

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-Ignition

The onset of the He-burning phase of stellar evolution occurs as He-core temperatures approach  $10^8$  K when the  $3\alpha$  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  $T \sim 10^8$  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 ( $\rho_c \simeq 10^4 \text{ g/cm}^3$ ), nuclear burning is thermally stable and helium ignition proceeds quietly (non explosive).
- Owing to the high-sensitivity to  $T$  of the  $3\alpha$  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  $3\alpha$  which converts  ${}^4\text{He} \rightarrow {}^{12}\text{C}$  inside the convective core.
- As the  ${}^{12}\text{C}$  abundance increases, the  ${}^{12}\text{C} + {}^4\text{He} \rightarrow {}^{16}\text{O} + \gamma$  reaction gradually takes over, so that  ${}^{16}\text{O}$  is produced at a rate which increases with time

## Core Helium-Burning – Intermediate Mass Stars – II

- When the central He mass-fraction  $X_{\text{He}} < 0.2$ , the mass-fraction of  $^{12}\text{C}$  starts decreasing as a result of the diminishing  $3\alpha$  rate (which is  $\propto X_{\text{He}}^3$ ).
- The final  $^{12}\text{C}/^{16}\text{O}$  ratio is  $\sim 0.3$ , 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  $^{12}\text{C}/^{16}\text{O}$  ratio depends on the uncertain rate of the  $^{12}\text{C}(^4\text{He}, \gamma)^{16}\text{O}$  reaction.
- The duration (E-H) of central He-burning in the  $5 M_{\odot}$  star is about 22 Myr or about  $0.27 \times \tau_{\text{MS}}$ .
- This 22 Myr 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 ( $L_{\text{He}}$ ) 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  $L_{\text{He}}$  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  $L_{\text{He}}$  increases accordingly.
- Another consequence is that  $L_{\text{He}}$  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  $T_{\text{eff}}$  increases.
- This is the start of a so-called **blue loop**, the hottest point of which is reached at G when  $X_{\text{He}} \simeq 0.3$ .
- 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  $X_{\text{He}} \simeq 0.05$ .
- 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  $T_{\text{eff}}$  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 occurrence 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  $M_c$ , 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  $M_c \simeq 0.45 M_{\odot}$

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  $T_c \simeq 10^8$  K and  $\rho_c \simeq 10^6$  g/cm<sup>3</sup>, so the He-core is strongly degenerate.
- He-burning under degenerate conditions is thermally unstable; energy generated by the  $3\alpha$ -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  $\rho$  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  $\rho_c - T_c$  diagram.
- Thermonuclear runaway leads to an enormous overproduction of energy. At maximum, the local luminosity ( $\ell$ ) in the He-core is  $\ell \sim 10^{10} L_{\odot}$  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  $\rho$ , 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  $T_c \simeq 10^8$  K and  $\rho_c \simeq 2 \times 10^4$  g/cm<sup>3</sup>.
- 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 losses during the preceding red giant phase.
- At high  $\rho$  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  $\ell$  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 ( $^{12}\text{C}$ ) produced in the  $3\alpha$  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.

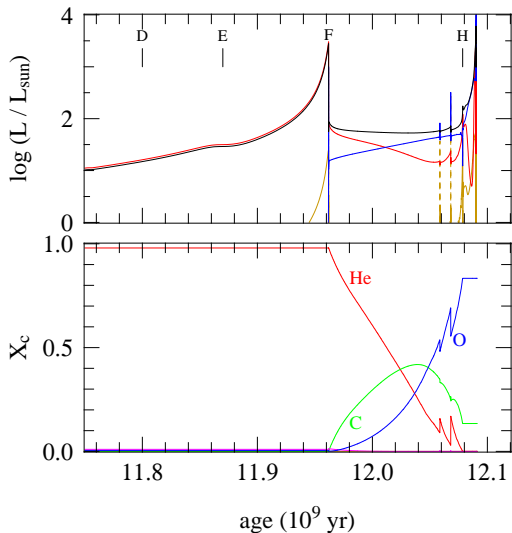
- Evolution through the Helium Flash was not calculated for the  $1 M_{\odot}$  evolution track shown previously.
- Instead, evolution of the star is resumed at G when the He-core has become non-degenerate and has settled into thermal equilibrium with stable He-burning in the centre and H-shell burning 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.
- $T_{\text{eff}}$  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

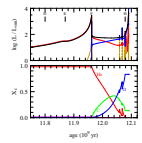




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# Stellar Evolution

- └ Post-Main Sequence Helium-Core Burning
  - └ Core Helium Burning
    - └ Core Helium-Burning – Low Mass Stars – VII



Evolution with time of the luminosities and central abundances in a  $1 M_{\odot}$  star during the late part of the Red Giant Branch and during helium burning. Letters D, E, . . . , H correspond to the same evolution phases shown in the  $1 M_{\odot}$  Hertzsprung-Russell Diagram previously.

# 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  $\tau_{\text{MS}}$  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:

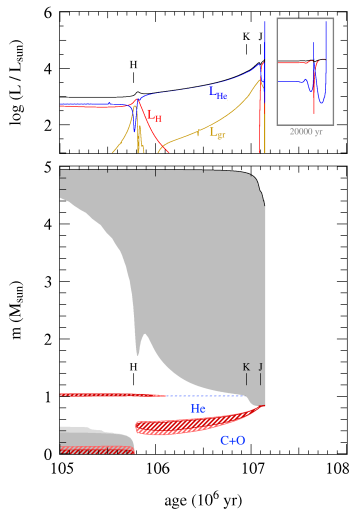
- In massive stars ( $M \gtrsim 8 M_{\odot}$ ) the core avoids degeneracy and undergoes further burning cycles.
- In low- and intermediate-mass stars ( $M \lesssim 8 M_{\odot}$ ), the C/O core becomes degenerate and stars evolve up the **Asymptotic Giant Branch (AGB)**
- The AGB is a brief but interesting 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.

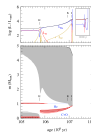
- The climb along the giant branch, interrupted by core He-ignition and burning, is resumed.
- For stars having  $M \lesssim 2.5 M_{\odot}$ , the AGB lies at similar  $L$  but higher  $T_{\text{eff}}$  than the preceding RGB phase.
- For stars having  $M \gtrsim 2.5 M_{\odot}$ , the AGB lies at higher  $L$ .
- 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



## Stellar Evolution

- └ Post-Main Sequence Helium-Core Burning
  - └ Asymptotic Giant Branch
    - └ Asymptotic Giant Branch – III



Evolution of luminosities (upper panel) and internal structure (lower panel) with time in a  $5 M_{\odot}$  star (with composition  $X = 0.70$ ,  $Z = 0.02$ ) during the last stages of helium burning on the Asymptotic Giant Branch (AGB). Compare with the figure “Intermediate and Massive Star H-Shell Burning – III” shown in the previous lecture. The early AGB starts at Point H, when He-burning shifts quite suddenly from the centre to a shell around the former convective core. The H-burning shell is extinguished at Point K and the Second Dredge-Up occurs. The H-burning shell is re-ignited some time later at Point J and starts the double shell-burning phase, which quickly leads to thermal pulses of the He-burning shell. The first thermal pulses can be seen in the upper panel inset which shows the last 20000 years of this model calculation. Strong mass-loss is then expected to remove the stellar envelope within  $\lesssim 10^6$  years, leaving the degenerate CO-core as a cooling white dwarf.

# 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.

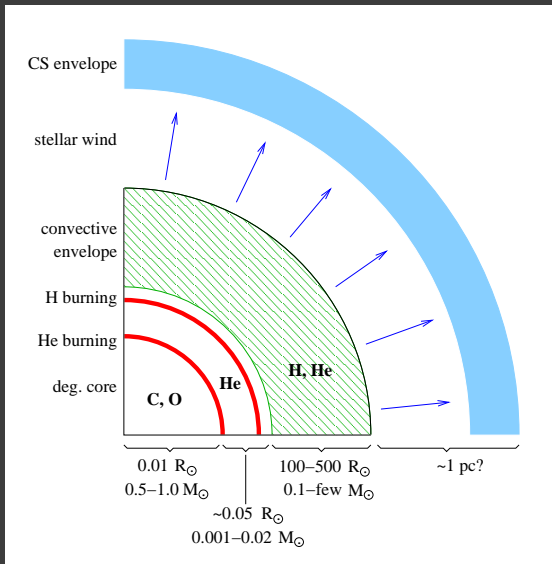
# Asymptotic Giant Branch – V

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  $^{12}\text{C}$  and  $^{16}\text{O}$  have been almost completely converted into  $^{14}\text{N}$  in the CNO-Cycle.
- Thus the Second Dredge-Up has a qualitatively similar but much more dramatic effect than the First Dredge-Up which occurred 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.



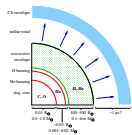
# Asymptotic Giant Branch – VI



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# Stellar Evolution

- └ Post-Main Sequence Helium-Core Burning
  - └ Asymptotic Giant Branch
    - └ Asymptotic Giant Branch – VI



## Schematic structure of an AGB Star

# Asymptotic Giant Branch – VII

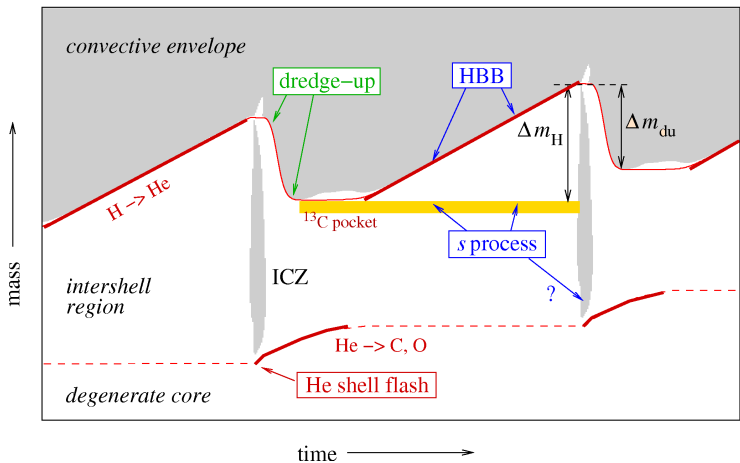
The **Thermally Pulsing AGB** (TP-AGB) begins as the He-burning shell approaches the H-He discontinuity or dormant H-burning shell:

- 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)  $^{12}\text{C}$ ,  $^{14}\text{N}$  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 ( $10^{-7} - 10^{-4} M_\odot/\text{yr}$ ), probably driven by pulsation combined with radiation pressure on dust particles formed in the cool atmosphere, gradually removes the envelope.

# Asymptotic Giant Branch – VIII



## Stellar Evolution

- └ Post-Main Sequence Helium-Core Burning
  - └ Asymptotic Giant Branch
    - └ Asymptotic Giant Branch – VIII



Schematic evolution of a AGB Star through two thermal-pulse cycles. Convective regions are shown as gray shaded areas, where 'ICZ' stands for the the intershell convection zone driven by the He-shell flash. The H-exhausted core mass is shown as a thin red solid line and the He-exhausted core mass as a dashed line. Thick red lines indicate when nuclear burning is active in these shells. Only the region around the two burning shells is shown, comprising  $\sim 0.01 M_{\odot}$ . Note that the time axis is highly non-linear: the He shell-flash and dredge-up phases (lasting  $\sim 100$  years) are expanded relative to the interpulse phase ( $10^4 - 10^5$  years).

# 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  $L_{\text{He}} \simeq 10^8 L_{\odot}$  are reached during  $\sim 1$  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  $^{12}\text{C}$  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 ( $\lambda$ ) is often measured as the ratio of mass dredged-up ( $\Delta M_{\text{du}}$ ) to the mass by which the H-exhausted core has grown ( $\Delta M_{\text{H}}$ ); that is

$$\lambda = \frac{\Delta M_{\text{du}}}{\Delta M_{\text{H}}}$$

- 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  $^{12}\text{C}$ .
- For a  $3 M_{\odot}$  TP-AGB star, the  $^{12}\text{C}$  abundance increases after every dredge-up episode and exceeds the  $^{16}\text{O}$  abundance after  $1.3 \times 10^6$  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 ( $T_{\text{BCE}} \gtrsim 3 \times 10^7$  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  $L - M_c$  relation and
  - the conversion of dredged-up  $^{12}\text{C}$  into  $^{14}\text{N}$ .
- HBB thus prevents massive AGB stars from becoming carbon stars, turning such stars into efficient producers of nitrogen.
- Other nuclei produced during HBB are  $^7\text{Li}$ ,  $^{23}\text{Na}$ ,  $^{25}\text{Mg}$  and  $^{26}\text{Mg}$ .



# 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 ( $M_{\text{Ch}} \simeq 1.4 M_{\odot}$ ), 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 ( $1 - 2 \times 10^6$  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.

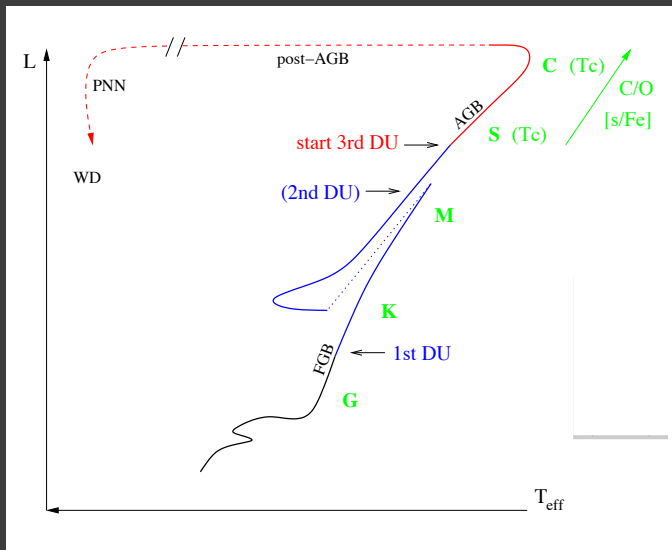
# Asymptotic Giant Branch – XIII

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  $\rho$  in the outer atmosphere.
- At about  $1.5 - 2 R$ ,  $T$  is low enough ( $\sim 1500$  K) for dust particles to condense; in the absence of pulsation,  $\rho$  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  $P_{\text{rad}}$  resulting from the high  $L$ .
- Even though gas in the atmosphere is mostly in molecular form ( $\text{H}_2$ ) 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

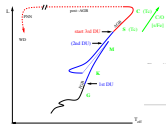


2016-03-10

## Stellar Evolution

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

Post-Asymptotic Giant Branch – I



Schematic evolution track of a low-mass star in the Hertzsprung-Russell Diagram, showing the occurrence of the various dredge-up episodes. Stars on the upper Asymptotic Giant Branch (AGB) are observed to be enriched in s-process elements (S stars) and in carbon (C stars).

# 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  $L - M_c$  relation.
- Thus the star follows a horizontal track in the HRD towards higher  $T_{\text{eff}}$  values.
- Complete equilibrium is maintained during this phase as evolution towards higher  $T_{\text{eff}}$  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  $T_{\text{eff}} \gtrsim 30000$  K, two processes begin:
  - A weak but fast wind, driven by  $P_{\text{rad}}$  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  $T_{\text{eff}} \approx 10^5$  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.

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