from the star for dust to form.
- Dust particles are very opaque and, once they have formed, are accelerated by P_{rad} resulting from the high L.
- Even though gas in the atmosphere is mostly in molecular form (H_2) and the dust fraction is only about 1%, molecular gas is dragged along by the accelerated dust particles resulting in a large-scale outflow.

The phase of a very high mass-loss rate is sometimes called a “superwind”; once an AGB star enters this phase, the H-envelope is largely removed and this marks the end of the AGB evolution stage.

Post-Asymptotic Giant Branch – I



Post-Asymptotic Giant Branch – II

When the mass of the H-rich envelope has become very small ($10^{-2} - 10^{-3}\,M_\odot$), depending on M_c, the envelope shrinks and the star leaves the AGB:

- The resulting decrease in R occurs at almost constant L because the H-burning shell remains active and the star adheres to the $L - M_\mathrm{c}$ relation.
- Thus the star follows a horizontal track in the HRD towards higher T_eff values.
- Complete equilibrium is maintained during this phase as evolution towards higher T_eff is caused by decreasing envelope mass, which is eroded at the bottom by H-shell burning and at the top by continuing mass-loss; a typical timescale for this is $\sim 10^4$ yrs.
- When $T_\mathrm{eff} \gtrsim 30000\,\mathrm{K}$, two processes begin:
  - A weak but fast wind, driven by P_rad in ultraviolet (UV) absorption lines as in OB-type stars, and
  - the UV flux destroys dust grains, dissociates molecules and finally ionises molecules.
- Part of the circumstellar envelope thus becomes ionised and starts radiating in recombination lines, appearing as a planetary nebula.

Post-Asymptotic Giant Branch – III

- Current ideas about the formation of planetary nebulae are that they result from an interaction between the slow AGB wind and the fast central star wind, giving a compressed optically thin shell from which radiation is emitted.
- Once the envelope mass has decreased to $10^{-5}\,M_\odot$, the H-burning shell is extinguished; this happens when $T_{\rm eff} \approx 10^5\,$K and from this point L starts decreasing.
- The remnant now cools as a white dwarf.
- In some cases the star can still experience a final thermal pulse during its post-AGB phase (a late thermal pulse), or even during the initial phase of white dwarf cooling (a very late thermal pulse).
- Both can temporarily bring the star back to the AGB (sometimes referred to as the "born-again AGB" scenario).

Summary

Subjects discussed in the Ninth Lecture include:

- Helium burning in stellar cores and subsequently in a shell surrounding a C/O core has been discussed; the nuclear reaction is the same for all stellar masses.
- Low and intermediate mass stars differ because in the former the helium core is degenerate.
- Low mass stars burn helium in a core while being located on the Horizontal Branch in the Hertzsprung Russell Diagram (HRD).
- While burning helium in their cores, higher mass stars are confined to a blue loop in the HRD; these stars being observed as cepheid variables.
- Except for the very high mass stars, evolution ends when the star ascends the Asymptotic Giant Branch, loses its entire envelope and becomes a planetary nebula before joining the white dwarf cooling track.

Acknowledgement

Material presented in this lecture on Post-Main Sequence Helium Burning is based almost entirely on slides prepared by N. Langer (Universität Bonn).