Evolution and nucleosynthesis of AGB stars

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Lecture Outline

1. Introduction to AGB stars; evolution prior to the AGB phase
2. Evolution and nucleosynthesis before the AGB phase
3. Evolution and nucleosynthesis of AGB stars
4. The slow-neutron capture process in AGB stars
5. Low and zero-metallicity AGB evolution
6. Super-AGB stars and post-AGB objects
Outline of this lecture

1. The thermal-pulse cycle
2. Evolution and nucleosynthesis during a thermal pulse including the third dredge-up
3. Evolution and nucleosynthesis during the interpulse period including hot bottom burning
4. Yields from AGB stars
Asymptotic Giant Branch stars

From previous lectures:
AGB is the last nuclear burning phase for 0.8 to 8 Msun stars
AGB stars are cool (~3000 K) evolved giants, spectral types M, S, C
Many AGB stars are observed to be losing mass rapidly ($\dot{M} \sim 10^{-5}$ Msun/yr)
FDU and SDU altered the surface prior to the AGB
AGB stars are observed to be long-period variables, $P \sim 100$-1000 days
Thermal pulse cycle in more detail

Deep convective envelope

H-burning shell

He-rich intershell

He-burning shell

Carbon-Oxygen core

He-shell burns brightly, producing up to $10^8 \text{ L}_{\odot}$
Thermal pulse cycle in more detail

Deep convective envelope
H-burning shell
He-rich intershell
He-burning shell
Carbon-Oxygen core

Convective pocket reaches maximum extent, mixing the intershell with the products of He-burning

On phase
Thermal pulse cycle in more detail

- Deep convective envelope
- H-burning shell
- He-rich intershell
- He-burning shell
- Carbon-Oxygen core

intershell convection starts to retreat

Power down
Thermal pulse cycle in more detail

Deep convective envelope
H-burning shell
He-rich intershell
He-burning shell
Carbon-Oxygen core

Power down
Thermal pulse cycle in more detail

Deep convective envelope

H-burning shell

He-rich intershell

He-burning shell

Carbon-Oxygen core

the outer envelope reaches the intershell, thus mixing $^{12}\text{C},^{25,26}\text{Mg}$ and s-process elements into the envelope
Thermal pulse cycle in more detail

- Deep convective envelope
- H-burning shell
- He-rich intershell
- He-burning shell
- Carbon-Oxygen core

H-shell is re-ignited and will provide most of the surface luminosity for the next $10^4$ years.

Interpulse phase
The AGB Evolution Cycle

1. **On phase:** He-shell burns brightly, producing up to 100 million $L_{\text{sun}}$, drives a convection zone in the He-rich intershell and lasts for $\sim$ 100 years

2. **Power-down:** He-shell dies down, energy released by flash drives expansion which extinguishes the H-shell

3. **Third dredge-up:** convective envelope moves inward into regions mixed by flash-driven convection. Mixes partially He-burnt material to surface.

4. **Interpulse:** star contracts and H-shell is re-ignited, provides most of the surface luminosity for the next $10^4$ to $10^5$ years

Pulse (He-burning) $\rightarrow$ TDU (mixing) $\rightarrow$ Interpulse
Few $\sim 10^2$ yrs $\rightarrow$ $\sim 10^2$ years $\rightarrow$ $\sim 10^4$ yrs
AGB evolution: 3M\textsubscript{sun}, Z = 0.02
Zoom in on first few TPs: 3Msun

Time is scaled: \((t-4.23 \times 10^8/1 \times 10^5)\)

White = radiated luminosity
Green = he-burning luminosity, and Red = H-burning luminosity
Convective pockets during TPs

The huge luminosities (~$10^8 \text{ L}_{\odot}$) produced by each TP drive a convective region in the He-rich intershell. The convective pocket extends over almost the whole intershell. It has the effect of homogenising abundances within this region. The mass of the pocket ~ few $10^{-3} \text{ M}_{\odot}$, depending on stellar mass. The duration of convection is ~few hundred years. Model number is a proxy for time.

Results for a 1.9M$_{\odot}$, Z = 0.008 model.

Convection zones = green, radiative = pink.
Luminosity variability

- Large amplitude red variables are all AGB stars near the tip of the AGB
- The LMC provides a large sample of long-period variables at a known distance, so absolute luminosities can be derived
- Pulsation periods, combined with pulsation theory, can be used to derive current stellar masses
- Three broad groups: Miras (up to 6 mag in visual!), semiregular and irregular variables
- Variability caused by envelope pulsation, with periods on the order of 100 to ~1000 days
- These pulsations are NOT related to thermal pulses, which have a cycle of $10^4$ years!
- Radial pulsations of the envelope linked to mass loss
Making Carbon Stars!

- Thermal pulses and third dredge-up can occur many times during the AGB
- Dredge up mixes $^{12}\text{C}$ from the He-shell to the surface, increasing the C/O ratio to $> 1$
- Can explain the transition from M-type star (with C/O $< 1$) to carbon star:
  \[ \text{M} \rightarrow \text{MS} \rightarrow \text{S} \rightarrow \text{SC} \rightarrow \text{C} \ (\text{C/O} > 1) \]
- Carbon stars are also observed to have enrichments ($[\text{X}/\text{Fe}] > 0$) of heavy elements (e.g. Ba, Tc, La)
- Fluorine is observed to be enriched in carbon stars (Jorissen et al. 1992), with a correlation between increasing C/O and $[\text{F}/\text{O}]$
- Reviews: Busso et al. (1999), Herwig (2005)
The third dredge-up

3 M_{\odot}, Z = 0.02
Carbon star at pulse 21

\begin{itemize}
  \item C/O = 1.09
  \item C/O = 1.00
  \item C/O = 0.32
\end{itemize}

\textbf{Mass of H-exhausted Core}

\textbf{Time (in years)}

\textbf{M_{H}} \quad \textbf{M_{He}}
Let’s look at a TP again

Extent of convective pocket is $1.68 \times 10^{-2} \, \text{M}_{\odot}$

About half gets mixed into envelope

H-exhausted core mass is decreased by TDU

He-exhausted core mass

22nd thermal pulse for the $3 \, \text{M}_{\odot}$, $Z = 0.02$ model
Efficiency of third dredge-up, $\lambda$

\[ \lambda = \frac{\Delta \text{Mass}_{\text{dredge}}}{\Delta \text{Mass}_h} \]

$\lambda = 0.78$ between 23rd and 22n TP
Lambda as a function of core mass

For the 5Msun, Z = 0.02 model

The efficiency of the third dredge up is a function of the core mass (or total mass) and metallicity.

General trend that we find:
For increasing M at a given Z: lambda increases
For decreasing Z at a given M: lambda increases!

This means it is easier to make C-stars in lower Z or higher mass models

….except we don’t see luminous C-stars!
….because of hot bottom burning!
Making carbon stars is easier at lower metallicity

\[ M = 3, \ Z = 0.004, \ [\text{Fe/H}] \sim -0.7 \]
Constraining the third dredge up

- It is important to know if the models are giving us an accurate description of mixing in AGB stars.
- Are we predicting enough TDU, or too much? Do we predict the right mass range for carbon stars?
- The distances to the LMC and SMC are well determined and we know of lots of C-stars (e.g. Groenewegen 2004).
- This data enables carbon-star luminosity functions to be constructed for both these locations.
- Long-standing problem forming C-stars at low enough luminosities, and hence core masses.
Nucleosynthesis: He-burning

- Main energy-generating reactions:
  - $3\alpha$ process: $3^4\text{He} \rightarrow ^{12}\text{C}$
  - $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ – relatively unimportant during thermal pulses

- Non-energetic reactions:
  - $^{14}\text{N}$ captures 2 $\alpha$ particles to make $^{22}\text{Ne}$
  - $^{22}\text{Ne}$ can capture an $\alpha$ particle to produce $^{25,26}\text{Mg}$. Only occurs when $T > 300$ million K
  - $^{19}\text{F}$ can be produced through complex series of reactions involving both H, He-burning
  - The slow-neutron capture process can occur to make elements heavier than Fe
Nucleosynthesis from He-shell burning

3\,\text{Msun}, \ Z = 0.008:
Intershell $^4\text{He}$ and $^{12}\text{C}$ abundance evolution during first 6 TPs

3.5\,\text{Msun}, \ Z = 0.008:
Surface $^{22}\text{Ne}$, $^{25}\text{Mg}$ and $^{26}\text{Mg}$ abundance evolution
How do AGB stars make F?

- The reaction chain: $^{18}\text{O}(p, \alpha)^{15}\text{N}(\alpha, \gamma)^{19}\text{F}(\alpha, p)^{22}\text{Ne}$
- Fluorine production takes place in the He-intershell region: He-rich, H poor
- There are almost no protons, and little $^{15}\text{N}$
- These are created by other reactions including:
  - $^{13}\text{C}(\alpha, n)^{16}\text{O}$ - produces free neutrons
  - $^{14}\text{N}(n, p)^{14}\text{C}$ - produces free protons
  - $^{18}\text{F}(\alpha, p)^{21}\text{Ne}$ - alternative proton production
  - $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+)^{18}\text{O}$ - main reaction to produce $^{18}\text{O}$
  - $^{14}\text{C}(\alpha, \gamma)^{18}\text{O}$ - alternative reaction
  - $^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}$ - main $^{18}\text{O}$ destruction reaction
  - $^{15}\text{N}(p, \alpha)^{12}\text{C}$ - destroys $^{15}\text{N}$
Fluorine production

Results for a 3Msun model:

Composition profile showing intershell region just after last TP. TDU will mix the $^{19}$F created by the pulse into the envelope.

Abundances from Jorissen et al. (1992) compared to model results. ⊘ - shows SC stars, with C/O = 1.0.
Hot bottom burning

- In massive ($M > 3 \text{Msun}$) AGB stars the base of the convective envelope can dip into the H-shell
- Typical temperatures between $\sim 50$ to $100$ million K
- Burning region is thin in mass ($10^{-4} \text{Msun}$) but efficient mixing means that entire envelope is exposed to hot region at least $1000$ times per interpulse!
- Envelope burning was originally proposed to explain existence of luminous O-rich AGB stars in the LMC (Wood, Bessel & Fox 1983)
- Many of these stars also rich in lithium and s-process elements (Smith & Lambert 1989, Garcia Hernandez et al. 2006)
- CNO cycling at the base of the envelope prevents the formation of a C-rich atmosphere
Dredge-up still occurs

6.5 Msun, Z = 0.012
HBB at ~ 90 million K
total of 53 TPs

C/O_final = 0.76
12C/13C = 10.4

Mass of H-exhausted Core

M_H

M_He

CO core

Time (in years)
But the base of the envelope is hot!

$6.5M_{\text{sun}}, Z = Z_{\text{solar}}$: Peak temperature $\sim 90 \times 10^6 \text{ K}$
HBB Nucleosynthesis

- Efficient mixing in the envelope, with a convective turn over time of ~1 year means that the surface composition is dramatically affected by HBB.
- The main result is CNO cycling: $^{12}\text{C}$ is destroyed to make $^{14}\text{N}$.
- Base of the envelope gets hot enough to activate the NeNa and MgAl chains.
- Ne isotopes (in particular $^{22}\text{Ne}$) are destroyed to make sodium.
- Mg isotopes, in particular $^{25}\text{Mg}$, are destroyed to make Al, including the radioactive $^{26}\text{Al}$ ($\tau_{1/2} \sim 750,000$ years).
- Fluorine is easily destroyed by proton captures.
- Lithium can be made! Via the Cameron-Fowler mechanism.
- Note that TDU mixing still occurs to bring He-fusion products to the surface.
The $^{13}\text{C}$ content increases, due to the processing of $^{12}\text{C}$ into $^{12}\text{C}$. In extreme cases, when the entire envelope can be processed many times between pulses, HBB can produce the equilibrium ratio of $^{12}\text{C}/^{13}\text{C}$ of about 3.5. A consequence of this burning is the copious production of primary $^{14}\text{N}$. 
C/O ratio as a function of M, Z
Examples: 6.5M_{\odot}, Z = 0.02

Surface abundance evolution during the AGB phase

Production of $^{25,26}\text{Mg}$

log $\gamma$

(Time - 1.0e+07)/ 1.0e+05 years

$\text{Na}^{23}$

$\text{Ne}^{22}$

$\text{Mg}^{26}$

$\text{Mg}^{25}$

$\text{Al}^{27}$
Lithium production

• The first thing to happen is that $^7$Li is produced via the Cameron-Fowler Beryllium Transport Mechanism.
• This is basically PP chains plus convection!
• The idea is that lithium is made by $^3$He($\alpha$, $\gamma$)$^7$Be
• and then to use convection to move the $^7$Be away from the hot region before it can complete the PPII or PPIII chains:

\[ ^7\text{Li} (p, \alpha)^4\text{He} = \text{PPI} \\quad \text{BAD!} \]

\[ ^3\text{He} (\alpha, \gamma)^7\text{Be} (\beta, \nu)^7\text{Li} \]

\[ ^7\text{Be} (p, \gamma)^8\text{B} (\beta^+, \nu) \text{ Be}(\alpha)^4\text{He} = \text{PPIII} \quad \text{BAD!} \]

Cameron-Fowler mechanism
The upward stream is rich in $^7\text{Be}$, where it was produced at the bottom of the convective envelope. The $^7\text{Be}$ is then taken to cooler regions where it captures an electron to form $^7\text{Li}$. The Li production is limited by how much He-3 is present initially: once it is all used up then the $^7\text{Li}$ will eventually decline again.
Range of observed Li abundances

Below: notice that the observed range of Li abundances, shown here in blue, match very well the models!
Stellar yields

**General definition**: Amount of matter ($\Delta M$) that is expelled from a star over the course of its life

**More precisely**... integrated amount (in mass) of species $k$ that is expelled into the interstellar medium (ISM) over the stellar lifetime, $\tau$,

\[
\int_{\tau} \left[ X_k(t) - X_k(0) \right] \frac{dM}{dt} \, dt,
\]

minus the amount of $k$ that is initially present in the wind ($X_k(0) \Delta M$)
Legend:

Black: my models
Blue: Izzard
Red: Marigo (2001)
Pink: van den Hoek & Groenewegen

Carbon-12

\[ Z = 0.02 \]

\[ Z = 0.008 \]

\[ Z = 0.004 \]
Nitrogen-14

Z = 0.02

Z = 0.008

Z = 0.004
Summary of AGB nucleosynthesis

- Experience brief bursts of He-shell burning (TPs)
- May be followed by mixing from the core to the surface (TDU)
- As well as a longer interpulse phase (H-burning)
- For stars between 1 to 3\,M_{\odot}:
  - The third dredge-up may occur after each thermal pulse
  - Mixes He-burning products to the surface
  - Important for producing s-process elements (Lecture 4)
- For stars between 4 to 8\,M_{\odot}:
  - Proton capture nucleosynthesis at the base of the envelope
  - Alongside TDU mixing of He-shell material
  - Do these also produce s-process elements?