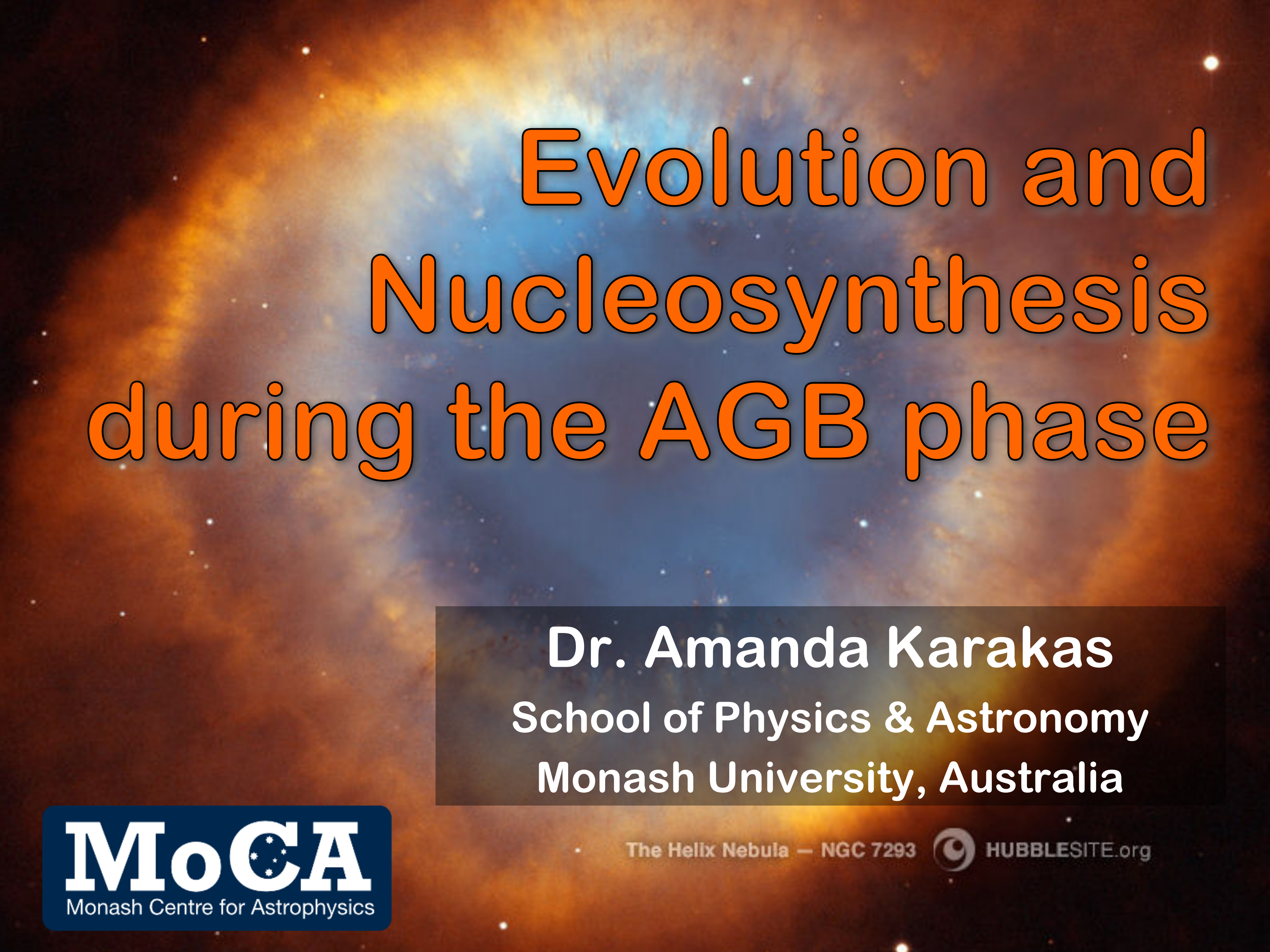

The Helix Nebula – NGC 7293 HUBBLESITE.org

Evolution and Nucleosynthesis during the AGB phase

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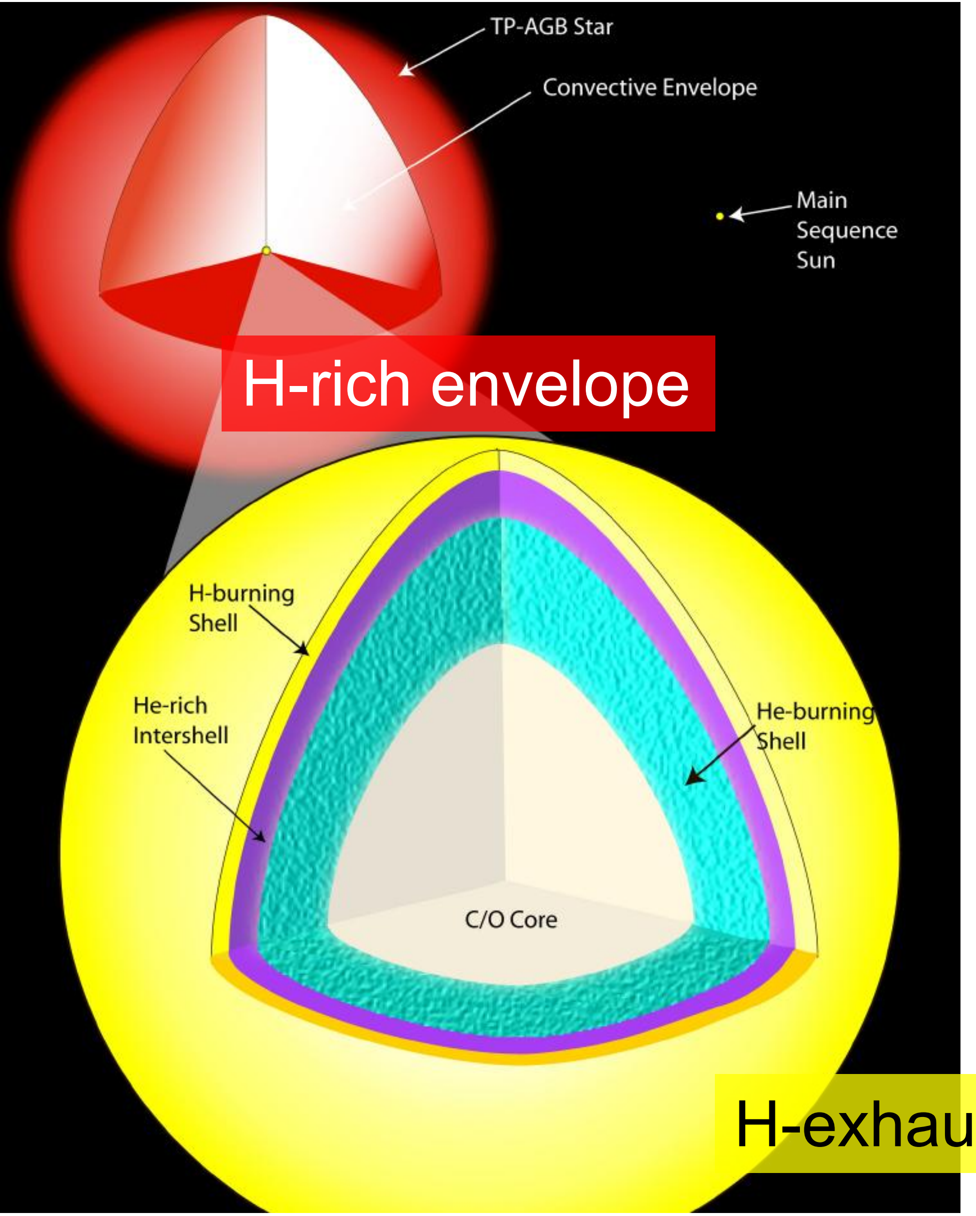
Outline of Lectures

I'm giving three lectures, which will be broken down into the following components:

1. Introduction – some basics
2. Nucleosynthesis prior to the asymptotic giant branch (AGB) phase
3. The evolution and nucleosynthesis of AGB stars
4. The slow neutron capture process

Asymptotic Giant Branch stars



H-rich envelope

H-exhausted core

- The asymptotic giant branch is the last nuclear burning phase for stars with mass < 8-10Msun
- AGB stars are cool (~3000 K) evolved giants, spectral types M, S, C
- It is during the AGB where the products of nucleosynthesis reach the stellar surface
- Many AGB stars are observed to be losing mass in dense outflows of material

➔ Enriching the interstellar medium

➔ Progenitors of planetary nebulae

➔ Reviews by Herwig (2005, ARAA) and Karakas & Lattanzio (2014, PASA)

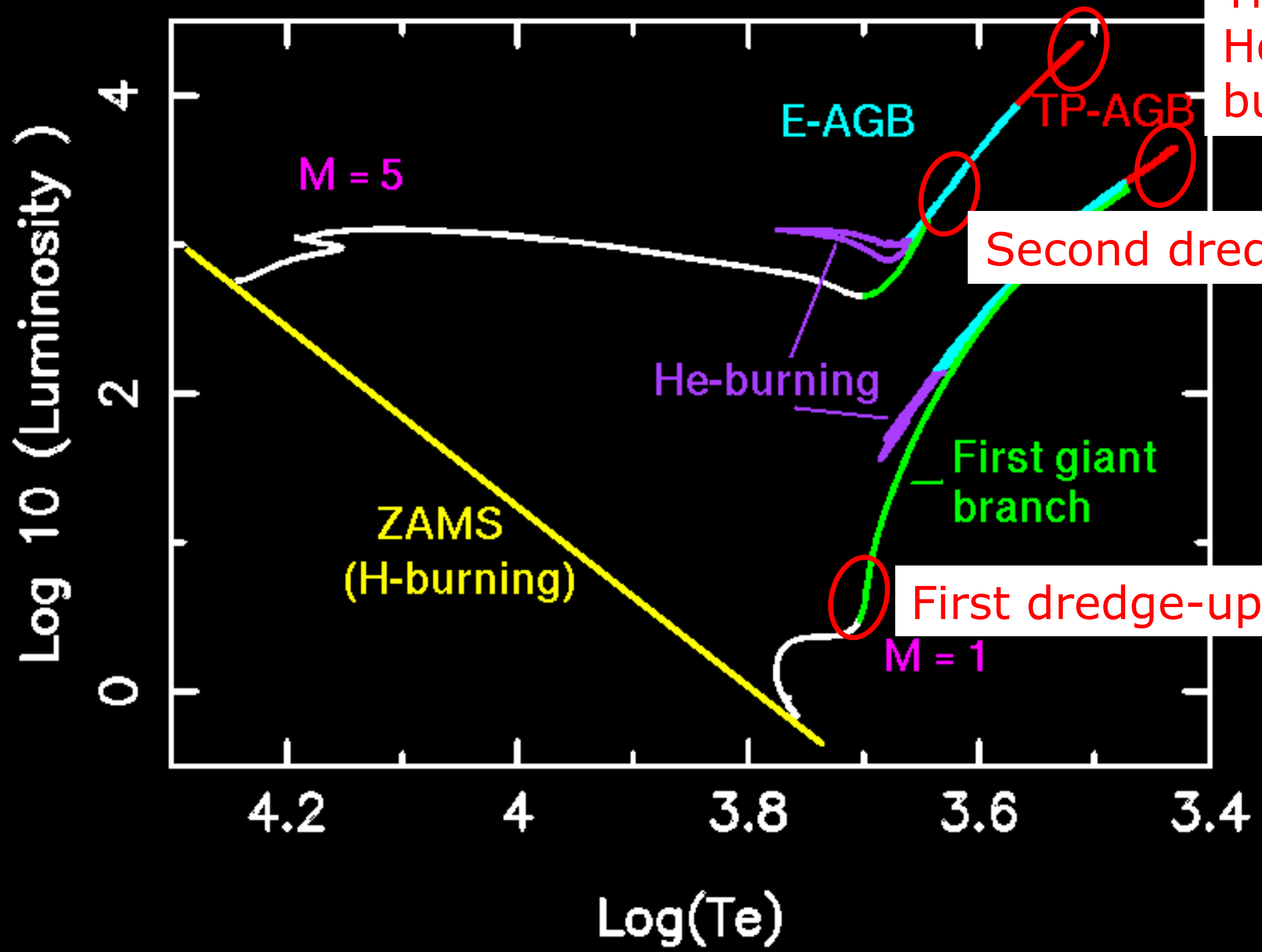
Mixing and mass loss

- Convective mixing (dredge-up) mixes the products of nucleosynthesis from the (hot) interior to the surface.
- Mass loss removes the enriched envelope, expelling the products into the interstellar medium.

→ When does most of the mass loss occur? When does the most nucleosynthesis occur?

For low and intermediate-mass stars, that is during the asymptotic giant branch (AGB)

Where mixing takes place



Third dredge-up
Hot bottom
burning

Second dredge-up

First dredge-up

Products of nucleosynthesis

Low and intermediate-mass stars go through central hydrogen and helium burning

During the AGB, they have shells burning H and He

1. First dredge-up: Products of (partial) H burning
2. Second dredge-up: Products of H burning
3. Third dredge-up: Products of H, He-burning and neutron-capture nucleosynthesis
4. Hot bottom burning: Products of H-burning
5. Extra mixing processes: Products of H-burning

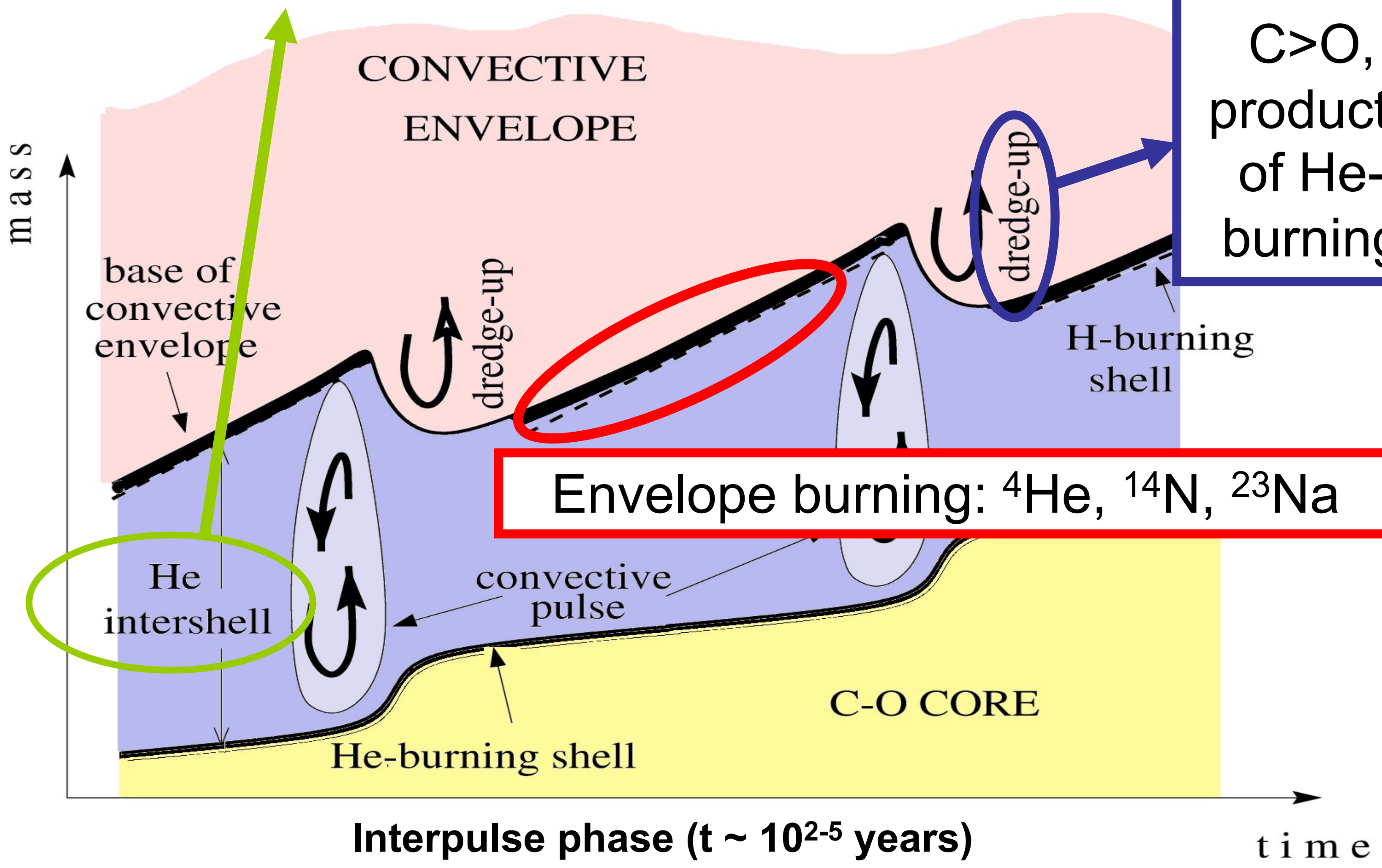
→ We we will now discuss the AGB phase of evolution

AGB nucleosynthesis

...

^{4}He, ^{12}C, ^{19}F, *s*-process elements: Zr, Ba, ...

At the stellar surface: C>O, products of He-burning



Envelope burning: ^{4}He, ^{14}N, ^{23}Na

Interpulse phase (t ~ 10$^{2-5}$ years)

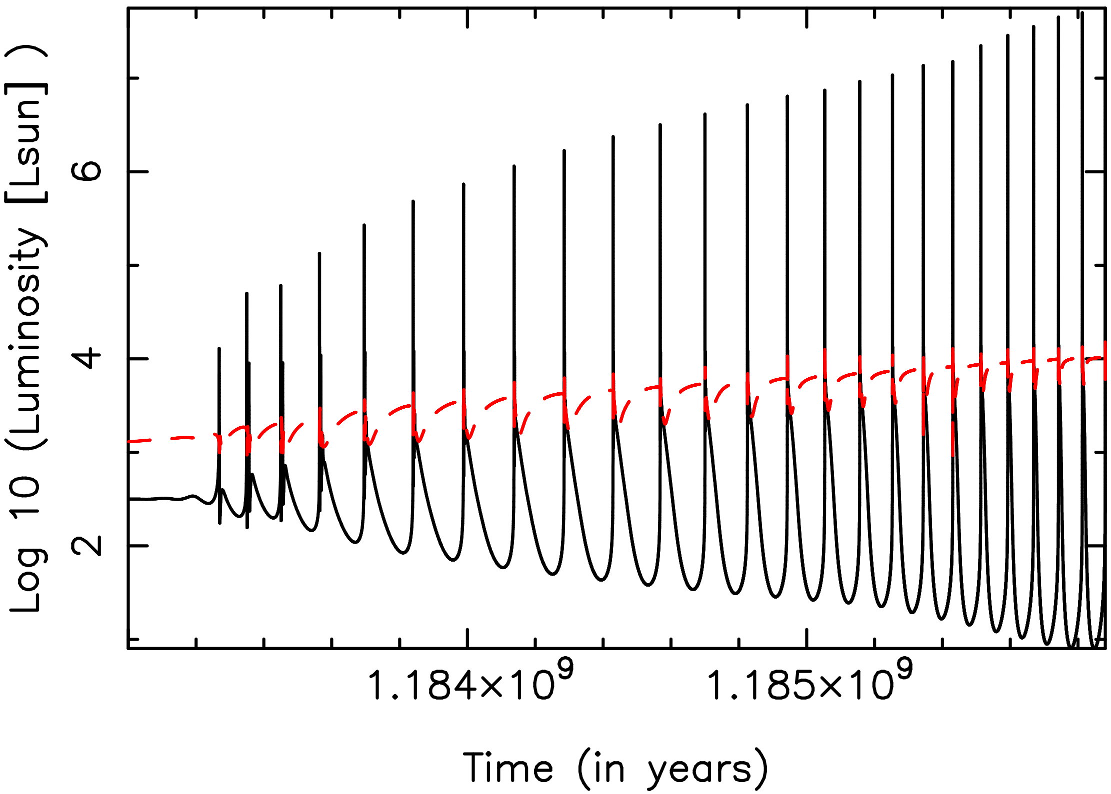
He-shell instabilities

- The He-shell thins as the star ascends the AGB and becomes thermally unstable
- He-burning in a thin shell leads to a thermal runaway, similar to the core He-flash
- Why?
- Not caused by electron degeneracy, although the shell is partially degenerate
- Caused by the shell being thin
- Contracting shell → hotter → $\varepsilon \propto T^{40}$ → but shell can't expand enough to cool → thermal runaway
- Luminosities can reach > 10^8 solar luminosities

He-shell burning in AGB stars

- Up to ~10^8 Lsun can be generated by a thermal pulse
- Energy goes into expanding the star
- He-shell becomes unstable to convection → mixes products of He-burning throughout shell

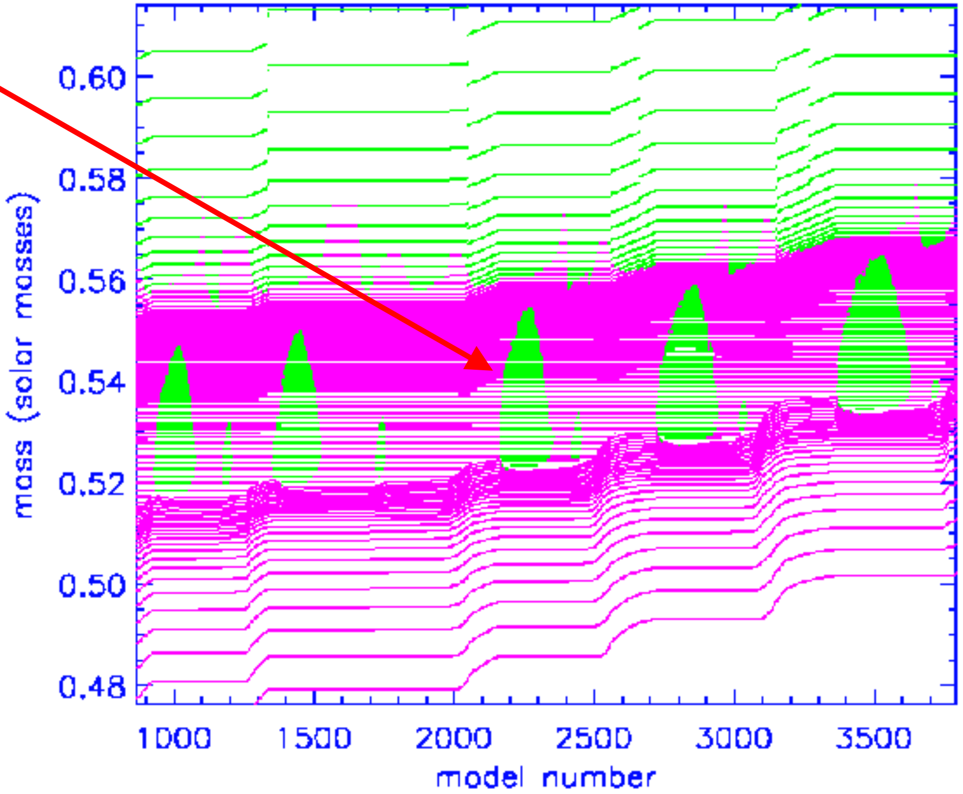
2Msun, Z = 0.014 model star:



Intershell convection during thermal pulses

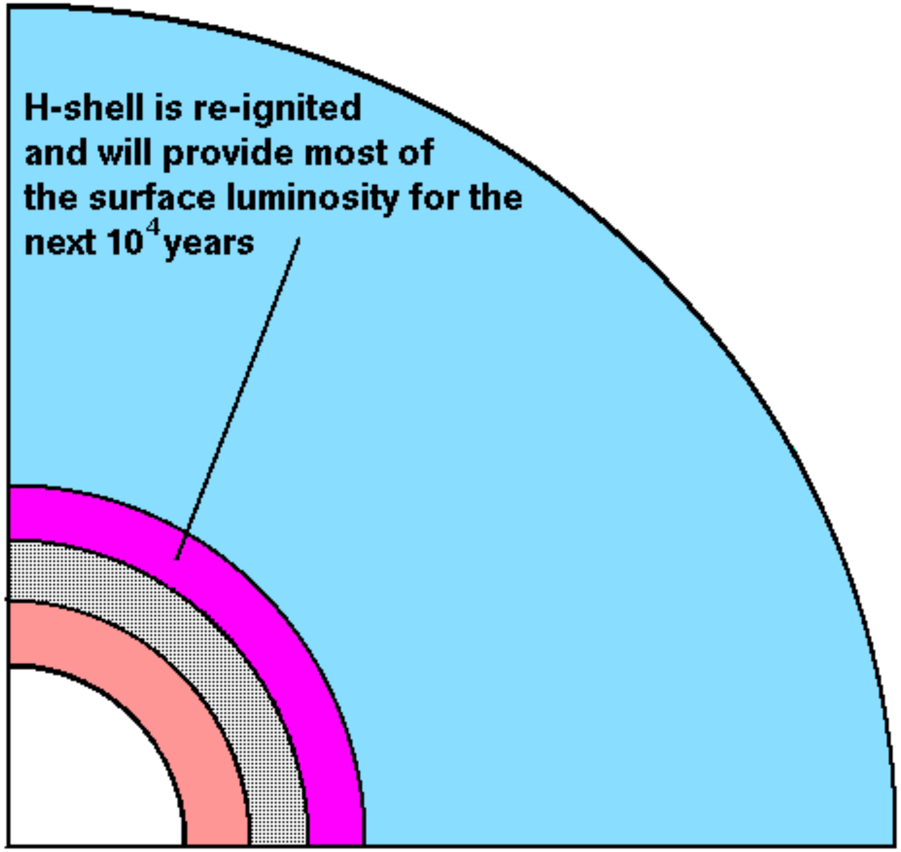
- The enormous amount of energy drives a convective region in the intershell
- Extends over almost the whole intershell
- Homogenises abundances within this region
- The mass of the pocket ~ few 10^{-2} Msun, depending on the stellar mass
- The duration of convection is ~few hundred years
- Composition: result of partial He-burning: ~70% ^{4}He, ~25 ^{12}C and ~5% other stuff (^{22}Ne, ^{16}O etc)

Convection zones = green, radiative = pink



Results for a 1.9Msun, Z = 0.008 model
Model number proxy for time

The thermal pulse cycle



Deep convective envelope

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

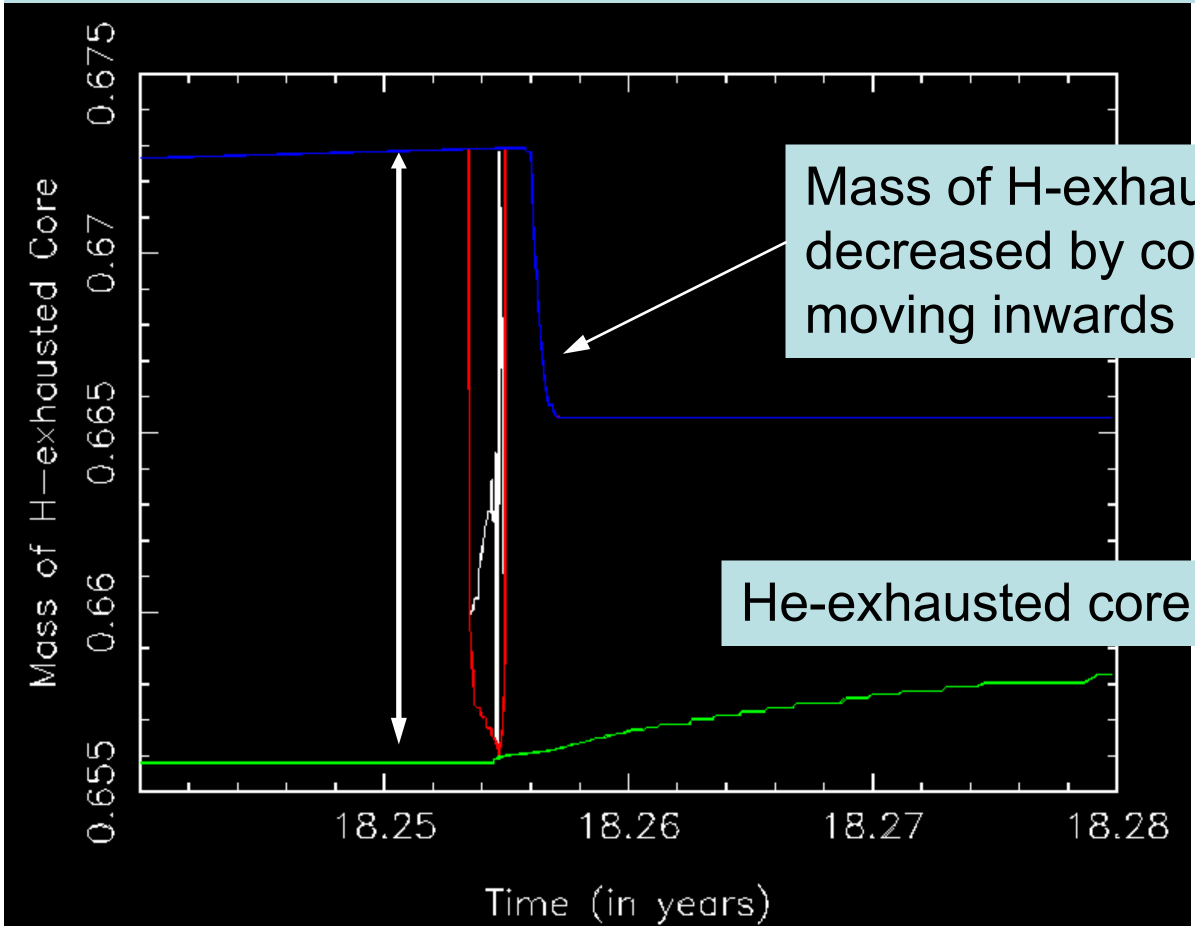
1. On phase: He-shell burns brightly, producing up to 10^8 L_{sun}, drives a convection zone in the He-rich intershell and lasts for ~ 100 years
2. Power-down: He-shell dies down, energy released by flash drives expansion which extinguishes the H-shell
3. Third dredge-up: convective envelope moves inward 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 ~10^5 years

Pulse (He-burning) → TDU (mixing) → Interpulse

Few ~10^2 yrs → ~10^2 years → ~10^5 yrs

Let’s look at a thermal pulse again

Extent of convective pocket is 1.7 x 10^{-2} Msun
About half gets mixed into envelope



Mass of H-exhausted core is decreased by convection moving inwards

He-exhausted core

22nd thermal pulse for the 3Msun, Z = 0.02 model

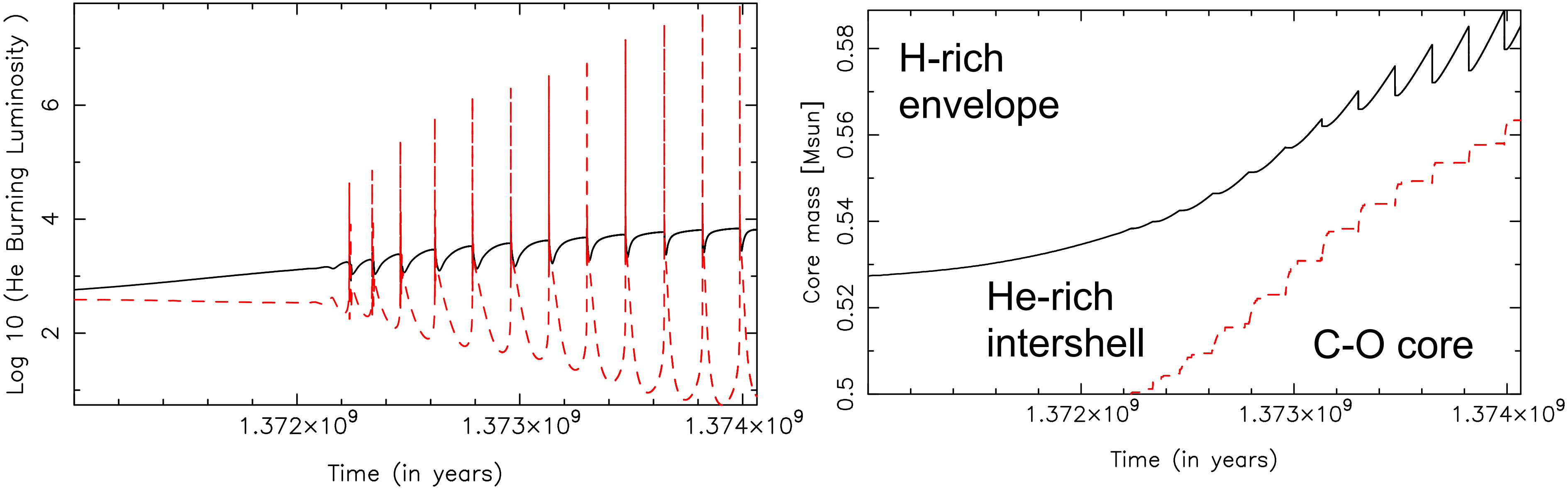
The importance of the third dredge-up

- The third dredge-up determines how much He-shell material is mixed from the core to envelope
- Mass loss determines the number of thermal pulses
- So the combination (depth of dredge-up and mass loss rate) determine the role that AGB stars play in the evolution and origin of elements in the Universe!!

Third dredge-up

- Badly named, can re-occur after each thermal pulse
- Inward movement of convective envelope, reaches into the He-shell
- Right-hand panel shows the evolution of the core in a low-mass AGB model
- Six (third)-dredge-up events are visible. Each one will mix He-shell material to the surface

Typical Galactic C-rich AGB star: 1.8Msun, Z = 0.01



Non-energetic reactions

- He-burning occurs in the *ashes* of H-burning
- The composition is typically 98% ^{4}He, ~2% ^{14}N
- Remember that the CNO cycle produces mostly ^{14}N, which can capture alpha particles to produce secondary nuclei, depending on T:
  - $^{14}N(\alpha, \gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha, \gamma)\mathbf{^{22}Ne}$
  - $\mathbf{^{22}Ne} + \alpha \rightarrow \mathbf{^{25,26}Mg}$ (+n or γ) when T > 300 million K
- These reactions produce little energy but are important for nucleosynthesis
- Example, the $^{22}Ne(\alpha,n)^{25}Mg$ ($Q = -0.478$MeV) reaction releases *free* neutrons that can be used to produce heavy elements i.e., $^{56}Fe(n,\gamma)^{57}Fe(n\ ,\gamma)$…

Fluorine production

- It's complicated! (e.g., Lugaro et al. 2004)
- The reaction chain: $^{18}O(p, \alpha)^{15}N(\alpha, \gamma)^{19}F(\alpha, p)^{22}Ne$
- Fluorine production takes place in the He-intershell: This is a region rich in ^{4}He, ^{12}C
- There are almost no protons or ^{15}N
- These are created by other reactions including:
  - $^{14}N(\alpha, \gamma)^{18}F(\beta^{+})^{18}O$ - main reaction to produce ^{18}O
  - $^{13}C(\alpha, n)^{16}O$ - produces free neutrons (also for the *s*-process)
  - $^{14}N(n, p)^{14}C$ - produces free protons
  - $^{18}F(\alpha, p)^{21}Ne$ - new, alternative proton production
  - $^{14}C(\alpha, \gamma)^{18}O$ - alternative reaction
  - $^{18}O(\alpha, \gamma)^{22}Ne$ - main ^{18}O destruction reaction
  - $^{15}N(p, \alpha)^{12}C$ - destroys ^{15}N

Helium burning: summary

From a nucleosynthesis point of view:

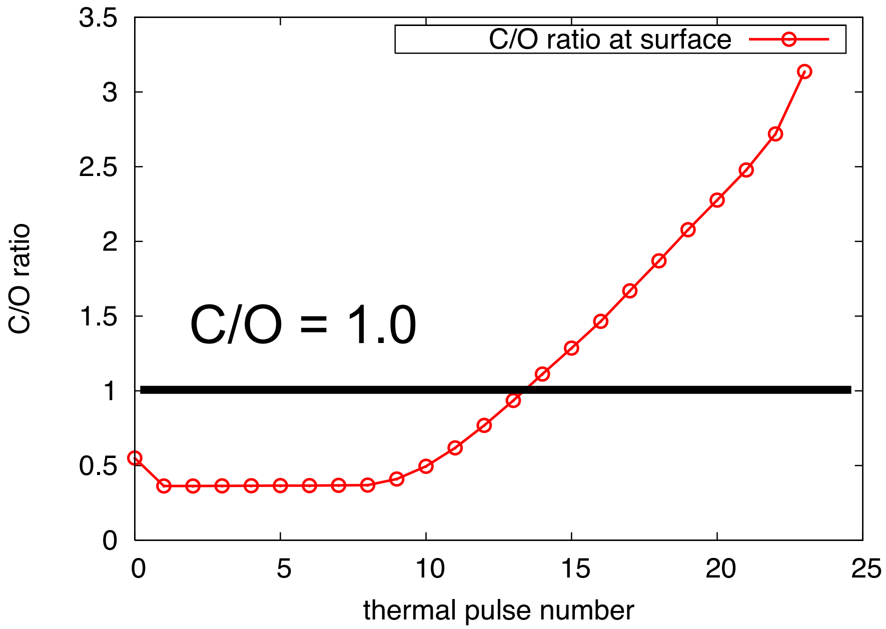
- The triple alpha and $^{12}C(\alpha, \gamma)^{16}O$ reactions convert ^{4}He into ^{12}C and ^{16}O
- Secondary reactions can produce ^{18}O, ^{19}F, ^{22}Ne, ^{25}Mg, ^{26}Mg
- Final composition depends on temperatures, densities, and the duration of burning
- Secondary reactions can produce free neutrons (e.g., $^{13}C(a,n)^{16}O$, $^{22}Ne(a,n)^{25}Mg$) which drives the s-process

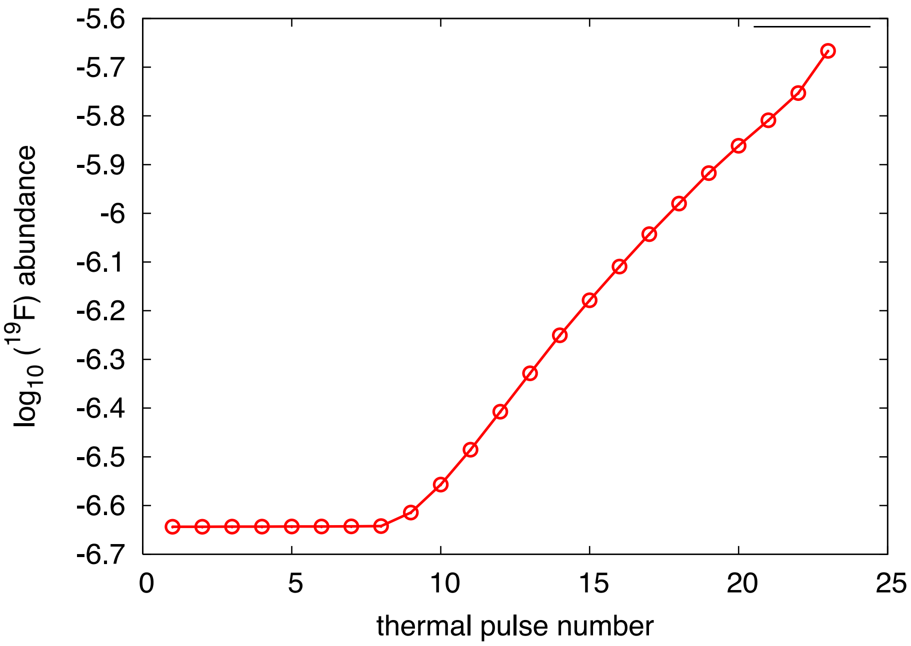
Products of He-shell nucleosynthesis

3Msun, Z = 0.014:

Surface abundance of carbon (left) and fluorine (right) during the AGB

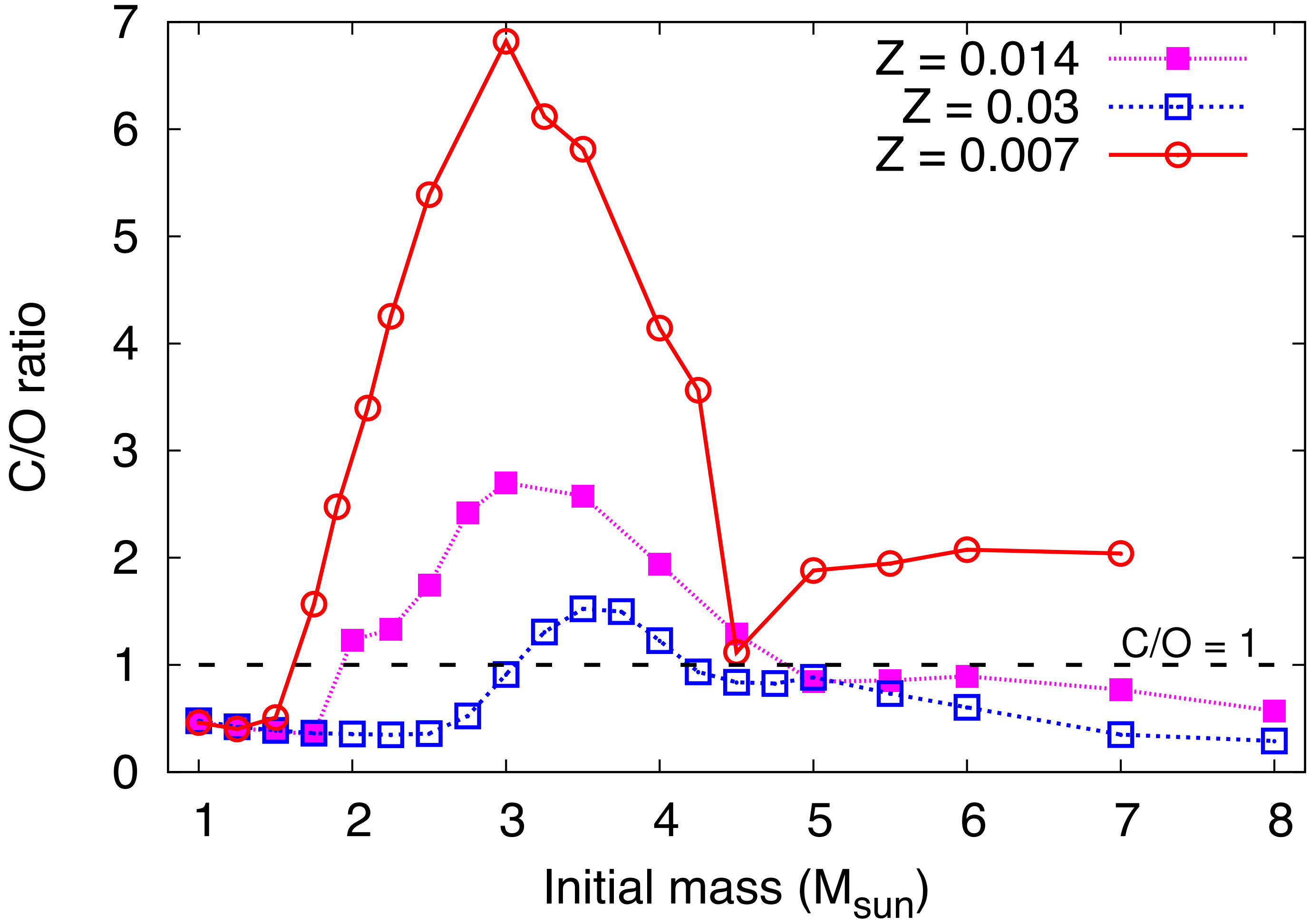
→ We can make a carbon-rich star, which has C/O > 1





Mass range of carbon stars?

- From Karakas (2014) for [Fe/H] = -0.3, 0.0, +0.3



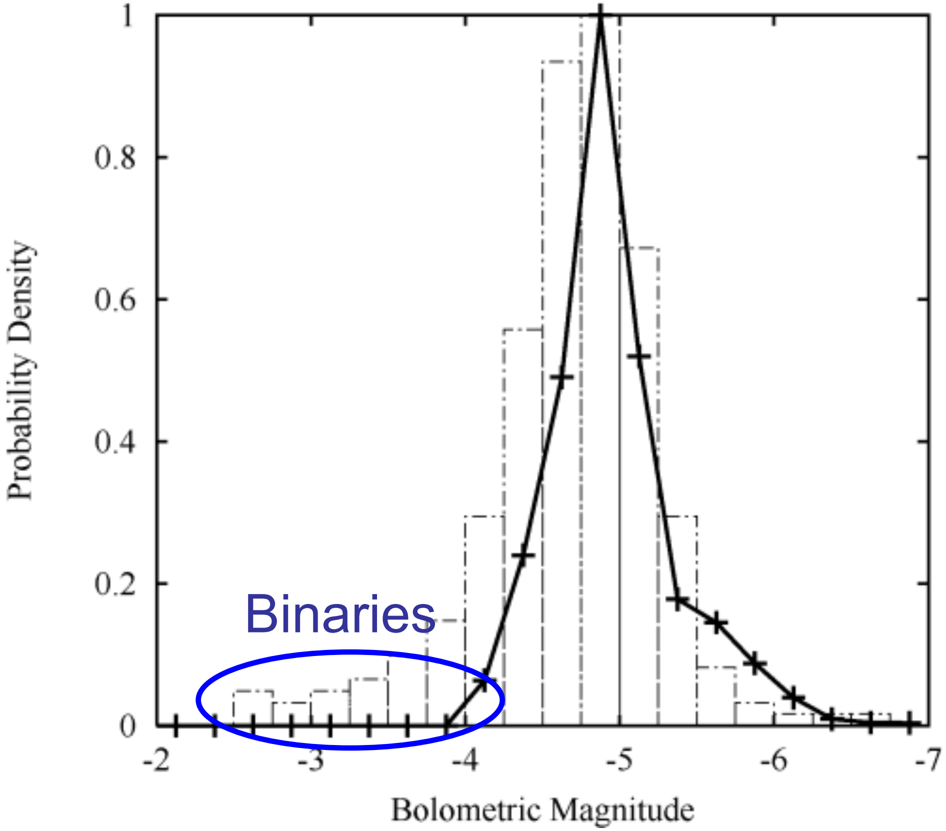
Third dredge-up uncertainties

- It is important to know if the models are providing an accurate description of mixing in real AGB stars
- Because the third dredge-up determines how much He-shell material is mixed from the core to envelope
- Do current models predict enough TDU?
- Or too much?

→ Do the model predict the right mass and luminosity ranges for carbon stars?

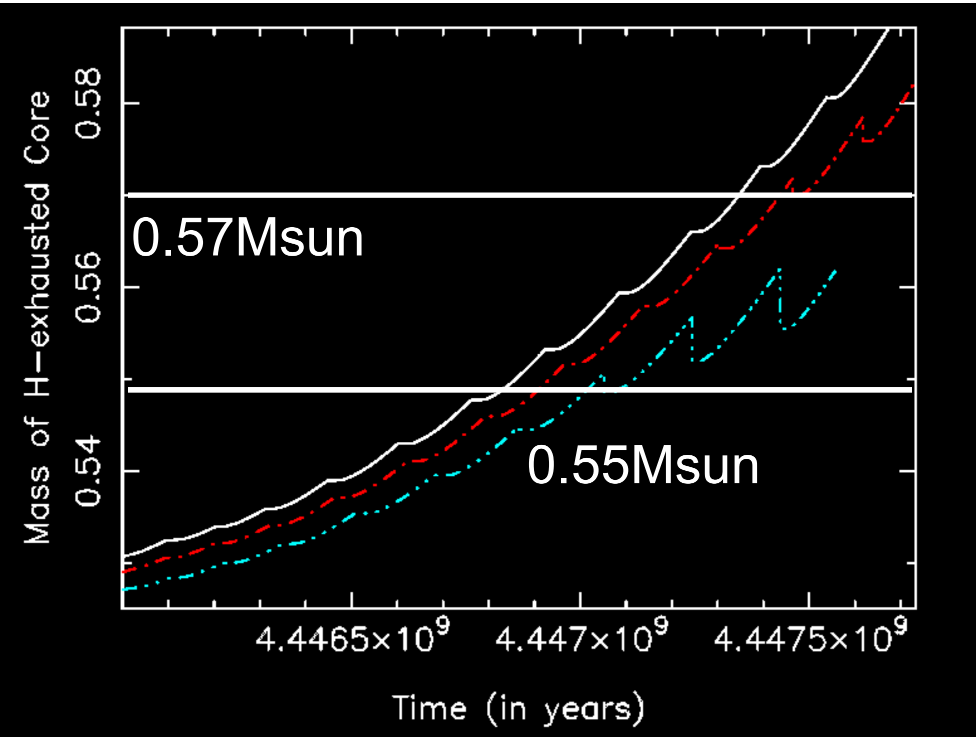
Carbon star luminosity functions

- Distances to the Magellanic Clouds are known
- Can derive accurate C-star luminosity functions
- These indicate that (most) stellar models do not predict enough dredge-up at low enough masses
- And it is deeper at these lowest masses than current models predict
- Can "force" the TDU in low-mass models…



Stancliffe, Izzard, & Tout (2005)

Uncertainties: The amount of third dredge up



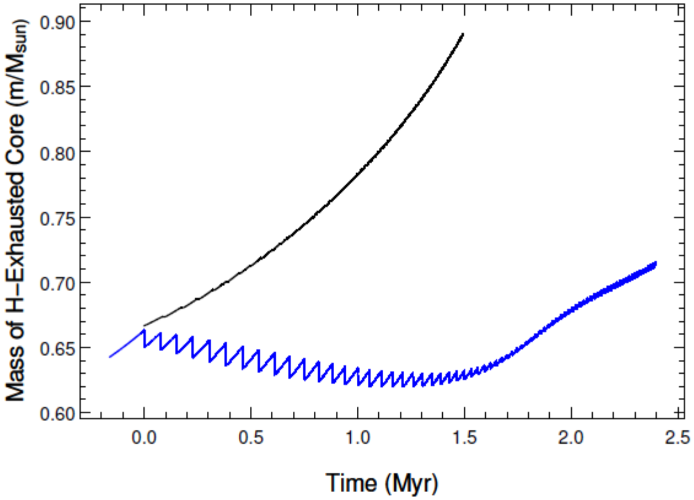


Figure 4.17: Highlighting the strong effect of including overshoot on the AGB. The time evolution of the mass of the H-exhausted core is plotted. Both stars, having a mass of 2 $M_\odot$ and a metallicity of [Fe/H]=-5.45, started with the same initial conditions except for the inclusion of overshoot in one (lower curve, $f_{OS} = 0.01$). An enormous difference in core mass evolution is clearly seen. The model with no overshoot (upper curve) has virtually no 3dup whilst the model with overshoot initially has $\lambda_{3dup} > 1$. As the core mass is the primary factor in AGB evolution, the vastly different core masses represent a very large uncertainty in AGB evolution.

1.25Msun, Z = 0.01:

Forcing dredge-up by extending the base of the envelope by N scale-heights
e.g., Karakas et al. (2010); Frost & Lattanzio (1996)

2Msun, [Fe/H]= -5.45:

Diffusive mixing + Herwig's scheme for extending the envelope using exponentially decaying overshoot
From Simon Campbell

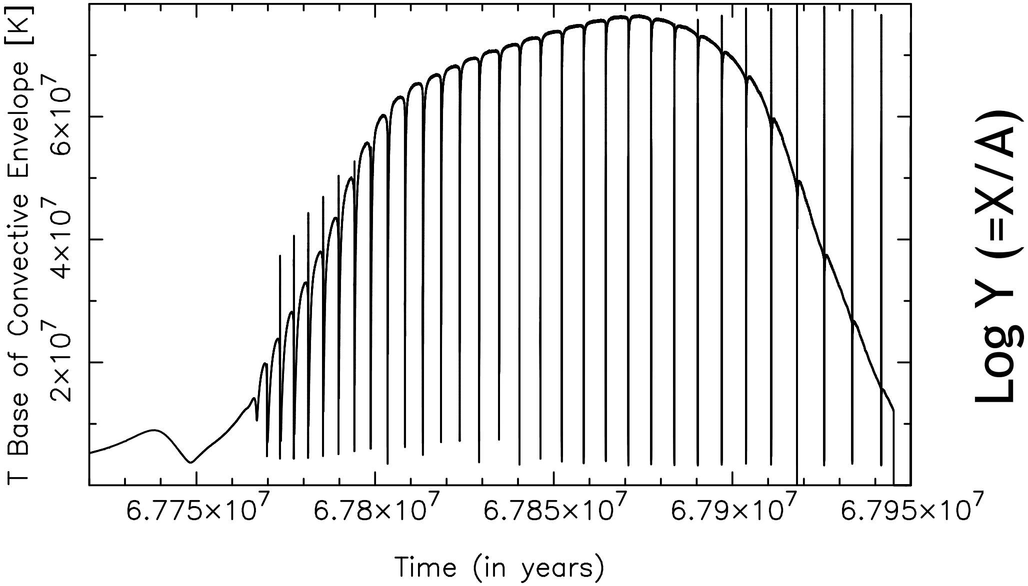
Hot bottom burning

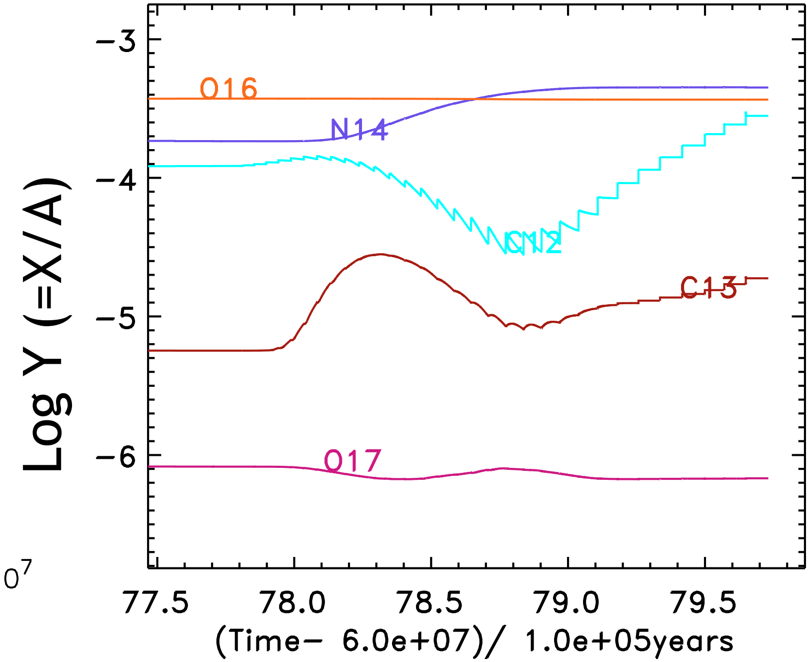
Occurs in stars over about 4.5Msun for Z = 0.014

Along with thermal pulses and the third dredge-up, these stars also have:

- Second dredge-up: Biggest ΔY (up to 0.1)
- Hot bottom burning: Proton-capture nucleosynthesis at base of envelope (products: N, Na, Al)

Example: 6Msun, Z = 0.02



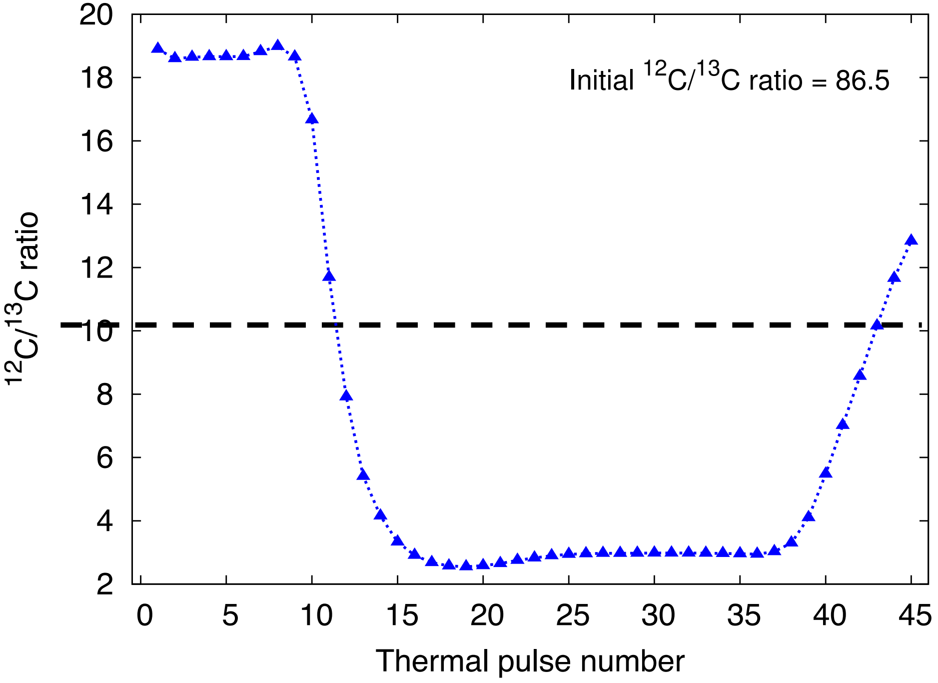


Hot bottom burning and third dredge up

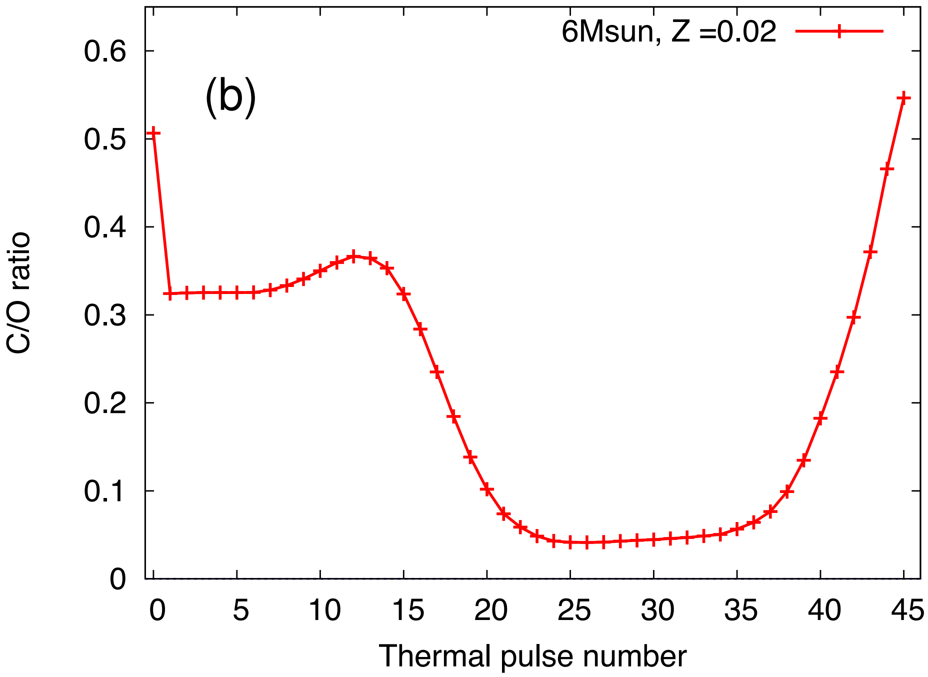
Example: 6Msun, Z = 0.02

Third dredge-up (TDU) and HBB act together

CN cycle is acting close to equilibrium for ~20 thermal pulses



$^{12}C/^{13}C$ ~ 3 is the equilibrium ratio

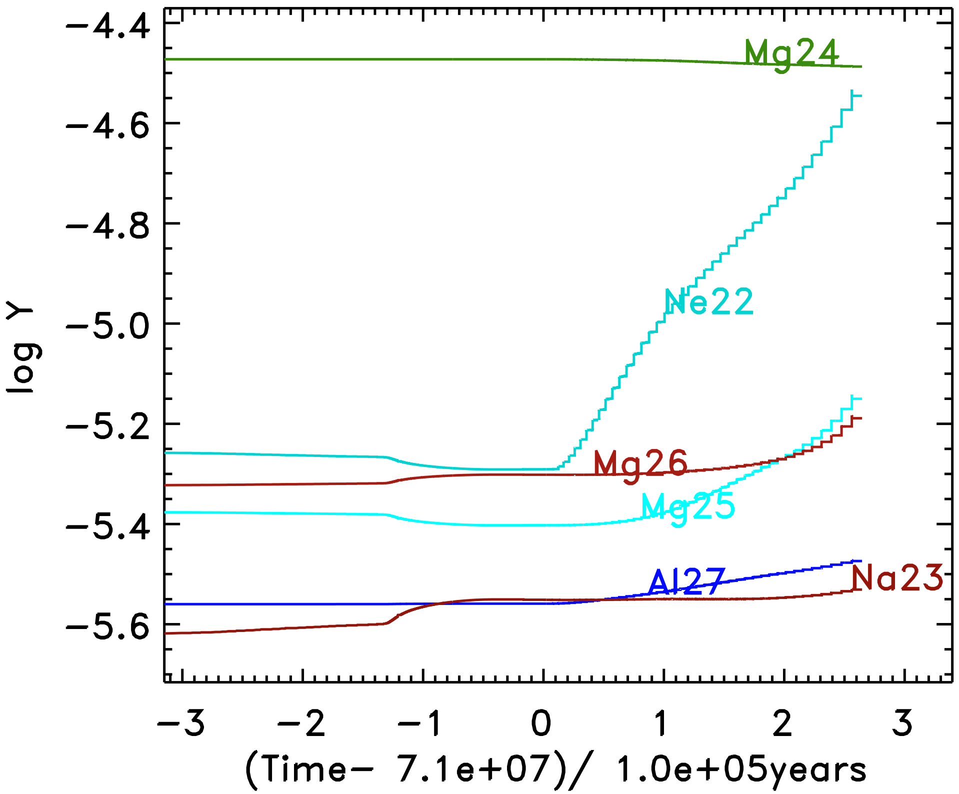


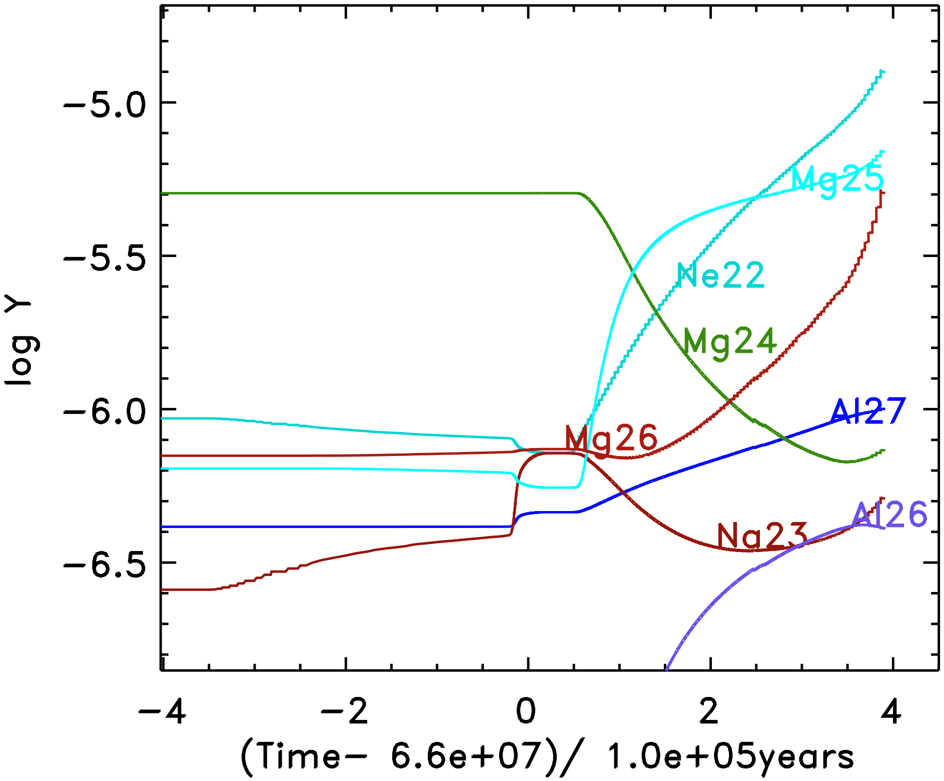
The C/O ratio never exceeds 1

Hot bottom burning and third dredge up

Looking at the surface abundances of Ne to Al as a function of metallicity:

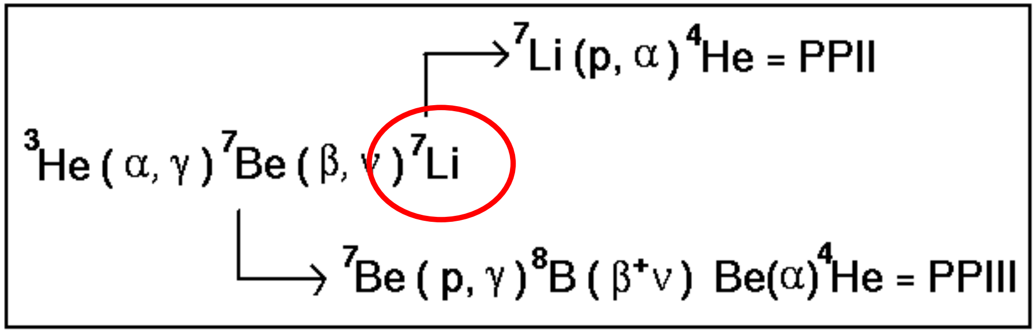
- 6Msun, Z = 0.02 has a peak temperature of ~80 million K
- 6Msun, Z = 0.004 has a peak of ~95 million K





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 $^{3}\mathrm{He}(\alpha, \gamma)^{7}\mathrm{Be}$
- and then to use convection to move the ^{7}Be away from the hot region before it can complete the ppII or ppIII chains:



$\rightarrow {}^{7}\mathrm{Li}\,(p, \alpha)\,{}^{4}\mathrm{He}$ = PPII

BAD!

${}^{3}\mathrm{He}\,(\alpha, \gamma)\,{}^{7}\mathrm{Be}\,(\beta, \nu)\,{}^{7}\mathrm{Li}$

$\rightarrow {}^{7}\mathrm{Be}\,(p, \gamma)\,{}^{8}\mathrm{B}\,(\beta^{+}\nu)\ \mathrm{Be}(\alpha)\,{}^{4}\mathrm{He}$ = PPIII

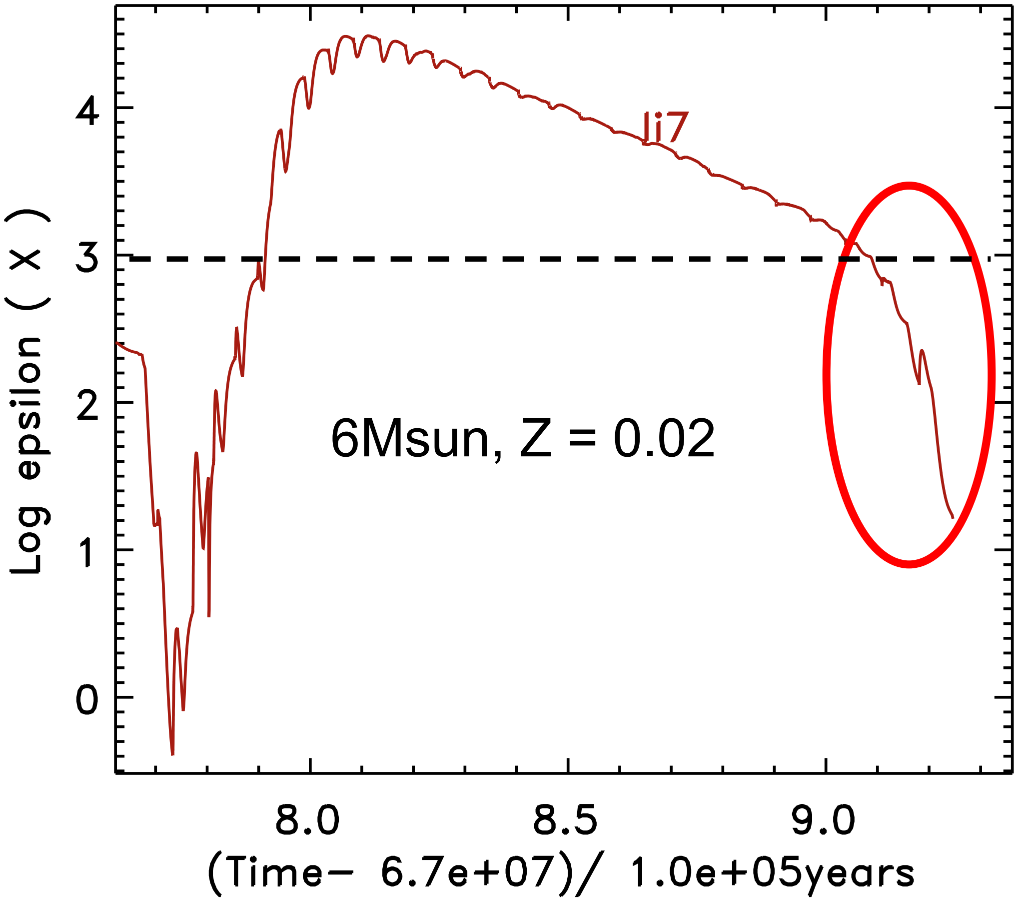
BAD!

Cameron-Fowler mechanism

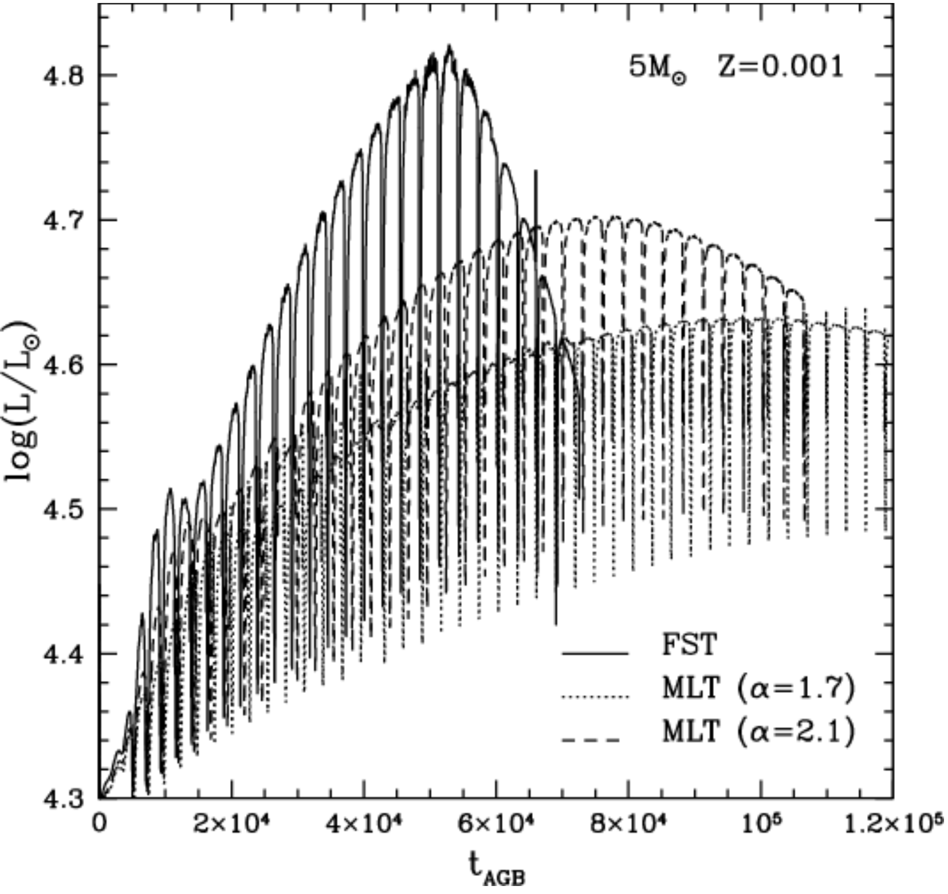
Lithium production

Lithium is produced by the Cameron-Fowler mechanism: ^{7}Be is transported by convection, where it captures an electron to produce ^{7}Li

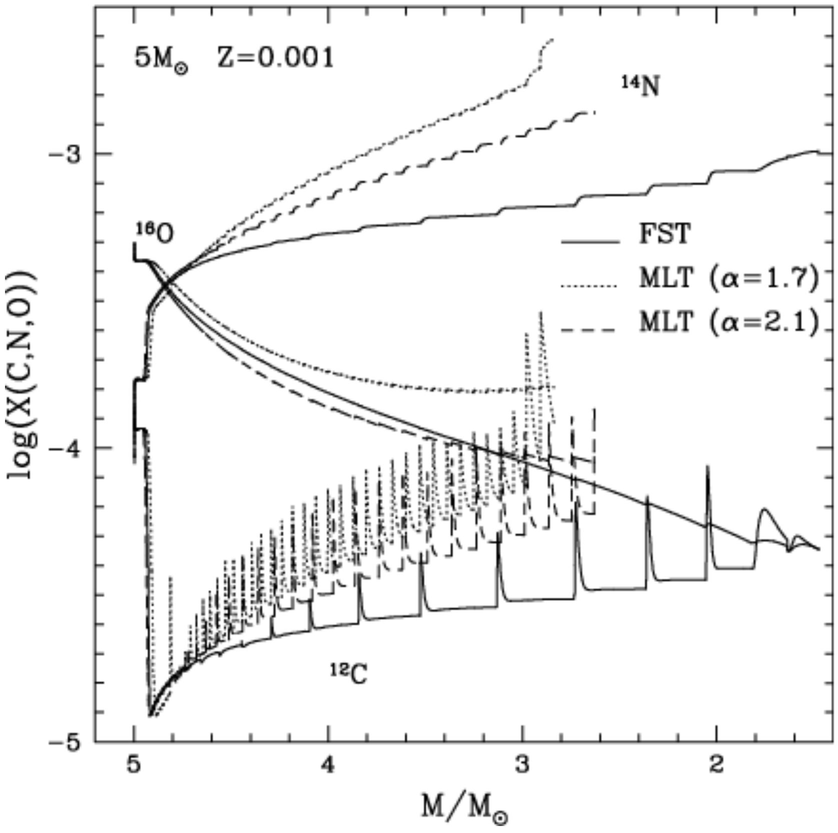
Log $\varepsilon(\mathrm{Li})_{max} = \log_{10}(\mathrm{Li/H})+12 = 4.5$



Uncertainties caused by convection



Surface luminosity as a function of time for three convective prescriptions



Surface CNO abundances as a function of total mass

From Ventura & D’Antona (2005)

Other mixing phenomena

- What is the impact of non-convective extra mixing processes on AGB evolution and nucleosynthesis?
- Examples include: rotation, thermohaline or double diffusive mixing, mixing induced by internal gravity waves, magnetic fields…
- Effect on the stellar yields?

I won’t have time to discuss these here

Reading: Karakas & Lattanzio (2014, PASA review, arXiv:1405.0062)

Summary of nucleosynthesis

- **C/O > 1**: ~1.5 to 4.5M_{sun} for Z = 0.014 (solar)
  - Inward movement of convection mixes the products of He-shell nucleosynthesis to the envelope (^{12}C,^{19}F, *s*-process)
- **C/O < 1**: Above ~4.5M_{sun} for Z = 0.014
  - Hydrogen burning reactions at base of convective envelope (e.g., ^{7}Li, ^{13}C, ^{14}N, ^{23}Na, $^{26,27}Al$, s-process?)

References: (focused on nucleosynthesis results)

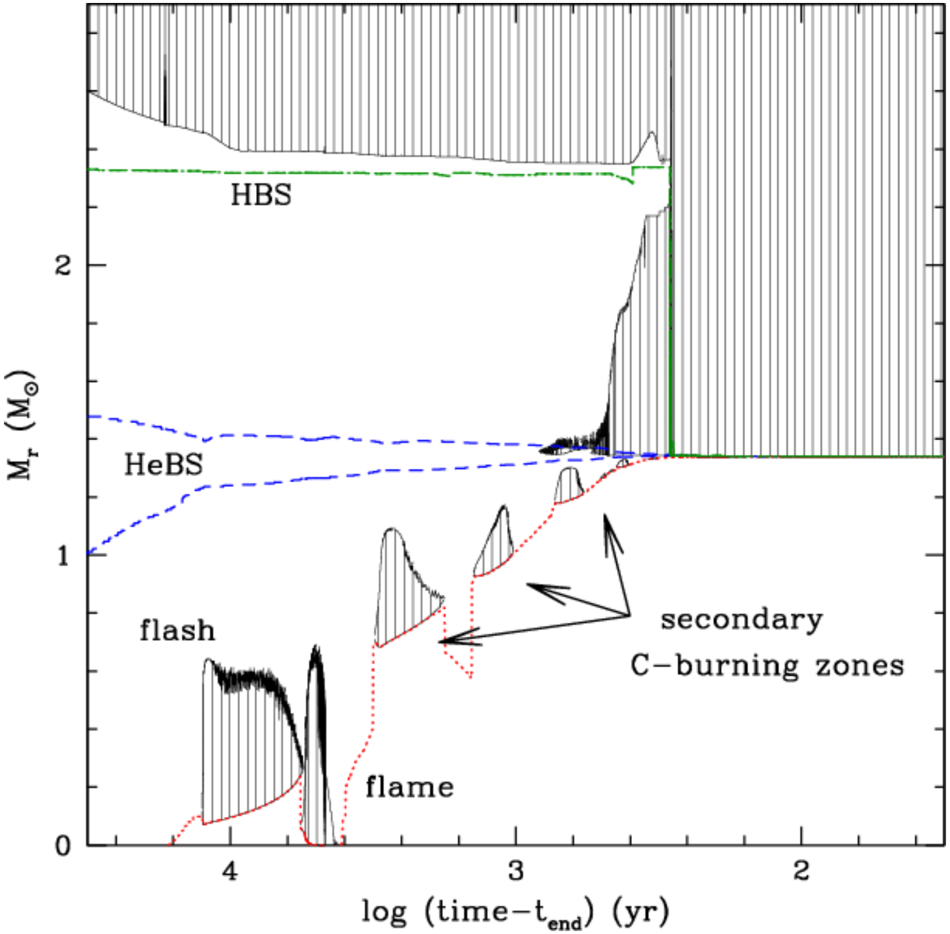
Busso, Gallino & Wasserburg (1999), Forestini & Charbonnel (1997), Straniero et al. (1997), Mowlavi (1999), Herwig (2000, 2005), Stancliffe & Jeffery (2007), Campbell & Lattanzio (2008), Suda & Fujimoto (2010), Cristallo et al. (2011, 2015), Wiess & Ferguson (2009), Marigo et al. (2013), Ventura et al. (2013), Cruz et al. (2013)

Super-AGB stars: 8-10 Msun stars

- The first models of stars in the range 8 to 10Msun were by Nomoto (1984), Garcia-Berro & Iben (1994), Ritossa et al. (1996), and Gutierrez et al. (1996)
- The paper by Garcia-Berro & Iben (1994) gave the name “super-AGB” for stars that ignite carbon and then experience thermal pulses
- These calculations are difficult, and no one really worked on them for a long time after, until Gil-Pons et al. (2001, 2002) and then Siess (2006)

Off-centre carbon ignition

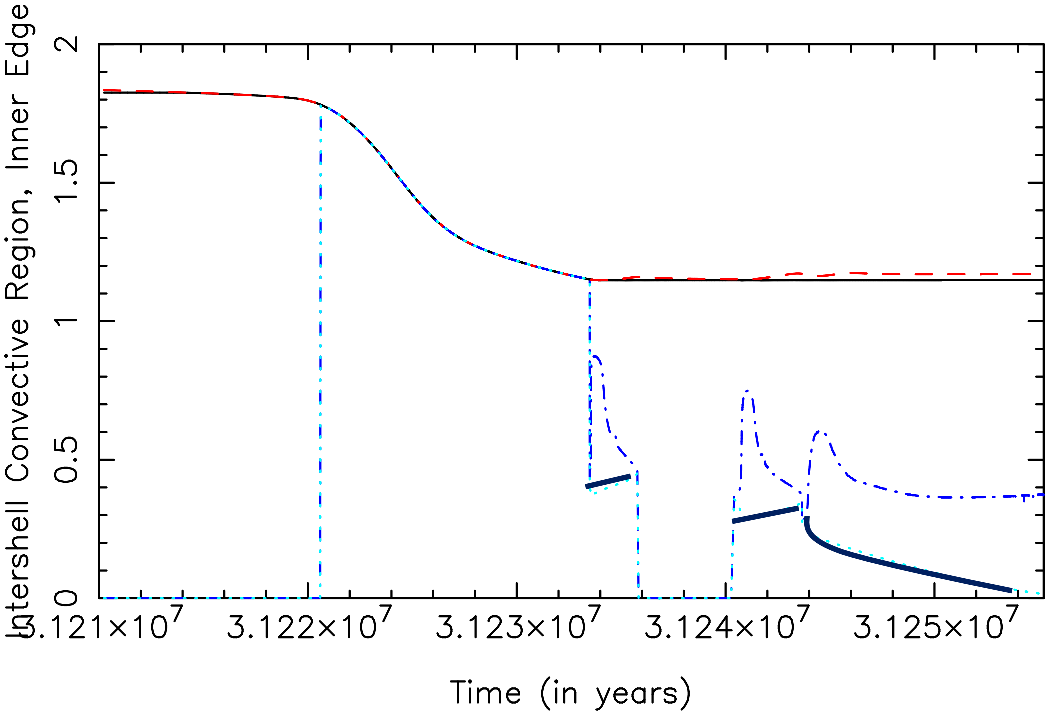
- Stars between ~8 to 10Msun go through degenerate carbon ignition
- Before ascending the thermally-pulsing AGB with O-Ne cores
- Q: What fraction explode as supernovae or leave massive white dwarfs?
- E.g., Poelarends et al. (2008), Gil-Pons et al. (2013), Jones et al. (2014)
- The brightest AGB stars in young populations, with Mbol ~ −7.6, brighter than the traditional AGB limit (Mbol ~ −7.1)



7.5Msun, Z= 10^{-4} model by Siess (2007)

Carbon ignition: 9Msun, Z = 0.02

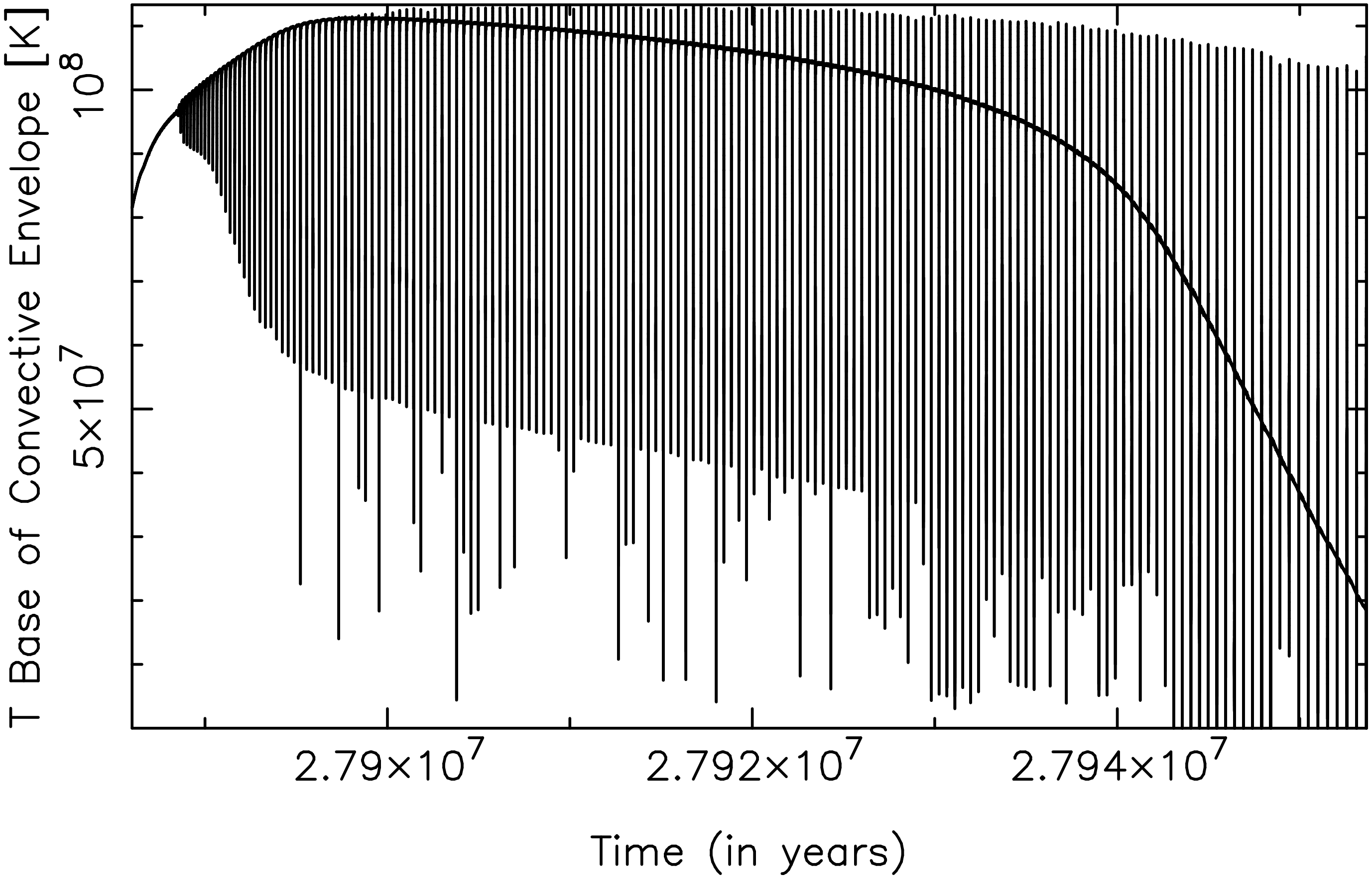
- Maximum temperature peaks at ~950 x 10^6 K.
- Duration of carbon flashes and central burning ~30,000 years (model from Karakas et al. 2012)
- Carbon burning occurs during early AGB, while second dredge-up is occurring (e..g., Gil-Pons et al. 2005, Siess 2006)
- Dredge-up is deep, can eat into the He-burning shell



Super-AGB stars

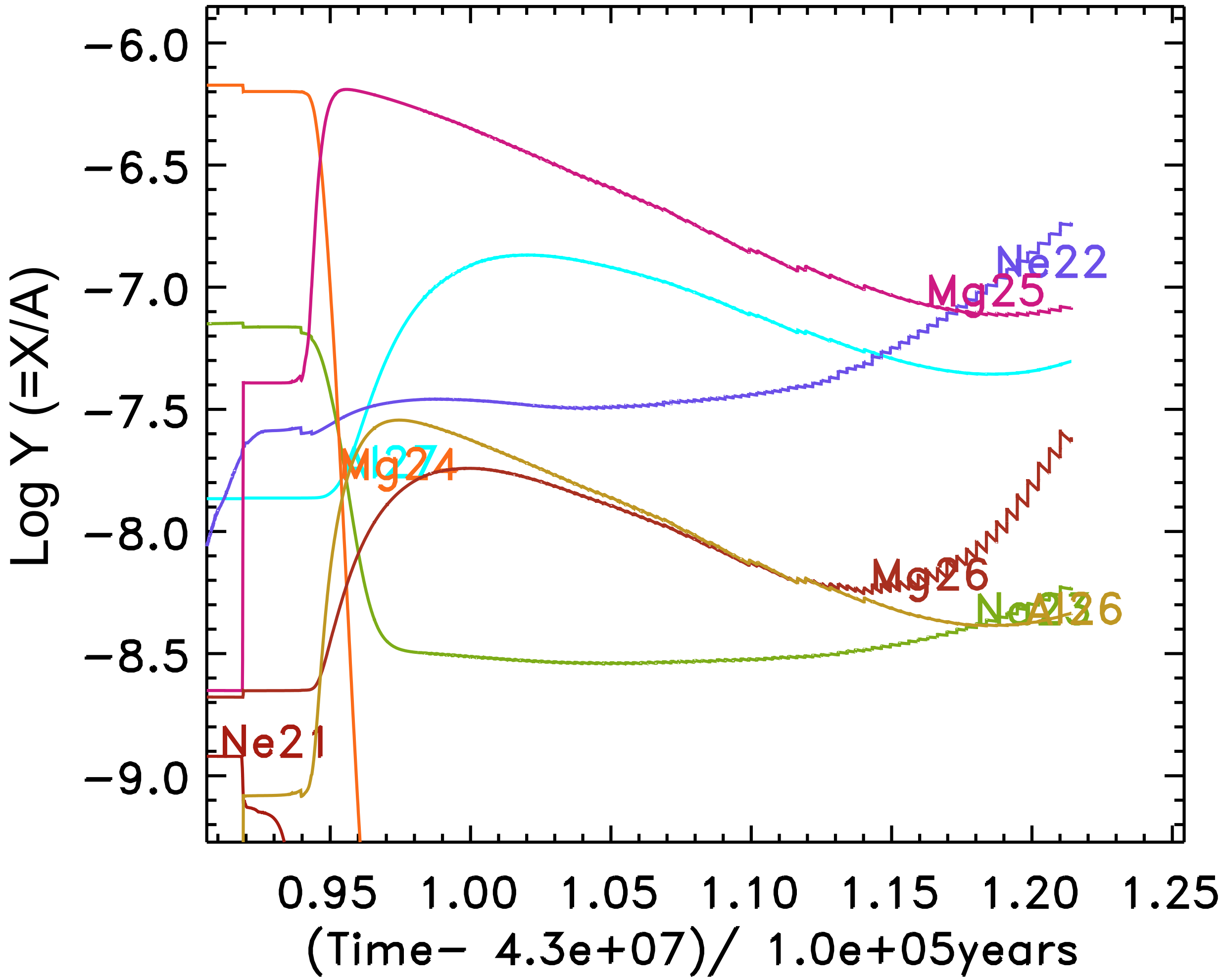
A 9Msun, Z = 0.02 model has a core mass of ~1.18Msun. Too low to become an electron capture supernovae (from Karakas et al. 2012)

It will produce an O-Ne white dwarf



Nucleosynthesis in super-AGB stars

7M$_{sun}$, Z = 0.002 (1/100th solar). Peak temperature ~ 140 x 10^6 K.
This is about as extreme as it gets in an AGB star!



Recent models:
Siess (2010)
Pumo et al. (2008),
Doherty et al. (2010)
Karakas et al. (2012)
Herwig et al. (2012)
Ventura et al. (2012)
Gil-Pons et at. (2013)
Takahashi et al. (2013)
Doherty et al. (2014a,b)
Fishlock et al. (2014)
Doherty et al. (2015)
Shingles et al. (2015)
Woolsey & Heger (2016)
Jones et al. (2016)

Final fate of Super-AGB stars?

The final fate of super-AGB stars is uncertain

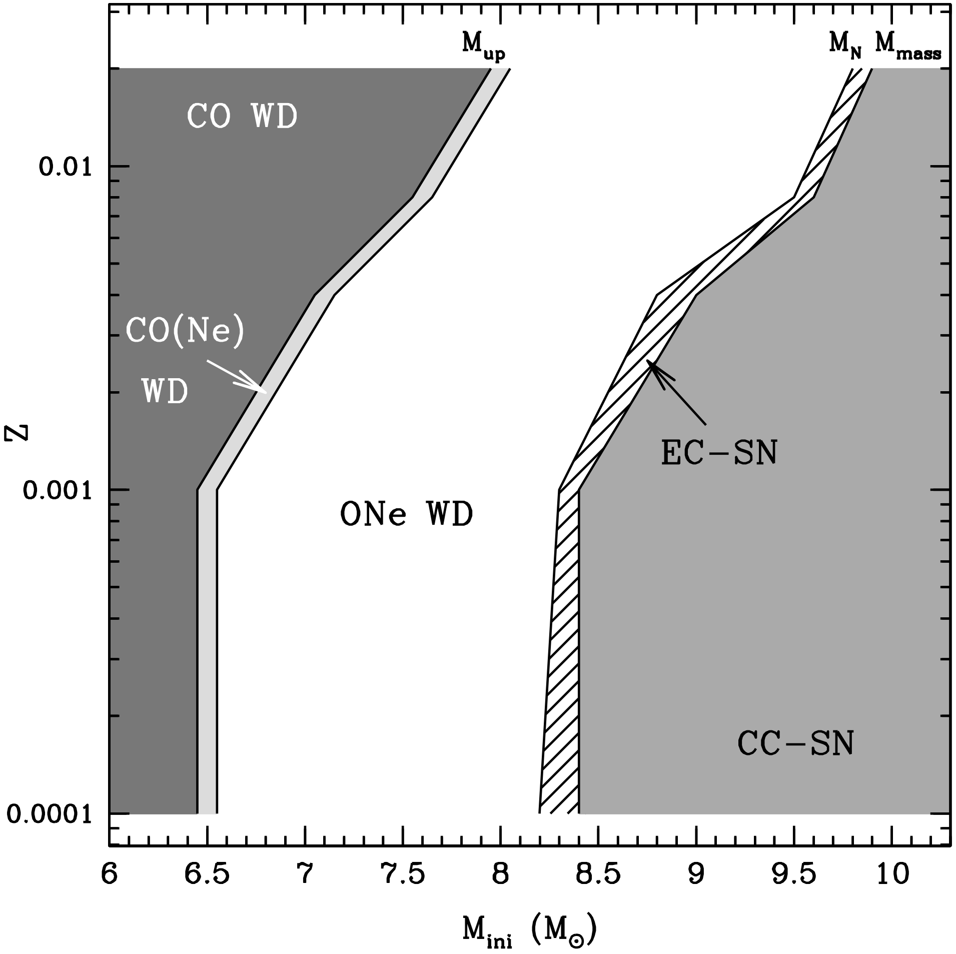
→ Will they mostly produce massive ONe white dwarfs

→ What fraction will explode as electron capture supernova?

→ What are their nucleosynthesis products? H burning? He-shell burning? The rapid neutron capture process?

→ What happens when they are in a binary system? Will more explode?

→ How do they affect the enrichment of the galaxy?



Lots of questions! Very exciting stuff

From Doherty et al. (2015)

Globular cluster abundances

In a typical cluster:

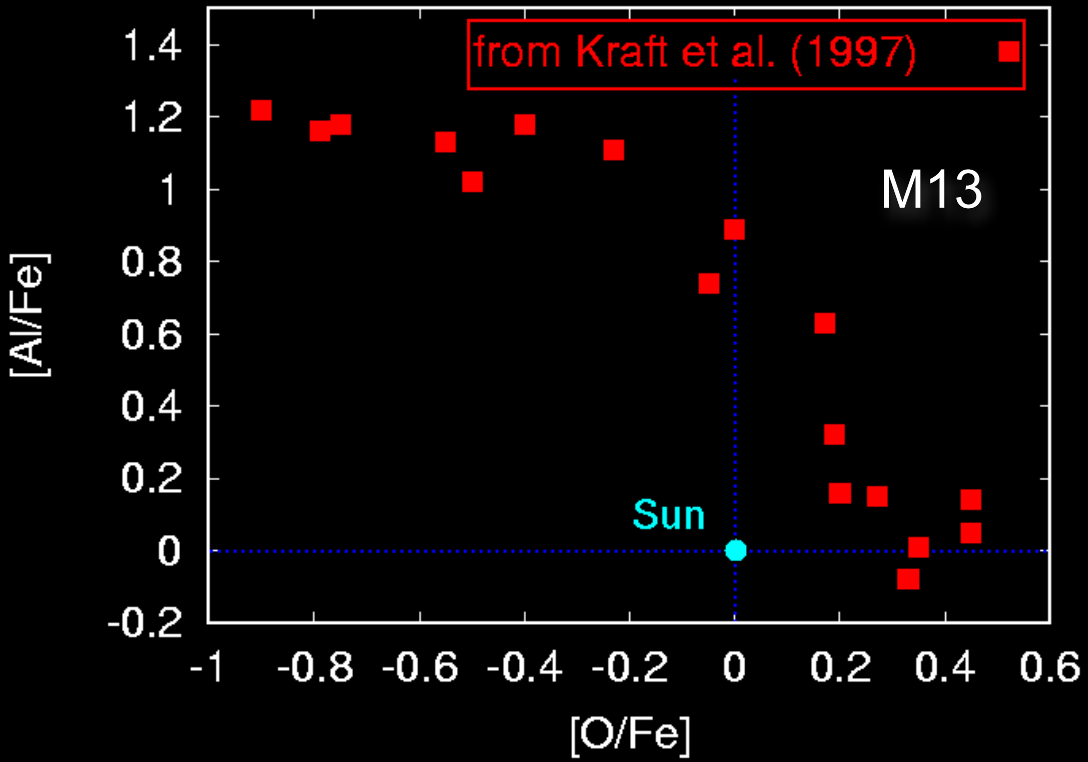
- The abundances of C-N, O-Na and Mg-Al are anti-correlated (Gratton et al. 2009, 2012)
- Sum C+N+O ~ constant (within a factor of ~2)
- No variation of alpha, s or r-process elements from star-to-star *within* a cluster…
- Does this imply the composition has been exposed to hydrogen burning (CNO, NeNa, MgAl)
- For an alternative hypothesis see Bastian et al. (2015)

In an atypical cluster: ~10%

- NGC 1851, ω Cen, M22, NGC 2419
- Show variations in C+N+O, s-process, r-process (rare) and iron-peak elements (e.g, Marino et al. 2012)

The O-Na anti-correlation

- Why is there a correlation between O and Na in some globular cluster stars?
- Seen in all globular clusters (e.g., Carretta et al. 2009)
- Now we think it is probably pollution when the stars we see now formed → But from what?



Field stars versus GC stars

- Evolved fields stars of the same metallicity as globular cluster stars show correlations between C and N
- This is caused by CN processed material being mixed into the envelope by the first dredge-up and extra mixing
- But field stars do not show correlations between O, Na (e.g., Gratton et al. 2000)
- But we also see C-N variations on the MS in GCs (e.g., figure from Cannon et al. 1998; also Briley et al. 2004)

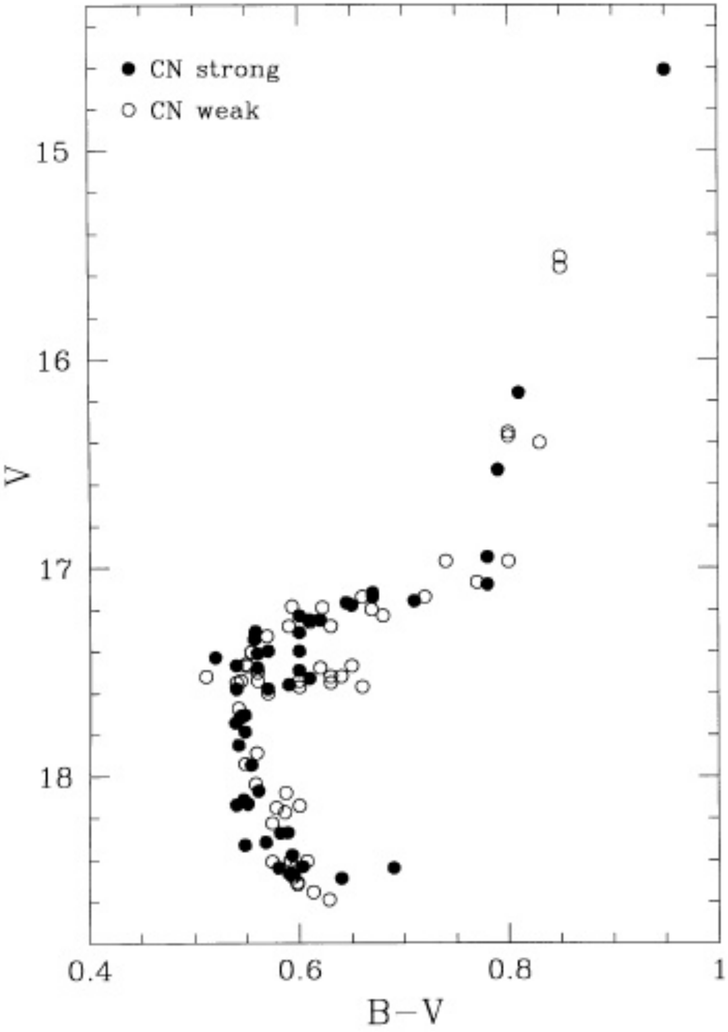


Figure 6. The 47 Tuc colour–magnitude diagram, using the same data as Fig. 2 but with the symbols of Fig. 4 to distinguish between the CN-strong and CN-weak stars.

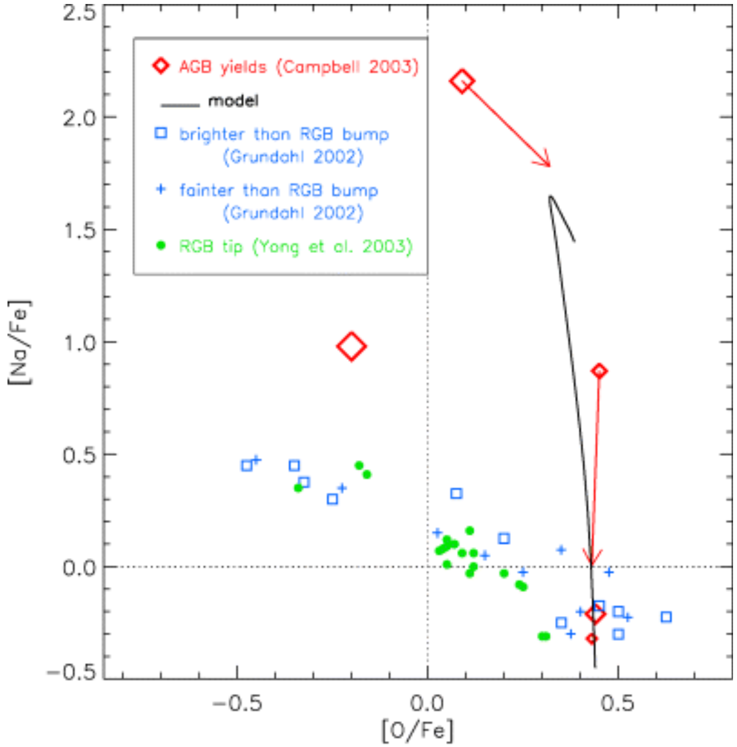
Pollution by what type of stars?

1. Deep mixing - can explain the Li, C-N trends with luminosity in some GCs (e.g., Lind et al. 2009)
2. Self-pollution by AGB stars experiencing hot bottom burning (e.g., Ventura et al. 2009)
3. Self-pollution by slow winds from rapidly rotating massive stars (Decressin et al. 2007)
4. Binary massive stars (De Mink et al. 2009)
5. Very massive stars (~10,000Msun; Denissenkov & Hartwick 2014)

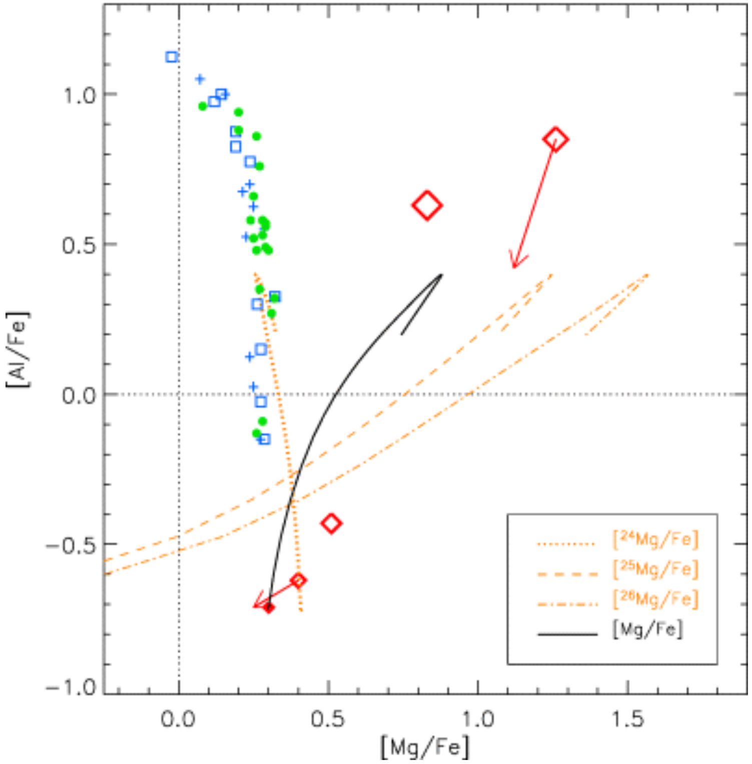
AGB stars have been favoured because their slow winds can be retained by the cluster, and they produce no metals

GC chemical evolution

O-Na abundances:



Mg-Al abundances:



- AGB models with third dredge-up cannot match helium enrichments along with O-Na, Mg-Al composition of GCs (e.g., NGC 6752 shown above; Fenner et al. 2004, Karakas et al. 2006)
- But see recent chemical evolution models from D'Ercole et al. (2010, 2016) using AGB models from Ventura et al. (2013)