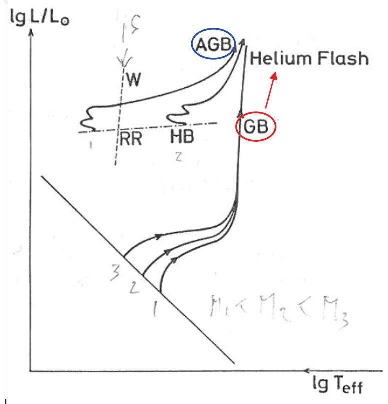
Evolution on the asymptotic giant branch (AGB)

Evolution towards AGB



HB crosses IS → RR Lyrae variables (HB-pulsating stars), post-HB evolution also crosses IS → type II Cepheids (BL Herculis, previously called pulsating W Virginis stars).

After core-He-burning has ended the H-shell continues burning *outwards* until *T*↓ → stops burning→ **E-AGB** (early AGB). For *M* > 4M$_\odot$ surface convection zone (envelope expansion) reaches layers of extinguished H-burning shell, thereby bringing H-burning ashes to surface – 2nd dredge up.

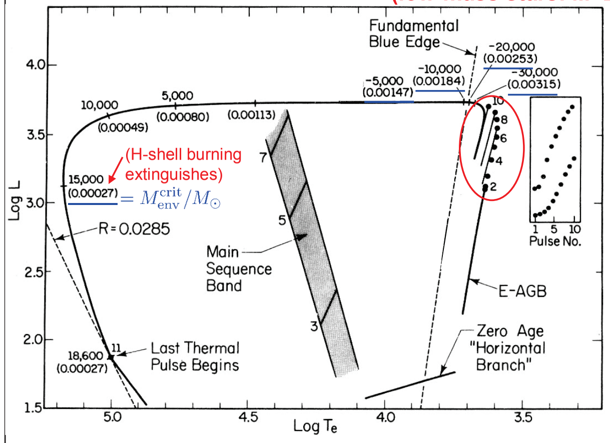
He-shell burning layer still grows in mass approaching H-rich envelope → H-burning re-ignited→ again two shell source, but shell burning becomes secularly unstable→**thermal runaway**.

↓ (geometrical effect!)

cyclic phenomenon – **thermal pulses** (Π~10^5 y)

Evolution on the asymptotic giant branch (AGB)

(low-mass stars: *M*<2.3 M$_\odot$)



Iben (1985; Ql. J. R. astr. Soc. 26, 1)
[evolution of a 2M$_\odot$ star, losing ~ 1.2M$_\odot$ after AGB phase via ordinary wind & PN]

(thermal) pulses (**T-AGB**) are more or less an envelope phenomenon with *no influence on core.*

inner part of C-O core resembles more and more a *white dwarf.*

H-rich envelope, small in *M* but thick in *R,* gives appearance of a red giant.

However, during thermal pulses envelope **loses mass** from surface, which is ejected into space; additional **mass loss** due to H-burning @ bottom.

Envelope shrinks and within ~ 10^4 y star moves to the left (**post-AGB**).

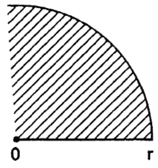
An originally 2M$_\odot$ star develops a C-O core of ~ 0.6M$_\odot$; Planetary Nebula (PN) ejection (superwind) occurs at ~ the 10th pulse. When $T_{\rm surf}$ of star reaches ~ 30 000K (@t=0), photons emitted from surface are 'hard' enough to ionize surrounding nebular shell. The star is then called a Planetary Nebular Nucleus (PNN).

H-shell burning extinguishes ($M_{\rm env}$ drops below 0.00027$M_\odot$) and the star becomes a white dwarfs (WD).

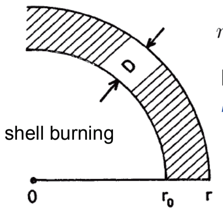
Evolution on the asymptotic giant branch (AGB)

Shell sources and their stability

Evolved stars can have several shell sources (H, He, …), which burn farther out, towards the surface, with time. While burning outwards, the shell sources have the tendency to concentrate the reactions over steadily decreasing mass ranges. The thickness *D* of the shell source starts playing a role in both computational issues (time step) and (shell source) stability. Procedure for stability consideration is similar to central nuclear burning but with 2 differences: (a) the geometry (thickness *D*) and (b) the density reaction $\mathrm{d}\rho/\rho$ to an expansion $\mathrm{d}r/r > 0$.



central burning



shell burning

$$r = r_0 + D \qquad m \sim \varrho r_0^2 D \qquad ; \; D/r_0 \ll 1$$

burning region expands with roughly r_0=constant: $\;\mathrm{d}r = \mathrm{d}D \qquad \mathrm{d}m = 0$

$$\frac{\mathrm{d}\varrho}{\varrho} = -\frac{\mathrm{d}D}{D} = -\frac{\boxed{r}}{\boxed{D}}\frac{\mathrm{d}r}{r}.$$

expansion $\mathrm{d}r/r > 0$ requires density change of

$$m \propto \rho r^3 \underset{\mathrm{d}m = 0}{\rightarrow} \frac{\mathrm{d}\rho}{\rho} = -\boxed{3}\frac{\mathrm{d}r}{r}$$

assume mass outside r_0+*D* expands homologously ($\dot{r}/r$ =const.):

from perturbed energy equation ↗ $\overset{T_0 + \mathrm{d}T}{c^*\frac{\mathrm{d}T}{dt}} = d\varepsilon \; ; \quad \overset{\text{gravothermal heat capacity}}{c^*} = c_P\left(1 - \nabla_{\rm ad}\frac{4\delta}{4\alpha - \boxed{r/D}}\right).$

if *c** > 0 shell source unstable, because any ε > 0 leads to an increase of *T* and further increased burning.

Evolution on the asymptotic giant branch (AGB)

Shell sources and their stability

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$$\frac{\mathrm{d}\varrho}{\varrho} = -\frac{\mathrm{d}D}{D} = -\frac{r}{D}\frac{\mathrm{d}r}{r}. \qquad c^*\frac{dT}{dt} = d\varepsilon \; ; \quad c^* = c_P\left(1 - \nabla_{\rm ad}\frac{4\delta}{4\alpha - r/D}\right).$$

We recover flash instability for strong degeneracy, i.e with δ →0, *c** > 0 .

New instability even for an ideal monoatomic gas with α=1, δ=1,∇$_{\rm ad}$ = 2/5, which depends only on thickness *D*:

$$\boxed{\text{if } D/r < 1/4 \rightarrow c^* > 0 \rightarrow \text{shell source is secularly unstable}}$$

↓

pulse instability

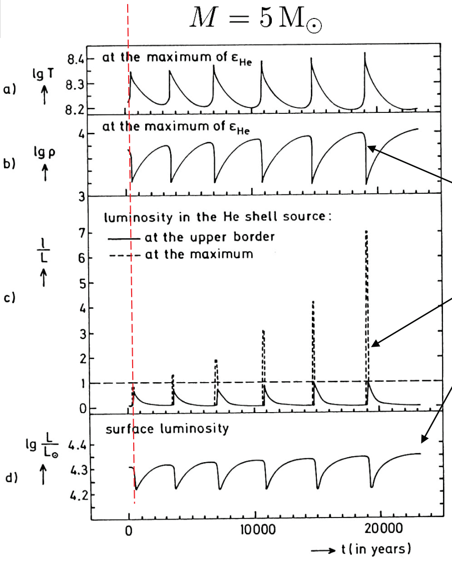
because of *D/r* <<1 any substantial increase d*D/D* >0 results in a relative density decrease dρ/ρ <0 of same absolute value, but only a very small relative increase d*r/r,* i.e. layers above are scarcely lifted, so that their weight remains about constant, i.e. d*P/P* ≈ 0.

with $\frac{\mathrm{d}P}{P} = -4\frac{\mathrm{d}r}{r} = 4\frac{D}{r}\frac{\mathrm{d}\rho}{\rho} \simeq 0 \longrightarrow \frac{\mathrm{d}\rho}{\rho} = -\delta\frac{\mathrm{d}T}{T} \longrightarrow \rho \propto \frac{1}{T}$ expansion $\mathrm{d}\rho/\rho < 0$ leads to increase of *T* ($\mathrm{d}T/T > 0$).

$$\alpha = 0,\; \delta = 1, \rightarrow c^* > 0 \longrightarrow \text{pulse instability}$$

Evolution on the asymptotic giant branch (AGB)

Thermal pulses of a shell source [occur in stars (models) with one or more shell sources.]



For $5M_\odot$ instability occurs in He shell source after it has reached $m/M \approx 0.1597$. It then contributes little to surface L, which is almost completely supported by near-by H-shell source @ $m/M \approx 0.1603$.

Instability results in thermal runaway: shell source reacts to surplus energy with T↑, which enhances nuclear energy release even further. *T* increase connected with expansion $d\rho/\rho < 0$.

Note: in a flash ρ = const., because of degeneracy!

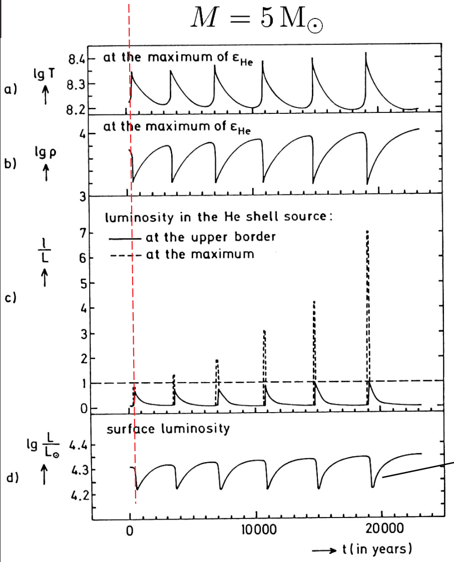
because $\varepsilon_{He} \sim T^{19} \rightarrow l$ increases (up to several L!) with most of energy used to expand outer layers (T↓ in H shell → L_H↓).

thermal runaway accelerates more until reaching a sharp peak within a few years → He-shell source is now *widely expanded* ($D/r > 1/4$) and therefore *no longer unstable.*

whole region starts to contract again, heating H-shell source & after few 10^3 y the He-shell source becomes unstable again → next pulse, etc.

Evolution on the asymptotic giant branch (AGB)

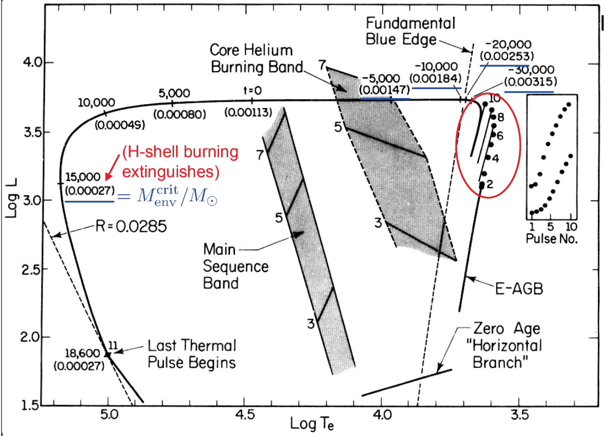
Thermal pulses of a shell source [occur in stars (models) with one or more shell sources.]



Period between consecutive pulses ~ 3200…4300 y.

Surface luminosity L drops in each pulse by about $\Delta \lg L \approx 0.1 \ldots 0.2$. Visible surface changes more pronounced if shell source is located close to surface.

Evolution on the asymptotic giant branch (AGB)



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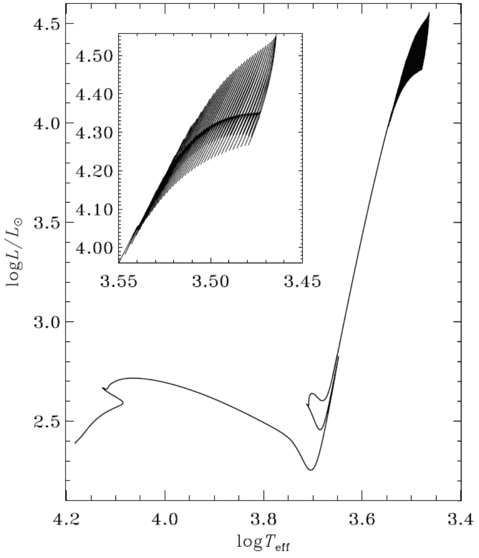
Evolution on the asymptotic giant branch (AGB)

Thermal pulses also in more massive stars ($4M_\odot$)



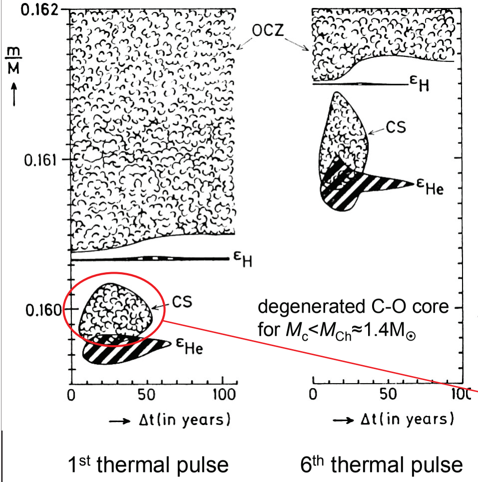
Evolution on the asymptotic giant branch (AGB)

Thermal pulses of a shell source: Nucleosynthesis on the AGB

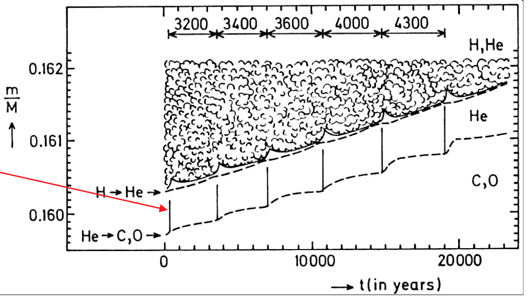
Evolution of mass shells around the two shell sources (5M$_\odot$) near maxima of 1st and 6th pulse.

high max(*L*) (peaks) create short-lived convective (inter-) shell (CS). Almost all matter between 2 shell sources (H, He) is mixed into He-burning shell (H down, C up).

Outer convection zone (OCZ), can reach down to H-shell source and even beyond the H-He discontinuity into the inter-shell region →H-rich material is then transported downwards and inter-shell material to the surface → 3rd dredge up.



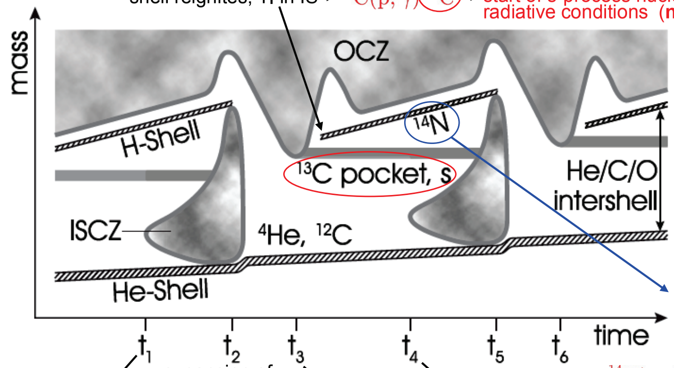
degenerated C-O core for M_c<M_{Ch}≈1.4M$_\odot$



Evolution on the asymptotic giant branch (AGB)

Thermal pulses of a shell source: Nucleosynthesis on the AGB

Sketch of additional mixing in **inter-shell region** (**ISR**) due to the inclusion of, e.g., OV, in order to produce observed surface abundance ratios of C/O >1 (carbon stars), by "forcing" a 3rd dredge-up.



upon contraction of ISR, OCZ recedes, H-shell reignites, T↑ in IS→ $^{12}C(p,\gamma)^{13}C$ → start of s-process nucleosynthesis under radiative conditions (**neutron source**)

pockets

thermal pulse starts

expansion of ISR extinguishes H-shell burning

after pulse OCZ expands and mixes protons (H) +C (from He-shell) in ISR.

next pulse cycle starts dredge-up of s-process elements and C to surface.

H-shell burning (CNO) converts ^{16}O and ^{12}C (both from He burning shell) into ^{14}N, which is swept by ISCZ into He-burning shell, where it is converted to

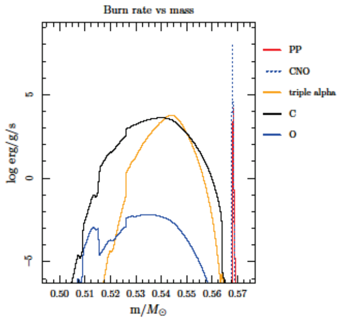
$^{14}N(\alpha,\gamma)^{18}F(\beta^+,\nu)^{18}O(\alpha,\gamma)^{22}Ne$;

^{22}Ne will become another **source of neutrons** for the s-process within a convective environment.

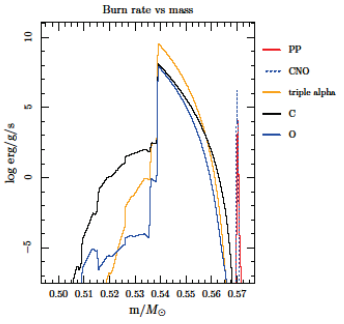
Evolution on the asymptotic giant branch (AGB)

MESA

age = 92435 y

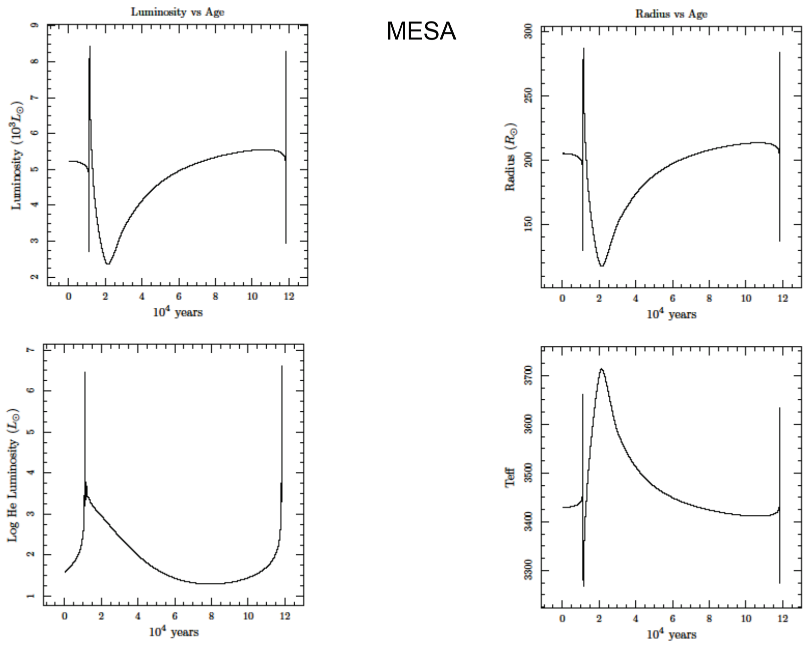


age = 118947 y



Evolution on the asymptotic giant branch (AGB)

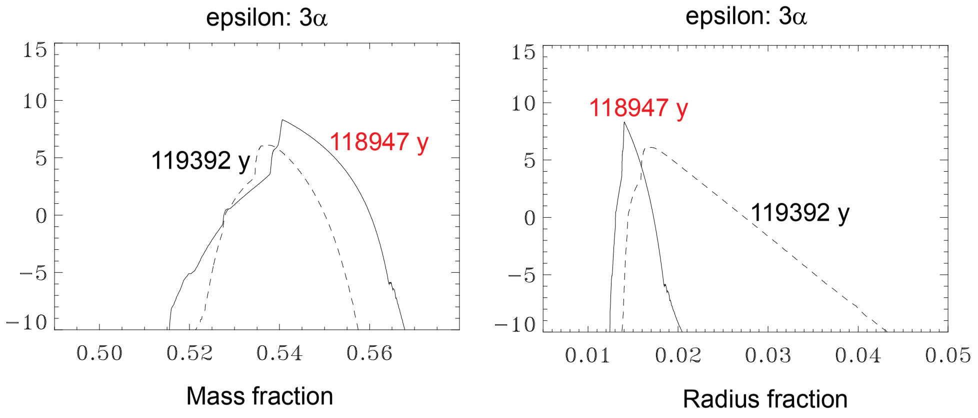
MESA



Evolution on the asymptotic giant branch (AGB)

MESA

2nd thermal pulse (beginning and after)



D/r < ¼ c* > 0

shell source is secularly unstable

Evolution on the asymptotic giant branch (AGB)
Nucleosynthesis on the AGB
Neutron sources for the **s process**

2 neutron-producing reactions available during He-shell burning:

(1) $^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(\alpha,n)^{16}O$ (^{13}C from CNO cycle)

- Requires the presence of both H and He in a He-burning region when normally there is no hydrogen
- Requires mixing of protons into He-burning region
- Occurs at T ~ 100 x 10^6 K, so in between thermal pulses, and under radiative conditions (t ~ 10^4 years)
- Dominant neutron source in low-mass AGB stars (1 to 3Msun stars)
- He-shell flashes imply many exposures to neutron source, produces heavy s-process elements A > 80

Evolution on the asymptotic giant branch (AGB)
Nucleosynthesis on the AGB
Neutron sources for the **s process**

2 neutron-producing reactions available during He-shell burning:

(2) $^{14}N(\alpha,\gamma)^{18}F\ (\beta^+\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$ (^{14}N undergoes a series of α captures)

- Plenty of ^{14}N left over from CNO cycling to produce the ^{22}Ne
- Occurs during thermal pulses when the temperature exceeds about 300 x 10^6 K, under convective conditions
- These temperatures are not reached in the He-shells of low-mass AGB stars, except perhaps in the last few TPs
- So only in:
- a) the cores of massive stars ($M > 12\ M_{sun}$)
- b) massive AGB stars (~3 to 8Msun) during He-shell flashes

Evolution on the asymptotic giant branch (AGB)
Nucleosynthesis on the AGB

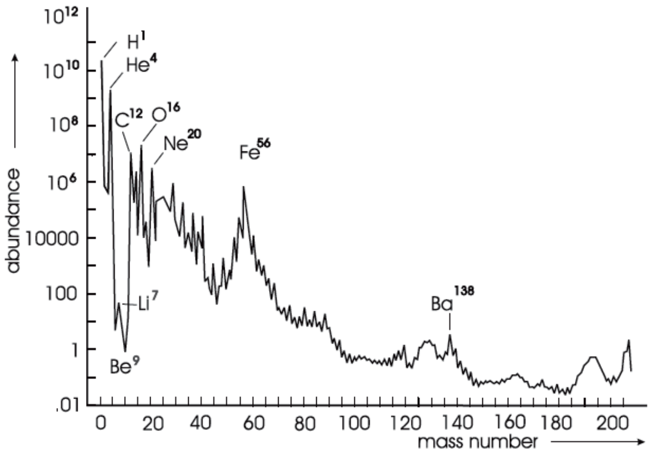


Fig. 18.9. The abundances (particle number fractions) of elements in the Sun, normalized to a value of 10^6 for ^{28}Si.

Evolution on the asymptotic giant branch (AGB)
Nucleosynthesis on the AGB

Neutron capture:

$$(Z,A)+n \rightarrow (Z,A+1)+\gamma$$

(followed by) β⁻ decay (**if** resulting nucleus is unstable):

$$(Z,A+1) \rightarrow (Z+1,A+1)+e^{-}+\overline{\nu}_e$$

or by another neutron capture leading to an even heavier isotope:

$$(Z,A+1)+n \rightarrow (Z,A+2)+\gamma$$

Evolution on the asymptotic giant branch (AGB)
Nucleosynthesis on the AGB

Neutron capture:

$$(Z,A)+n \rightarrow (Z,A+1)+\gamma$$

(followed by) β⁻ decay (**if** resulting nucleus is unstable);

$$(Z,A+1) \rightarrow (Z+1,A+1)+e^{-}+\overline{\nu}_e$$

β⁻ decay is a relatively slow process

or by another neutron capture leading to an even heavier isotope:

$$(Z,A+1)+n \rightarrow (Z,A+2)+\gamma$$

Evolution on the asymptotic giant branch (AGB)
Nucleosynthesis on the AGB

β decay

p ⟷ n conversion within a nucleus via weak interaction

Modes (for a proton/neutron in a nucleus):

β^+ decay	$p \longrightarrow n + e^+ + \nu_e$	Favourable for n-deficient nuclei (or p-rich)
electron capture	$e^- + p \longrightarrow n + \nu_e$	
β^- decay	$n \longrightarrow p + e^- + \overline{\nu}_e$	Favourable for n-rich nuclei (or n-excess)

Electron capture (or EC) of atomic electrons or, in astrophysics, of electrons in the surrounding plasma

Inverse β decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

note: e⁻ capture is also sometimes referred to as inverse β decay.

Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis on the AGB

Typical β decay half-lives:

very near “stability” : occasionally Mio’s of years or longer

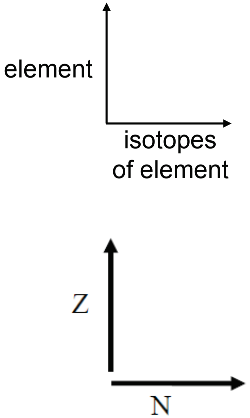
more common within a few nuclei of stability: minutes - days

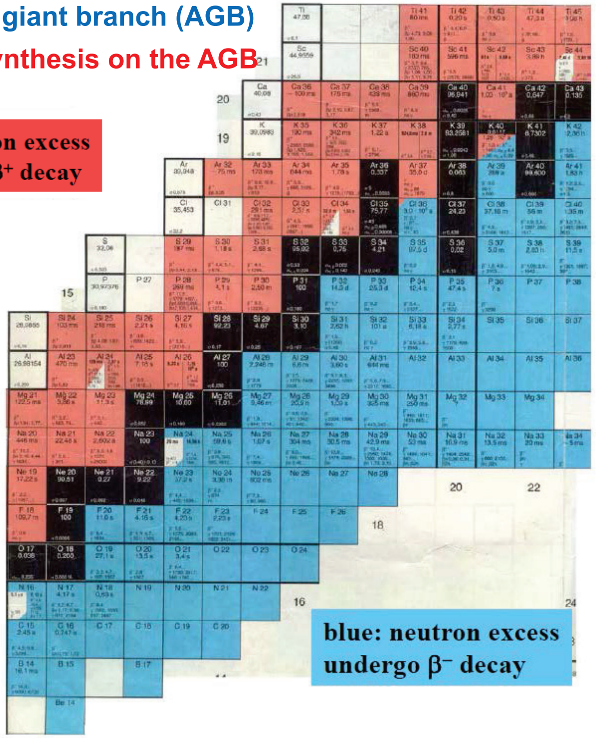
most exotic nuclei that can be formed: ~ milliseconds

Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis on the AGB

Chart of nuclides





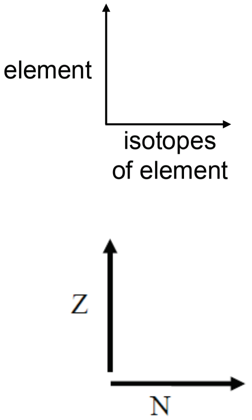
red: proton excess undergo β^+ decay

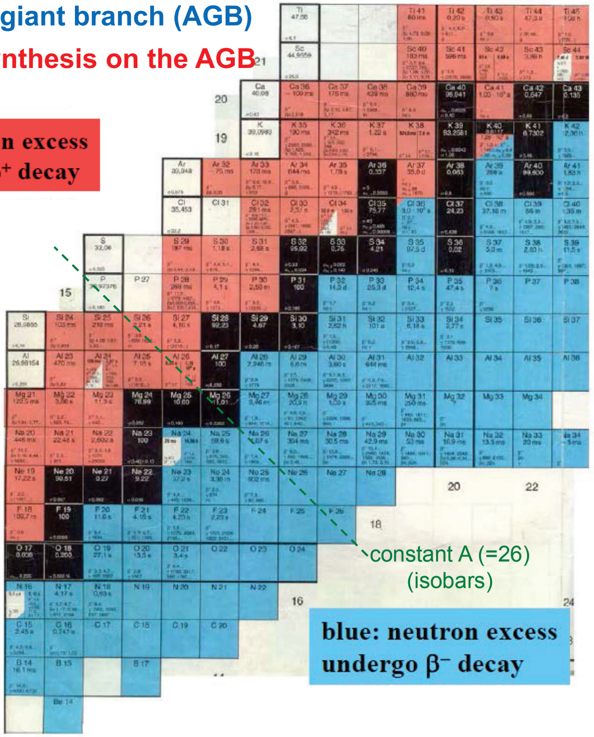
blue: neutron excess undergo β^- decay

Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis on the AGB

Chart of nuclides





red: proton excess undergo β^+ decay

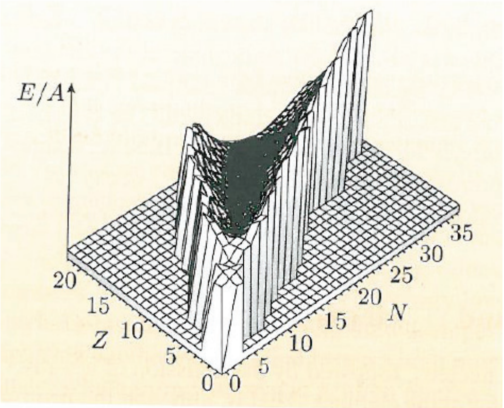
blue: neutron excess undergo β^- decay

Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis on the AGB

The valley of stability

Binding energy per nucleon f=E/A



Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis on the AGB

2 types of neutron (n) capture:

(1) **s process** (for slow): where n capture is much slower (>1000 y) than β⁻ decay:

$$(Z,A)+n\rightarrow(Z,A+1)+\gamma$$

$$\downarrow$$

$$(Z,A+1)\rightarrow(Z+1,A+1)+e^{-}+\bar{\nu}_e$$

$$\downarrow$$

$$(Z+1,A+1)+n\rightarrow(Z+1,A+2)+\gamma$$

Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis on the AGB

2 types of neutron (n) capture:

(2) **r process** (for rapid): where n capture is much faster (~1s) than β⁻ decay:

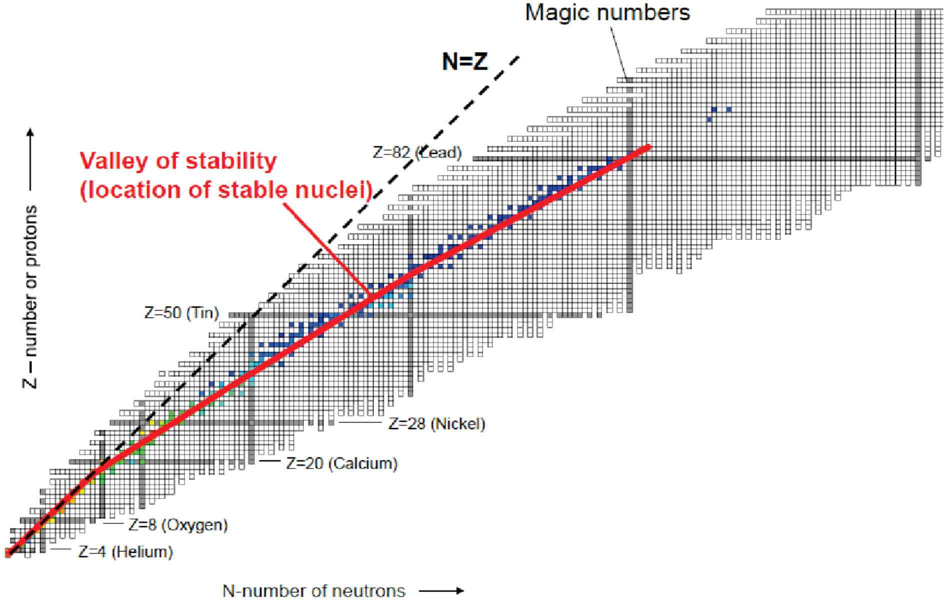
$$(Z,A)+n\rightarrow(Z,A+1)+\gamma$$

$$\downarrow$$

$$(Z,A+1)+n\rightarrow(Z,A+2)+\gamma$$

Evolution on the asymptotic giant branch (AGB)

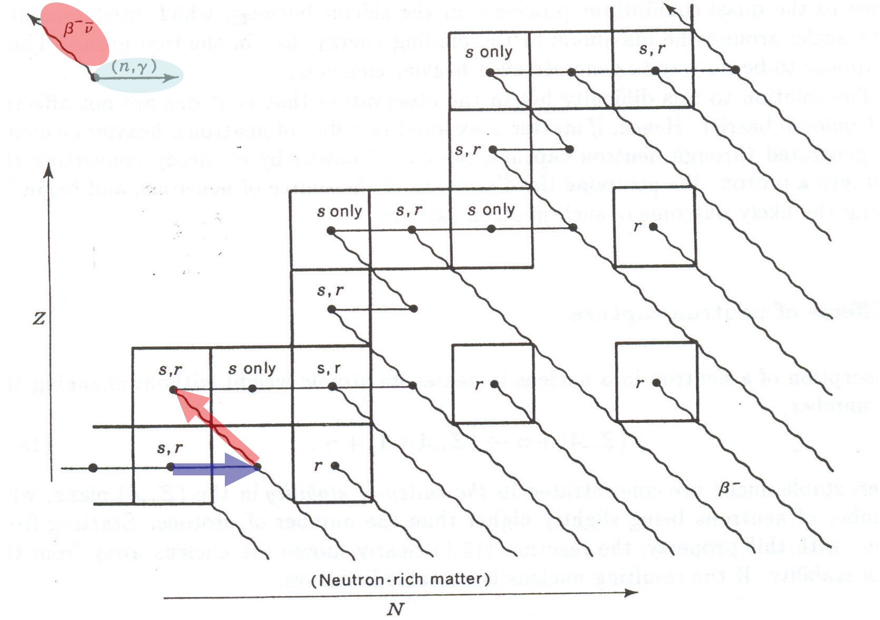
The valley of stability



Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis on the AGB

Low neutron density (flux): s process



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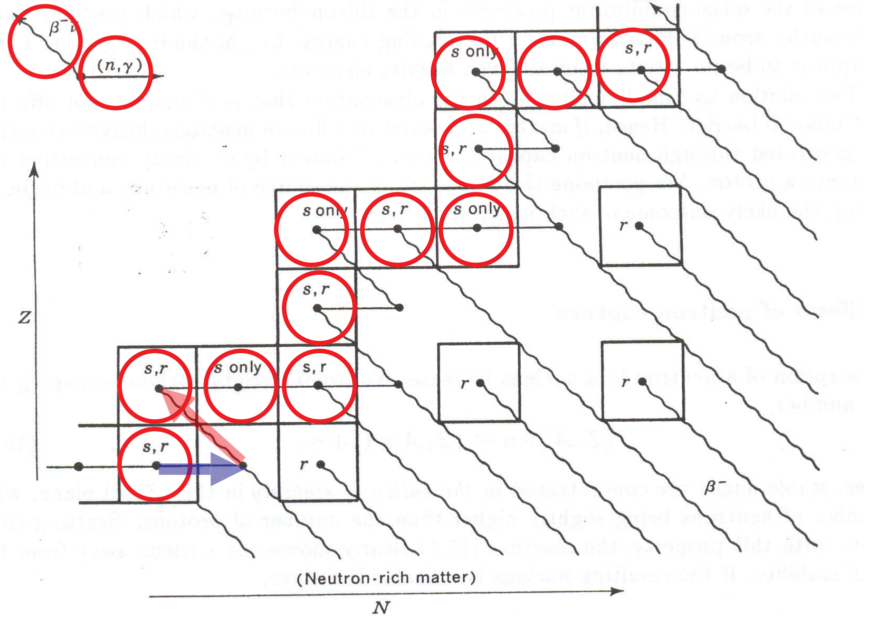

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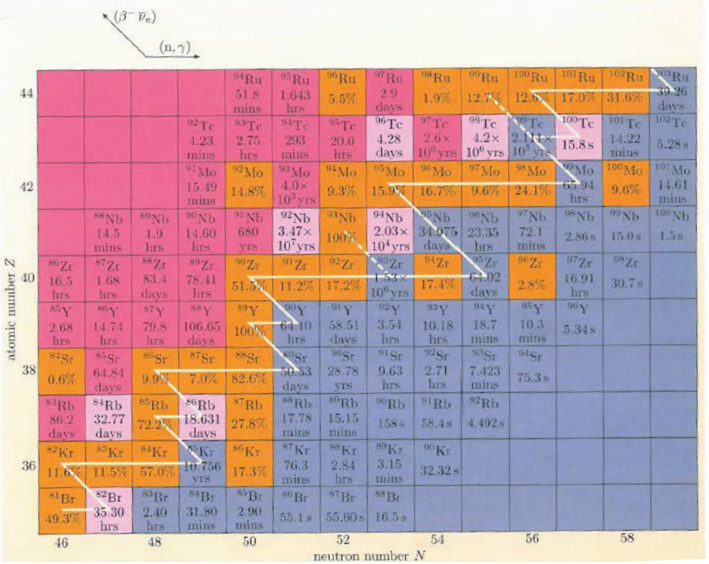
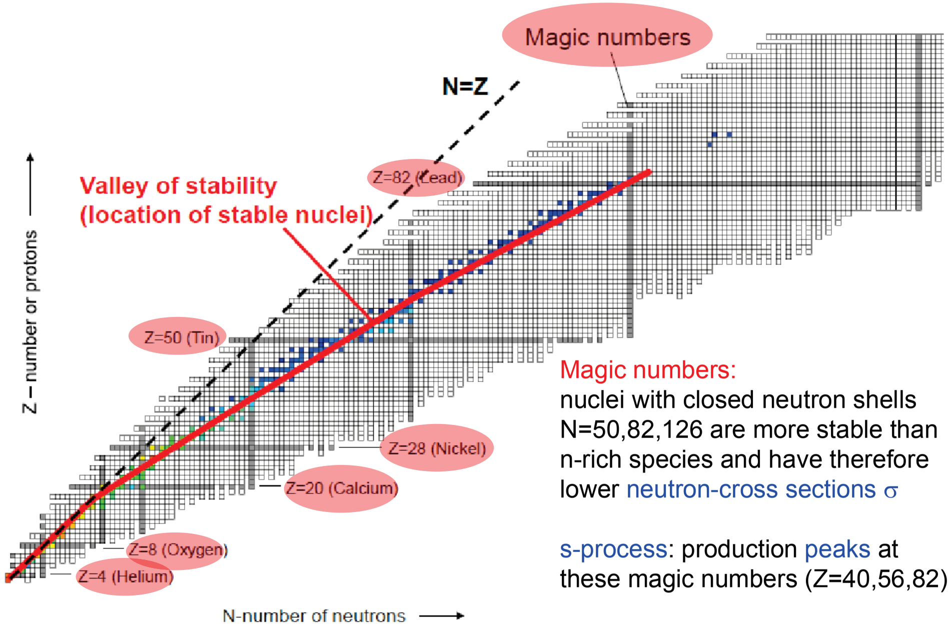


	46		48		50		52		54		56		58	
44					^{94}Ru 51.8 mins	^{95}Ru 1.643 hrs	^{96}Ru 5.5%	^{97}Ru 2.9 days	^{98}Ru 1.9%	^{99}Ru 12.7%	^{100}Ru 12.6%	^{101}Ru 17.0%	^{102}Ru 31.6%	^{103}Ru 39.26 days
				^{92}Tc 4.23 mins	^{93}Tc 2.75 hrs	^{94}Tc 293 mins	^{95}Tc 20.0 hrs	^{96}Tc 4.28 days	^{97}Tc 2.6×10^6 yrs	^{98}Tc 4.2×10^6 yrs	^{99}Tc 2.111×10^5 yrs	^{100}Tc 15.8 s	^{101}Tc 14.22 mins	^{102}Tc 5.28 s
42				^{91}Mo 15.49 mins	^{92}Mo 14.8%	^{93}Mo 4.0×10^3 yrs	^{94}Mo 9.3%	^{95}Mo 15.9%	^{96}Mo 16.7%	^{97}Mo 9.6%	^{98}Mo 24.1%	^{99}Mo 65.94 hrs	^{100}Mo 9.6%	^{101}Mo 14.61 mins
		^{88}Nb 14.5 mins	^{89}Nb 1.9 hrs	^{90}Nb 14.60 hrs	^{91}Nb 680 yrs	^{92}Nb 3.47×10^7 yrs	^{93}Nb 100%	^{94}Nb 2.03×10^4 yrs	^{95}Nb 34.975 days	^{96}Nb 23.35 hrs	^{97}Nb 72.1 mins	^{98}Nb 2.86 s	^{99}Nb 15.0 s	^{100}Nb 1.5 s
40	^{86}Zr 16.5 hrs	^{87}Zr 1.68 hrs	^{88}Zr 83.4 days	^{89}Zr 78.41 hrs	^{90}Zr 51.5%	^{91}Zr 11.2%	^{92}Zr 17.2%	^{93}Zr 1.53×10^6 yrs	^{94}Zr 17.4%	^{95}Zr 64.02 days	^{96}Zr 2.8%	^{97}Zr 16.91 hrs	^{98}Zr 30.7 s	
	^{85}Y 2.68 hrs	^{86}Y 14.74 hrs	^{87}Y 79.8 hrs	^{88}Y 106.65 days	^{89}Y 100%	^{90}Y 64.10 hrs	^{91}Y 58.51 days	^{92}Y 3.54 hrs	^{93}Y 10.18 hrs	^{94}Y 18.7 mins	^{95}Y 10.3 mins	^{96}Y 5.34 s		
38	^{84}Sr 0.6%	^{85}Sr 64.84 days	^{86}Sr 9.9%	^{87}Sr 7.0%	^{88}Sr 82.6%	^{89}Sr 50.53 days	^{90}Sr 28.78 yrs	^{91}Sr 9.63 hrs	^{92}Sr 2.71 hrs	^{93}Sr 7.423 mins	^{94}Sr 75.3 s			
	^{83}Rb 86.2 days	^{84}Rb 32.77 days	^{85}Rb 72.2%	^{86}Rb 18.631 days	^{87}Rb 27.8%	^{88}Rb 17.78 mins	^{89}Rb 15.15 mins	^{90}Rb 158 s	^{91}Rb 58.4 s	^{92}Rb 4.492 s				
36	^{82}Kr 11.6%	^{83}Kr 11.5%	^{84}Kr 57.0%	^{85}Kr 10.756 yrs	^{86}Kr 17.3%	^{87}Kr 76.3 mins	^{88}Kr 2.84 hrs	^{89}Kr 3.15 mins	^{90}Kr 32.32 s					
	^{81}Br 49.3%	^{82}Br 35.30 hrs	^{83}Br 2.40 hrs	^{84}Br 31.80 mins	^{85}Br 2.90 mins	^{86}Br 55.1 s	^{87}Br 55.60 s	^{88}Br 16.5 s						

Evolution on the asymptotic giant branch (AGB)

The valley of stability



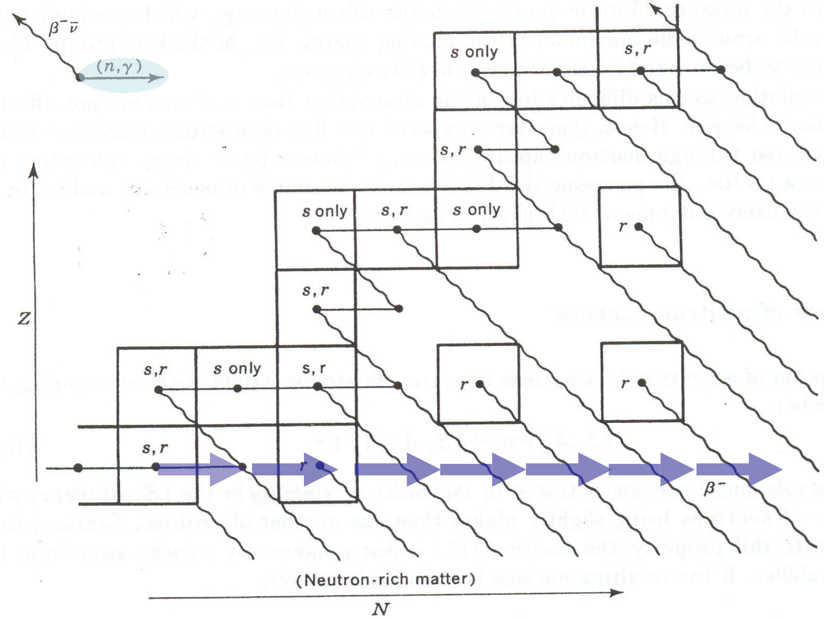
Valley of stability
(location of stable nuclei)

Magic numbers:
nuclei with closed neutron shells N=50,82,126 are more stable than n-rich species and have therefore lower neutron-cross sections σ

s-process: production peaks at these magic numbers (Z=40,56,82).

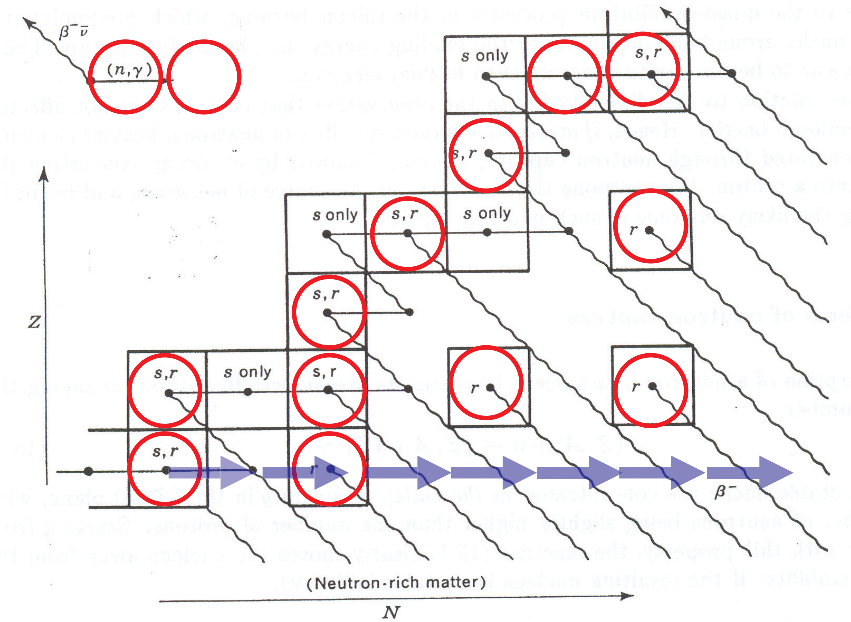
Nucleosynthesis

High neutron density: r process



Nucleosynthesis

High neutron density: r process

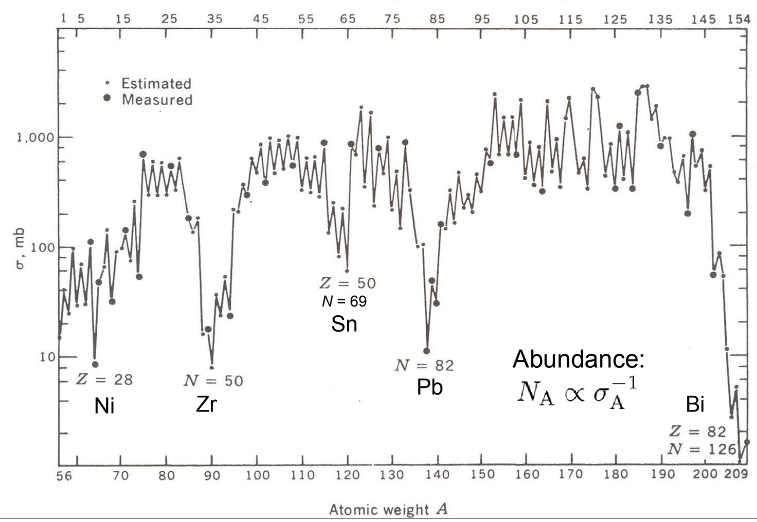


Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis

Approximate equilibrium between produced and destroyed isotopes:

rate of production of nucleus A from nucleus A-1 (neutron cross section) → $\sigma_{A-1} N_{A-1} \simeq \underbrace{\sigma_A N_A}_{\sim \text{ constant along s-path}}$ ← rate of destruction of nucleus A



Abundance: $N_A \propto \sigma_A^{-1}$

Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis on the AGB

$$N_A \propto \frac{1}{\sigma_A}$$

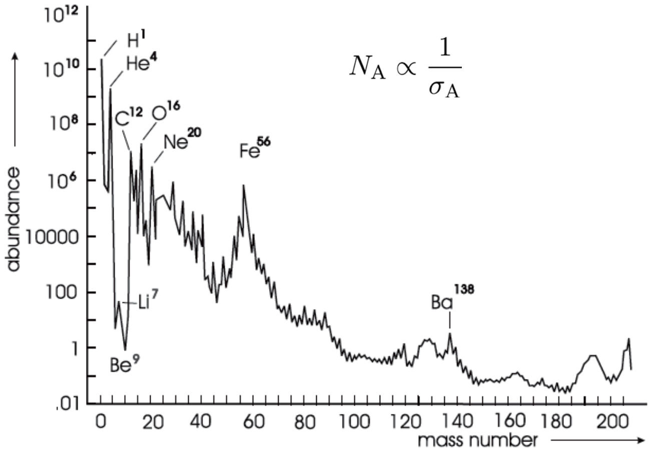
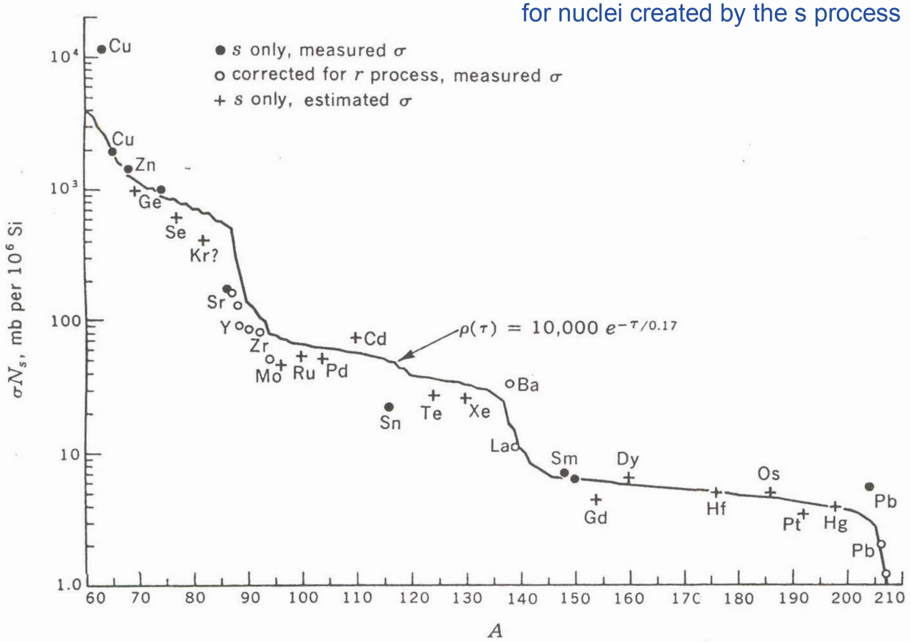


Fig. 18.9. The abundances (particle number fractions) of elements in the Sun, normalized to a value of 10^6 for ^{28}Si.

Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis on the AGB

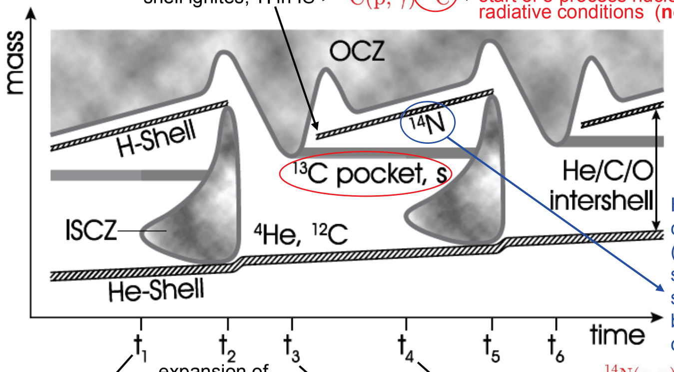
More accurate description shows that $\sigma_A N_A$ is a slowly varying function of A for nuclei created by the s process



Evolution on the asymptotic giant branch (AGB)

Thermal pulses of a shell source: Nucleosynthesis on the AGB

Sketch of additional mixing in inter-shell region (ISR) due to the inclusion of, e.g., OV, in order to produce observed surface abundance ratios of C/O >1 (carbon stars), by “forcing” a 3rd dredge-up.



upon contraction of ISR, OCZ recedes, H-shell ignites, T↑ in IS→ $^{12}C(p,\gamma)^{13}C$ pockets → start of s-process nucleosynthesis under radiative conditions (**neutron source**)

thermal pulse starts

expansion of ISR extinguishes H-shell burning

after pulse OCZ expands and mixes protons (H)+C in ISR.

next pulse cycle starts dredge-up of s-process elements and C to surface.

H-shell burning (CNO) converts ^{16}O and ^{12}C (both from He burning shell) into ^{14}N, which is swept by ISCZ into He-burning shell, where it is converted to $^{14}N(\alpha,\gamma)^{18}F(\beta^+,\nu)^{18}O(\alpha,\gamma)^{22}Ne$; ^{22}Ne will become **another source of neutrons** for the s-process within a convective environment.

Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis on the AGB

Neutron sources for the **s process**

2 neutron-producing reactions available during He burning:

(1) $^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(\alpha,n)^{16}O$ (^{13}C from CNO cycle)

- Requires the presence of both H and He in a He-burning region when normally there is no hydrogen
- Requires mixing of protons into He-burning region
- Occurs at T ~ 100 x 10^6 K, so in between thermal pulses, and under radiative conditions (t ~ 10^4 years)
- Dominant neutron source in low-mass AGB stars (1 to 3Msun stars)
- He-shell flashes imply many exposures to neutron source, produces heavy s-process elements A > 80

Evolution on the asymptotic giant branch (AGB)

Nucleosynthesis on the AGB

Neutron sources for the **s process**

2 neutron-producing reactions available during He burning:

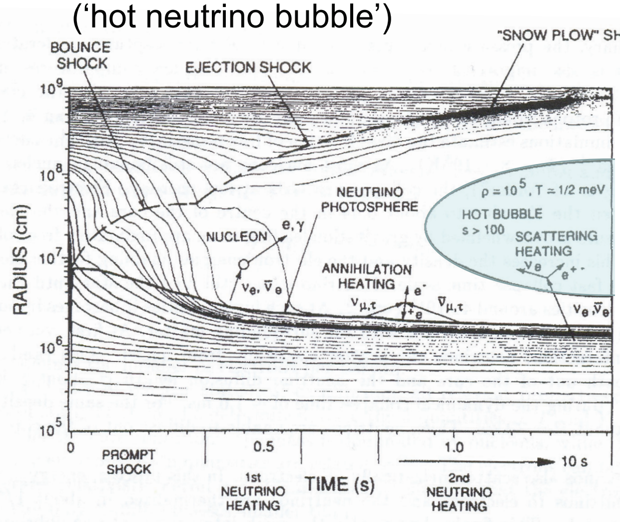
(2) $^{14}N(\alpha,\gamma)^{18}F\ (\beta^+\nu)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$ (^{14}N undergoes a series of α captures)

- Plenty of ^{14}N left over from CNO cycling to produce the ^{22}Ne
- Occurs during thermal pulses when the temperature exceeds about 300 x 10^6 K, under convective conditions
- These temperatures are not reached in the He-shells of low-mass AGB stars, except perhaps in the last few TPs
- So only in:
- a) the cores of massive stars ($M > 12\ M_{sun}$)
- b) massive AGB stars (~3 to 8Msun) during He-shell flashes

Nucleosynthesis

Neutron sources for the **r process**

- sites for r process are still unclear
- requires extreme neutron fluxes
- e.g. region just above newly born neutron star in Type II SN (‘hot neutrino bubble’)



“cooling” neutrinos “trapped” within *neutrinosphere*

neutrino-nucleon interaction:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

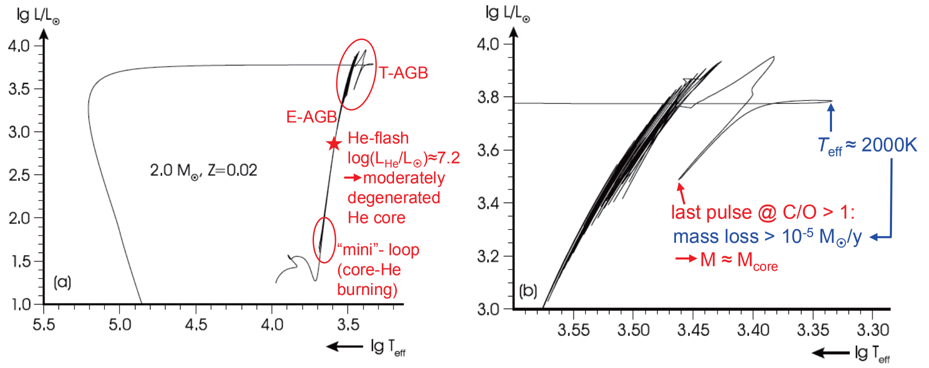
some of the n combine with p to form α particles.

Excess n are captures by heavy nuclei to produce nuclear r process.

But also neutron-star mergers are also believed to be n source for r process!

Evolution on the asymptotic giant branch (AGB)

A sample AGB evolution of 2 $M_\odot$ star



T-AGB

E-AGB

He-flash $\log(L_{He}/L_\odot) \approx 7.2$ → moderately degenerated He core

"mini"- loop (core-He burning)

$T_{eff} \approx 2000$K

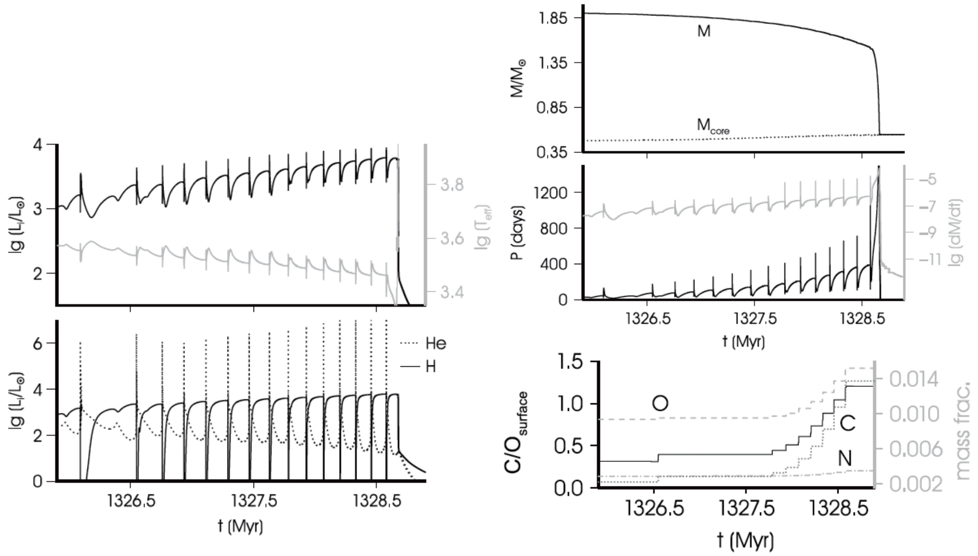
last pulse @ C/O > 1:

mass loss > 10^{-5} $M_\odot$/y

→ $M \approx M_{core}$

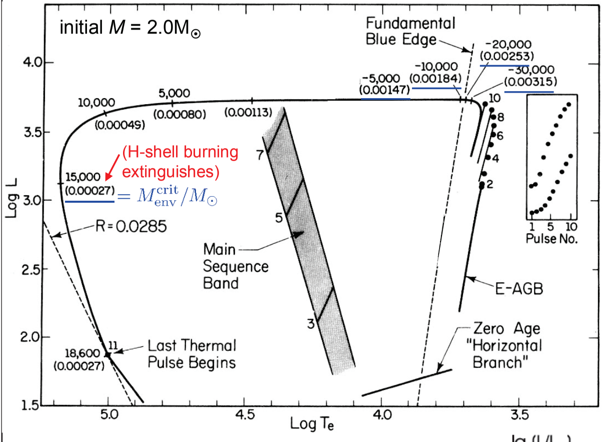
Evolution on the asymptotic giant branch (AGB)

A sample AGB evolution of 2 $M_\odot$ star



Evolution on the asymptotic giant branch (AGB)

post-AGB evolution



(H-shell burning extinguishes)

$= M_{\rm env}^{\rm crit}/M_\odot$