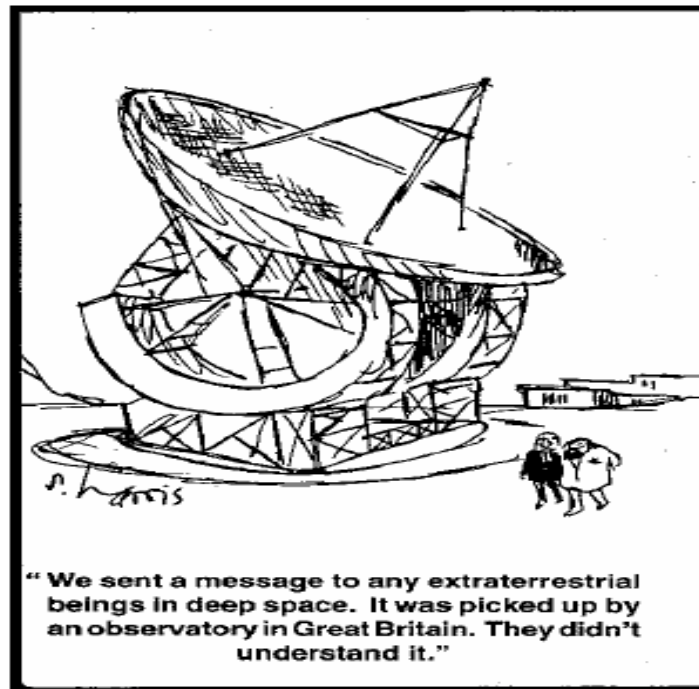


The s Process – I

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Slow Neutron Captures: a Simple, Understandable Process



<http://www.univie.ac.at/strv-astronomie/unterhaltung.html>

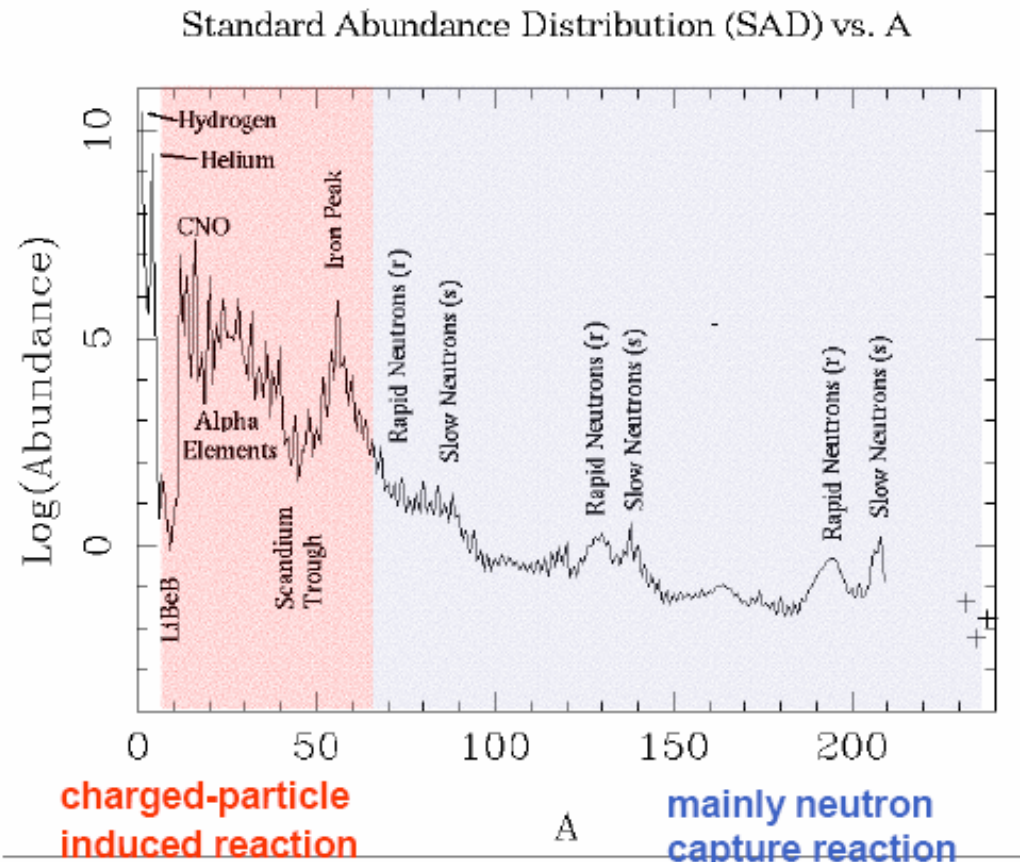


CONTENT

- 1. Basic properties of the s-process
(analytical solutions, components, branchings, neutron densities, temperatures)**
 - 2. Neutron sources**
 - 3. Constraints on stellar models: mainly for AGB stars (see Pignatari for massive stars)**
 - 4. Observational constraints (summary)**
 - 5. Luminosities and masses of s-element producers: C stars and S stars**
 - 6. Requirements for producing the main neutron source (& other things): extra-mixing**
- (For model details: see next talk by Oscar)**



n-Capture Nucleosynthesis beyond Fe



slow-process nuclei in
quiescent stages

rapid-process nuclei in
explosive stages

involve mainly STABLE NUCLEI

involve mainly UNSTABLE NUCLEI

n-captures:



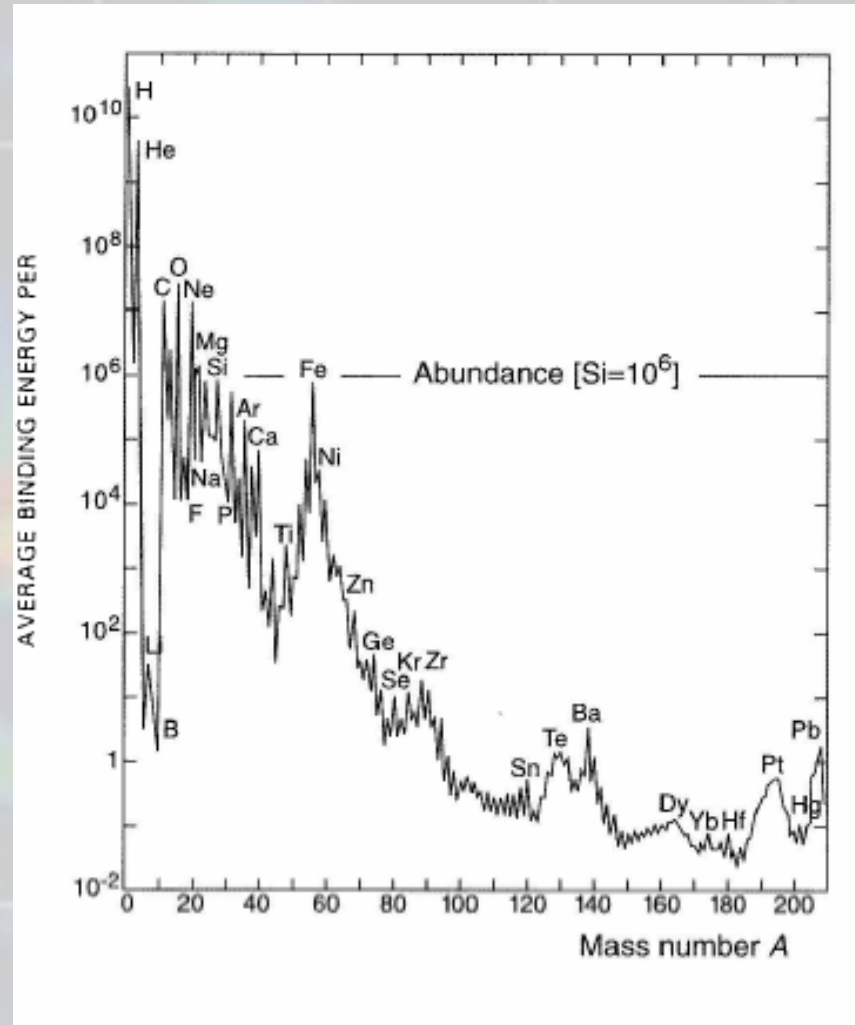
Why Neutron Captures beyond Fe?

Failure of charged-particle reactions:

- i) Binding energy: maximum at Fe (fusion reactions are endothermic after Fe)
- ii) Coulomb barrier exceedingly high, (too much even for supernovae)

Hints that neutrons are involved:

- i) Abundance peaks at magic neutron numbers
- ii) Neutron cross sections for heavy elements increasingly larger



Basic characteristics of the s-process

start with Fe *seeds* for neutron capture

whenever an unstable species is produced one of the following can happen:

- the unstable nucleus decays (before reacting)
- the unstable nucleus reacts (before decaying)
- the two above processes have comparable probabilities

if $\tau_n \gg \tau_\beta \Rightarrow$ unstable nucleus **decays**

if $\tau_n \ll \tau_\beta \Rightarrow$ unstable **reacts**

if $\tau_n \sim \tau_\beta \Rightarrow$ **branchings** occur

with:

$$\tau_n(X) = \frac{1}{N_n \langle \sigma v \rangle}$$

mean lifetime of nucleus X against destruction by neutron capture

$$\tau_\beta(X)$$

mean lifetime of nucleus X against β decay

NOTE: τ_n varies depending upon stellar conditions (T, ρ)
 \Rightarrow different processes dominate in different environments

ALSO: τ_β can be affected too by physical conditions of stellar plasma!



WEAK INTERACTIONS ARE THEREFORE IMPORTANT!

factors influencing the β -decay lifetime of an unstable nucleus

- both β^- and β^+ decay are hampered in the presence of electron or positron degeneracy
- β^- and β^+ decays may occur from excited isomeric states maintained in equilibrium with ground state by radiative transitions
- electron-capture rates are affected by temperature and density through population of the K electronic shell

example: ${}^7\text{Be}$

${}^7\text{Be}$ nucleus can only decay by electron capture with a lifetime: $\tau_{\text{EC}} \sim 77 \text{ d}$

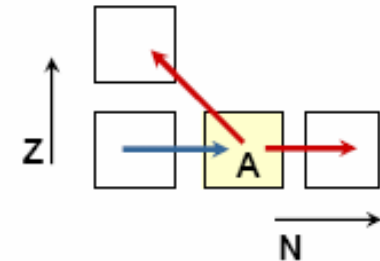
in the Sun, $T \sim 15 \times 10^6 \text{ K} \Rightarrow kT \sim 1.3 \text{ keV} \Rightarrow$ low-Z nuclei almost completely ionized
e.g. binding energy of innermost K-shell electrons in ${}^7\text{Be}$: $E_b = 0.22 \text{ keV}$
 \Rightarrow if no electrons available ${}^7\text{Be}$ becomes essentially STABLE!

in fact free electrons present in the plasma can be captured
for solar conditions: $\tau_{\text{EC}} \sim 120 \text{ d} \Rightarrow$ factor **1.6** larger than in terrestrial laboratory



time dependence of abundance N_A given by:

$$\frac{dN_A(t)}{dt} = \underbrace{N_{A-1}(t)N_n(t)\langle\sigma v\rangle_{A-1}}_{\text{production}} - \underbrace{N_A(t)N_n(t)\langle\sigma v\rangle_A - \lambda_\beta(t)N_A(t)}_{\text{destruction}}$$



For stable nuclei:

$$\frac{dN_A}{d\tau} = \langle\sigma\rangle_{A-1} N_{A-1} - \langle\sigma\rangle_A N_A$$

with: $\langle\sigma\rangle = \frac{\langle\sigma v\rangle_A}{v_T}$ Maxwellian averaged cross section

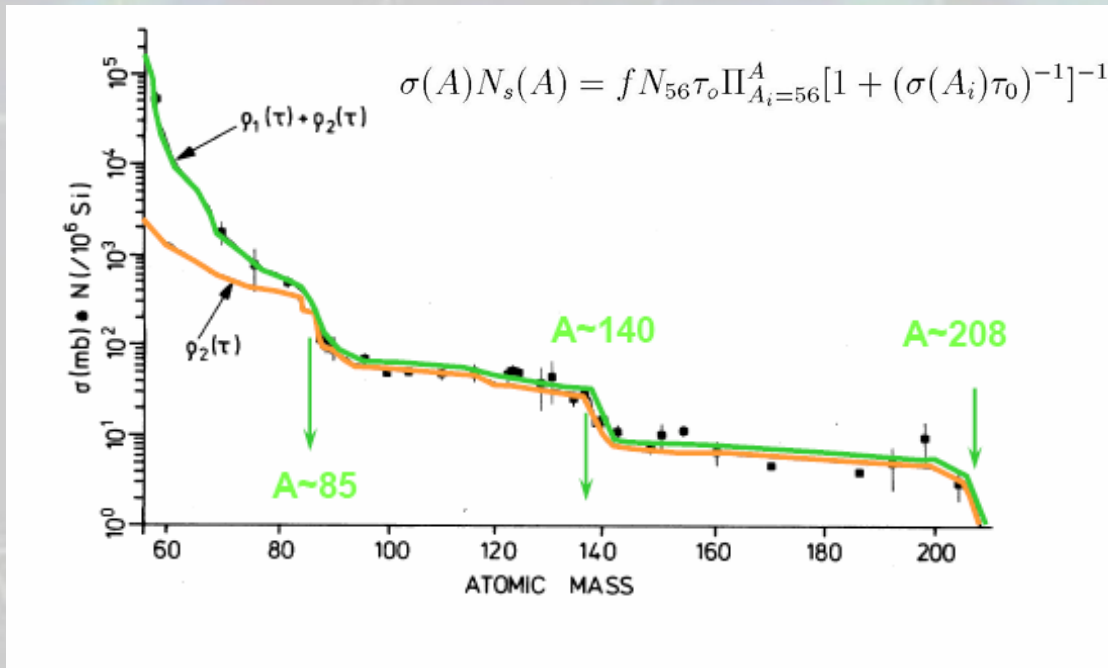
$$\tau = \int_0^t v_T N_n(t) dt \quad \text{neutron exposure}$$

in steady state condition (so-called *local equilibrium approximation*):

$$\frac{dN_A}{d\tau} = 0 \quad \Rightarrow \quad \langle\sigma\rangle_{A-1} N_{A-1} = \langle\sigma\rangle_A N_A = \text{constan t} \quad \Rightarrow \quad N_A \propto \frac{1}{\langle\sigma\rangle_A}$$

The classical analysis

- Definition of s-process: in B²FH – [Merrill (1952) had seen Tc before].
- First era: mathematical tools laid down for a *phenomenological approach*
- Based on the σN_s curve in the Solar System (Clayton et al. 1961, Ann Phys.12, 331; Seeger et al. 1965, Ap.J. Suppl. 11,121).
- Two main results:



- Multiple irradiations are needed to bypass the bottlenecks of nuclei with very small cross sections (*magic nuclei*);
- Far from bottlenecks, steady flow conditions prevail where $\sigma N \sim \text{const.}$ (for unbranched nuclei).

Deducing stellar conditions

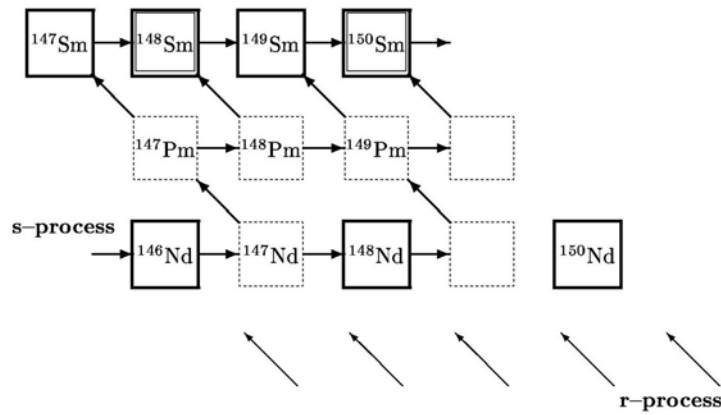


Fig. 1. The s-process path in the Nd/Pm/Sm-region

$$f_{\beta} = \lambda_{\beta} / (\lambda_{\beta} + \lambda_n)$$

- Clayton and Rassbach (1961): three *components* for the s-process:
- Weak (up to $A = 88$): Massive Star He-burning (Lamb et al. 1977)
- Main ($88 < A < 208$): AGB thermal pulses of He-shell (Ulrich 1973)
- Strong (50% ^{208}Pb): Origin unknown till 10-y ago (Gallino et al 1998)
- Reaction Branchings (Clayton & Ward 1974): β -decays compete with n-captures, branching ratios f_{β} and abundances inform on (T, n_n) conditions in the parent star.
- Branching analysis yielded conditions $\sim 30\text{KeV}$, as typical of IMS AGB during thermal pulses (few years long).

AGB Stars: not only s-process parents!

- They contribute for 75% to the total mass return from stars to the ISM (Sedlmayr 1994);
- They produce other elements that are crucial for organic chemistry and life cycles (C, N): specifically, more than half of galactic ^{12}C ;
- They produce ^{26}Al , whose presence in the Early Solar System may have been essential in melting large bodies;
- The most massive members produce ^7Li , hence affect any model of light element synthesis;
- They are the source of most extrasolar grains recovered in meteorites and of isotopic anomalies in them: pieces of their envelopes are available for experimental studies;
- They are bright mid- and far-IR sources, through dust formed in their mass losing envelopes. They eventually form PNe (and white dwarfs from the remnants).

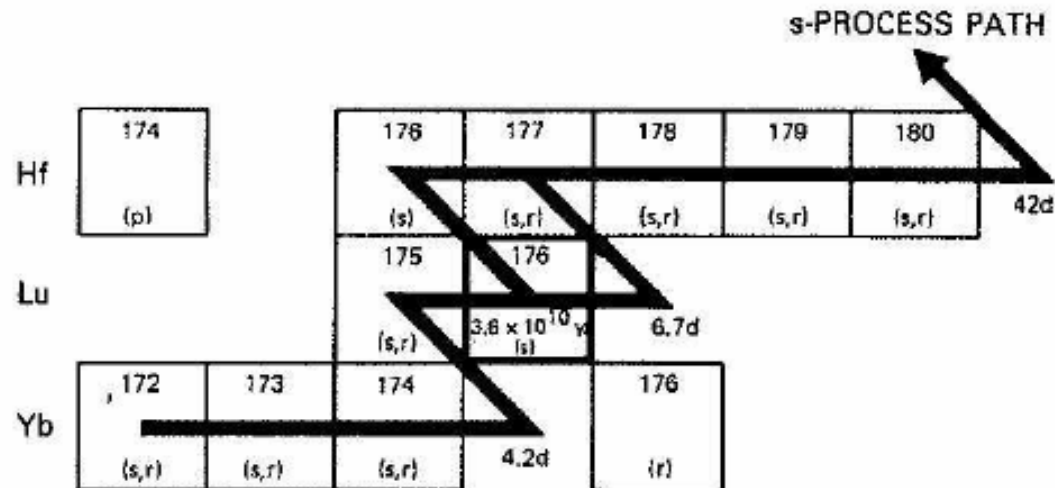


s-process (s = slow neutron capture process)

unstable nucleus decays before capturing another neutron



$$\tau_{\beta} \ll \tau_n$$



how many neutrons are needed?

typical lifetimes for unstable nuclei close to the valley of β stability:

seconds \rightarrow years

assuming:

$$\sigma \sim 0.1 \text{ b} \quad @ E = 30 \text{ keV} \quad \rightarrow \quad v = 3 \times 10^8 \text{ cm/s}$$

$$\langle \sigma v \rangle = 3 \times 10^{-17} \text{ cm}^3 \text{ s}^{-1} \quad \Leftrightarrow \quad \tau_n N_n = \frac{1}{\langle \sigma v \rangle} = 3 \times 10^{16} \text{ s} \frac{\text{n}}{\text{cm}^3}$$

requiring:

$$\tau_n \sim 10 \text{ y} \quad \Leftrightarrow \quad N_n \sim 10^8 \text{ n/cm}^3$$

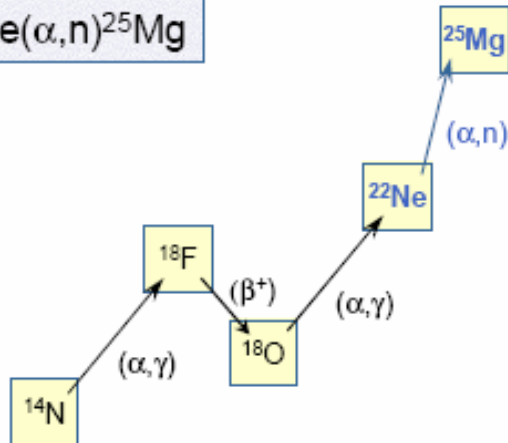
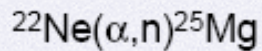
POSSIBLE NEUTRON SOURCES

free neutrons are unstable \Rightarrow they must be produced in situ

in principle many (α, n) reactions can contribute

in practice, one needs suitable reaction rate & abundant nuclear species

most likely candidates as neutron source are:



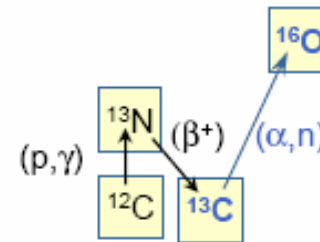
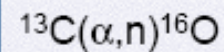
astrophysical site:

core He burning (and shell C-burning)
in massive stars (e.g. 25 solar masses)

$$T_8 = 2.5 - 3.5, N_n > 5 \cdot 10^8$$



contribution to weak s-process



astrophysical site:

He-flashes followed by H mixing
into ^{12}C enriched zones
low-mass (1.5 - 3 M_{sun}) TP-AGB stars

$$T_8 = 0.9 - 1.1, N_n < 10^7$$



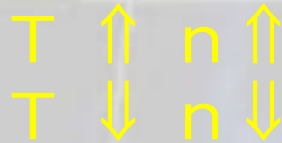
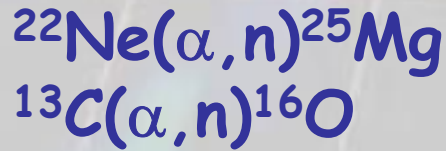
contribution to main s-process

Observations against theory

- IMS too luminous compared to Magellanic Cloud C-stars ($M_{\text{bol}} > -4$, Blanco et al. 1980; Mould & Reid 1987 [**OOPS THIS WAS (partly) WRONG!**]) *** see later
 - $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg} \rightarrow$ enhanced ^{25}Mg : not observed (Clegg et al. 1979; McWilliam et al. 1988).
 - At $T_8=3.5$, n_n too high to fit the solar n-rich isotopes, crucial tests from ^{86}Kr , ^{87}Rb and ^{96}Zr (Käppeler et al. 1982, 1989, 1990).
- LOWER MASSES MUST BE INVOLVED
(Iben & Renzini 1982; Hollowell & Iben 1987)
- MUCH BETTER SITUATION IF $^{13}\text{C}(\alpha, n)^{16}\text{O}$ IS AT PLAY!
(Gallino et al. 1988)

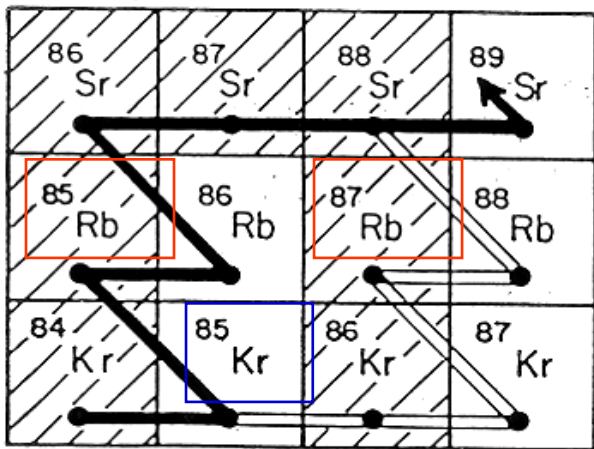


Constraining observationally the neutron density from abundances of Rb vs. Sr, Y, Zr



Mass: 4 - 8 M_{\odot}
 $\leq 3 M_{\odot}$

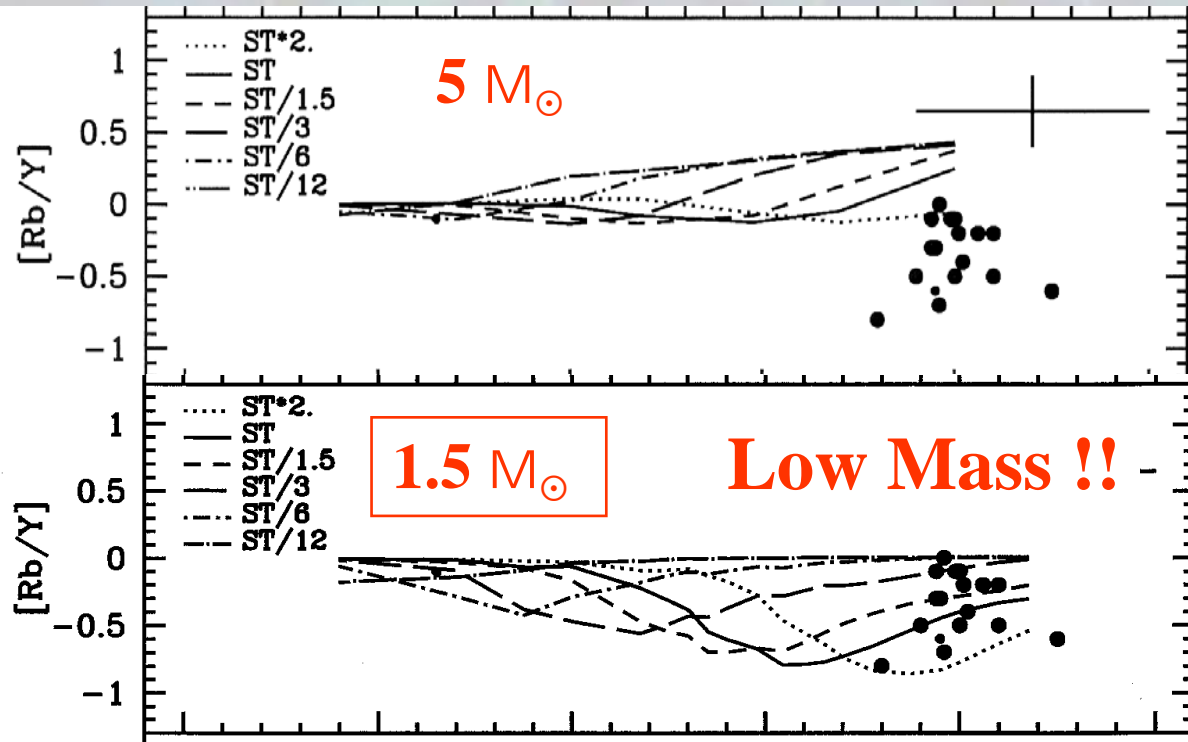
$$\frac{\sigma(^{85}\text{Rb})}{\sigma(^{87}\text{Rb})} \approx 10$$



Stable Unstable

Low density chain
 High density chain

^{85}Kr

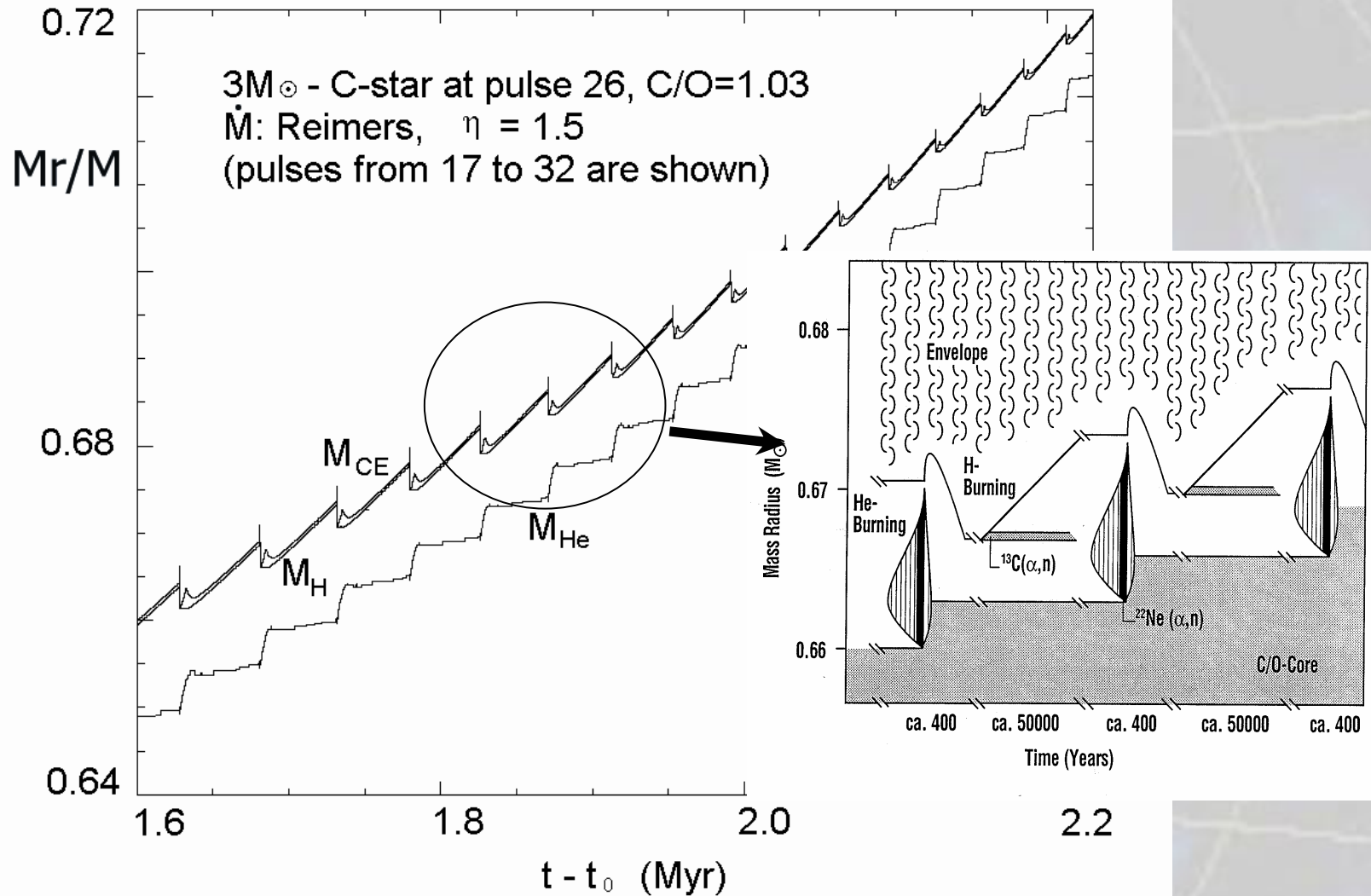


Neutron Density in AGB Stars

- Low mass stars ($M < 3-4 M_{\odot}$) barely reach, in convective pulses, values of T sufficient to activate α -captures on ^{22}Ne . These would produce neutrons at relatively high neutron density ($n_n > 3-5 \times 10^8 \text{ cm}^{-3}$). The neutron production is therefore mainly due to α -captures on ^{13}C in the radiative interpulse periods, yielding $n_n < 10^7 \text{ cm}^{-3}$: (Gallino et al. 1998).
- Intermediate Mass Stars ($M > 4 M_{\odot}$) burn ^{22}Ne efficiently and are therefore expected to generate s-processing at relatively high neutron density (see e.g. Iben & Renzini 1983; Kaeppeler et al. 1990).
- However, the presence of s-process nuclei whose production depends on n_n and/or T (through reaction branchings: e.g. ^{96}Zr , ^{150}Sm , ^{176}Lu) says that some ^{22}Ne must also burn.
→ s-elements come from moderately low masses, $M > 1.2 - 1.5 M_{\odot}$



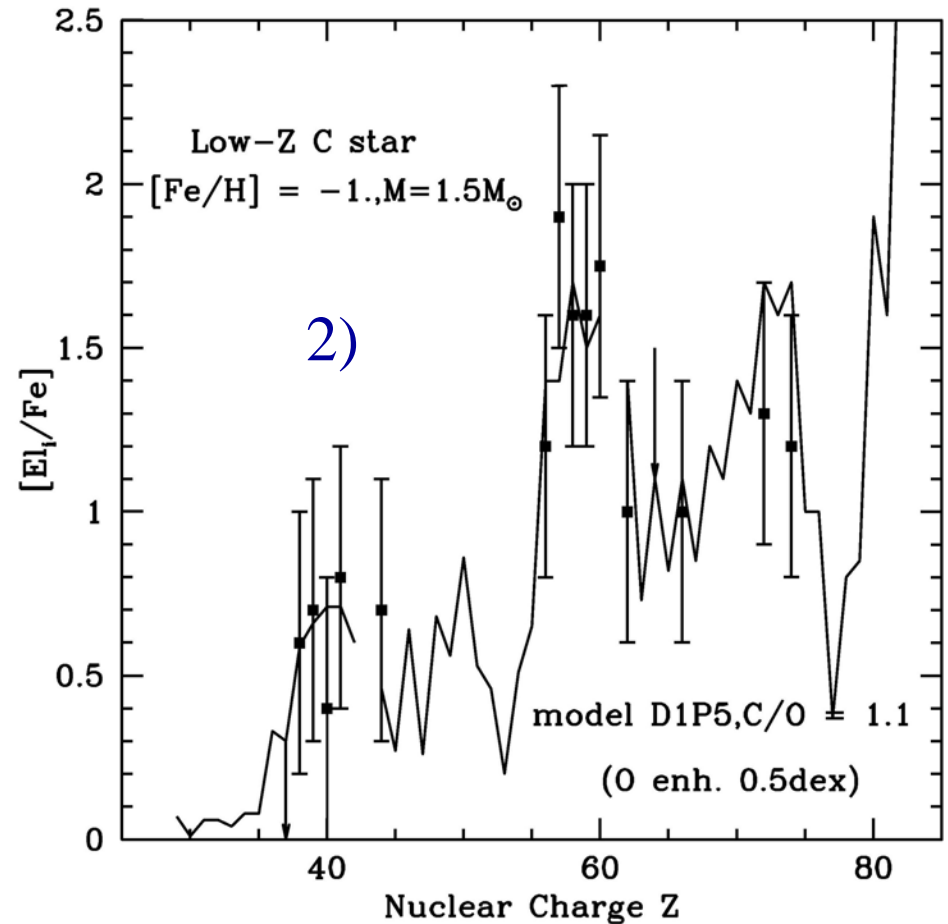
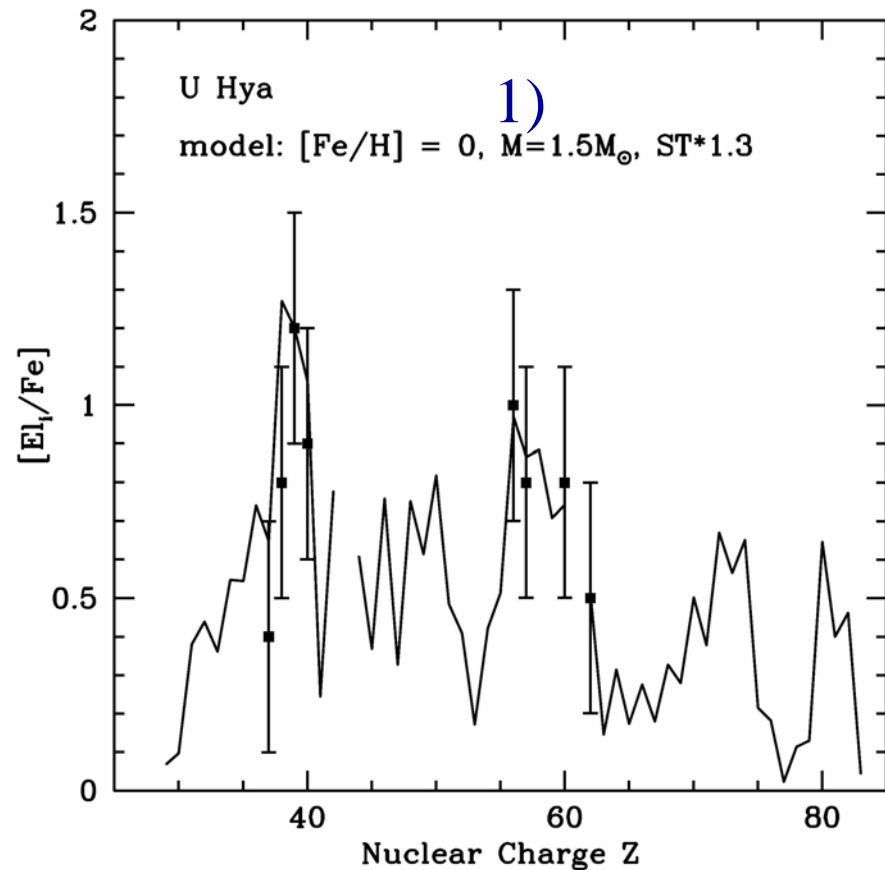
Slow neutron captures from Fe to Pb require repeated neutron exposures: thermally pulsing AGB phases in low mass stars.



Detailed Abundances. C(N) and Peculiar Stars

1) Abia et al. 2002

2) Busso, Abia et al 2004



Production of heavy s-nuclei at low Z

Abundances in the He-intershell zone – Same amount of ^{13}C burnt (same amount of neutrons) at different metallicities

$$[\text{Fe}/\text{H}] = \log(N(\text{Fe})/N(\text{H}))_* - \log(N(\text{Fe})/N(\text{H}))_{\odot}$$

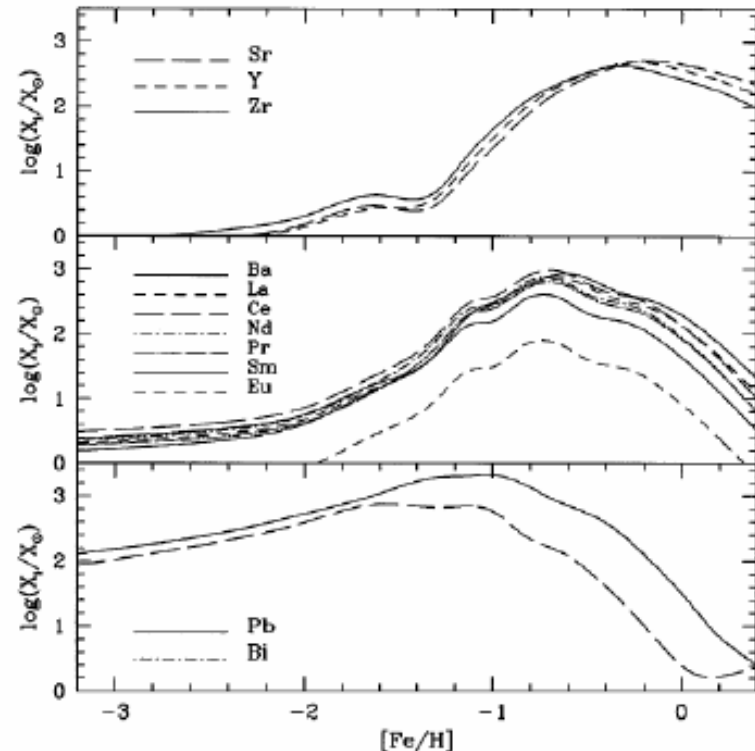
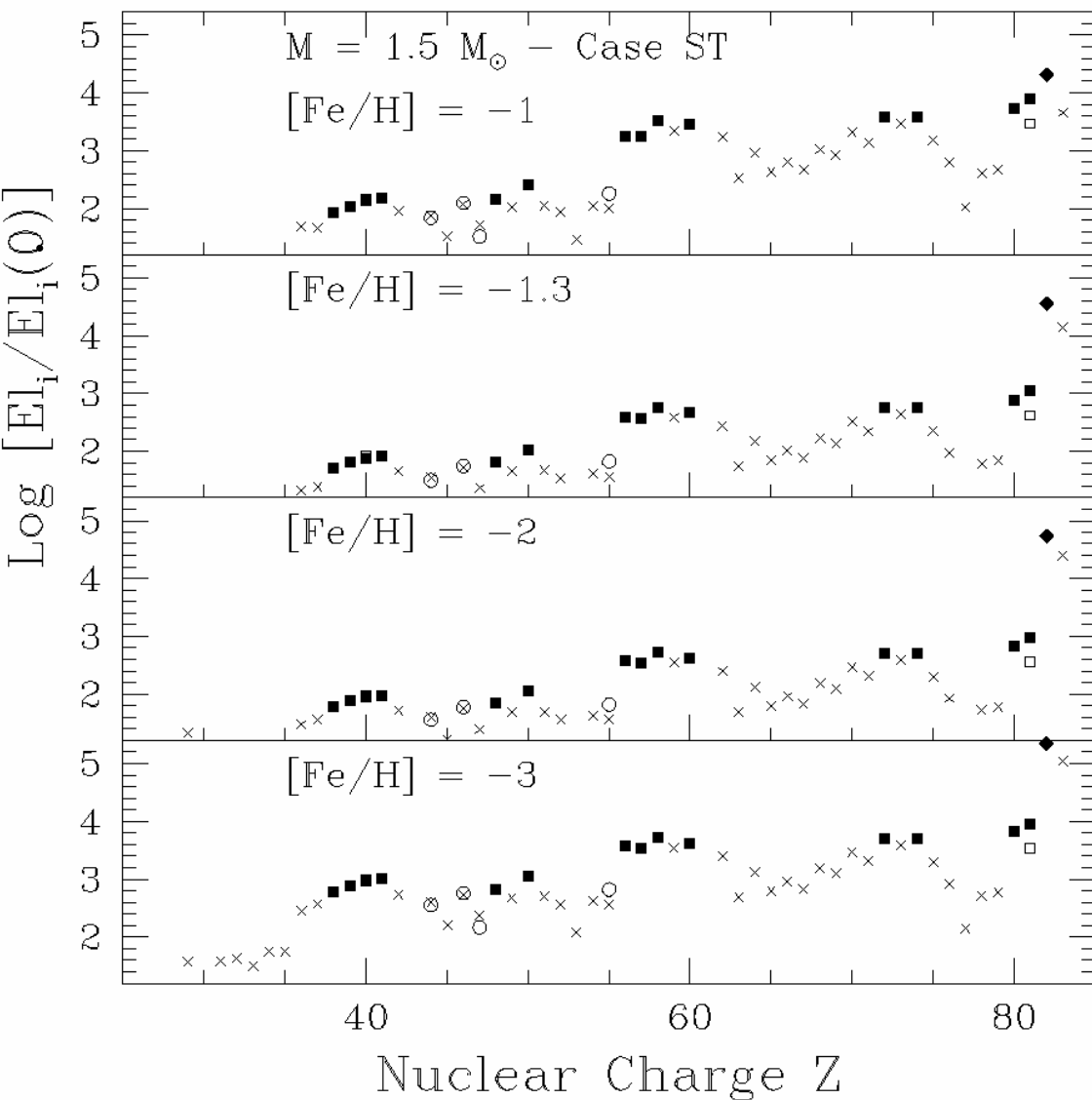


FIGURE 6. Enhancement factors (relative to solar distribution) for a $2M_{\odot}$ model with the Gallino et al (1998) “standard” ^{13}C pocket, burned radiatively between pulses. Note that lower metallicity stars produce relatively more heavy nuclides than the more metal rich stars. (From Busso et al 1999.)

Dependence of s-processing on [Fe/H]



ST Case: $4 \times 10^{-6} M_{\odot}$
of ^{13}C in the pocket



Oops! The amount of
 ^{13}C burned is a
FREE PARAMETER!

AGB stars of masses 1.5 to 3, maybe 4, recognized to be the source for the main s-process component from nuclear and spectroscopic arguments.

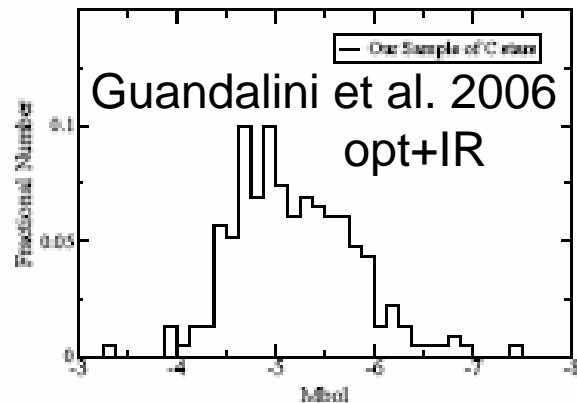
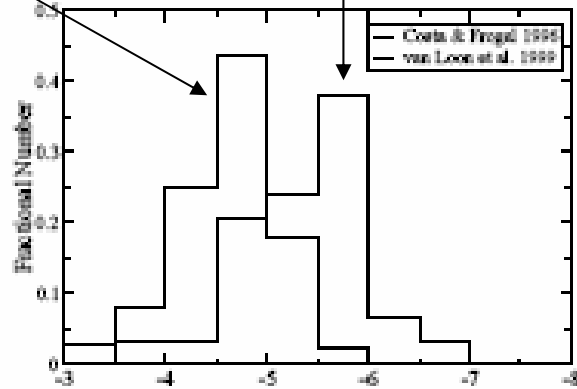
BUT:

1. Photometric surveys of TP-AGB stars (Miras, Semiregular variables) DISAGREED: they always found luminosities (magnitudes) too faint: $M_{\text{bol}} > -4.5$. (Carbon stars, rich in s-elements, seen at an average of $M_{\text{bol}} = -4$). [Blanco, McCarthy and Blanco 1980; Costa & Frogel 1996 + extragalactic surveys still going on today (Battinelli & Demers 2004, 2005)]
→ the C-star Luminosity Problem
(Modelists started to introduce **extreme convective overshoot** from the envelope to obtain dredge-up and s-element enrichment for lower luminosities).
2. No self-consistent model found for the mixing mechanisms needed to inject protons into the He&C rich layers, producing ^{13}C and then $^{13}\text{C}(\alpha, n)$. (AGB stars also sources of presolar grains: good understanding of s-process isotopes, but evidence of extramixing of unknown origin from light isotopes. **Parametric models**).
3. Poor knowledge of mass loss.

1. The C star Luminosity problem: is it real?

Costa&Frogel 96
optical

vanLoon 99
infrared



Guandalini et al. 2006; Busso et al. 2007

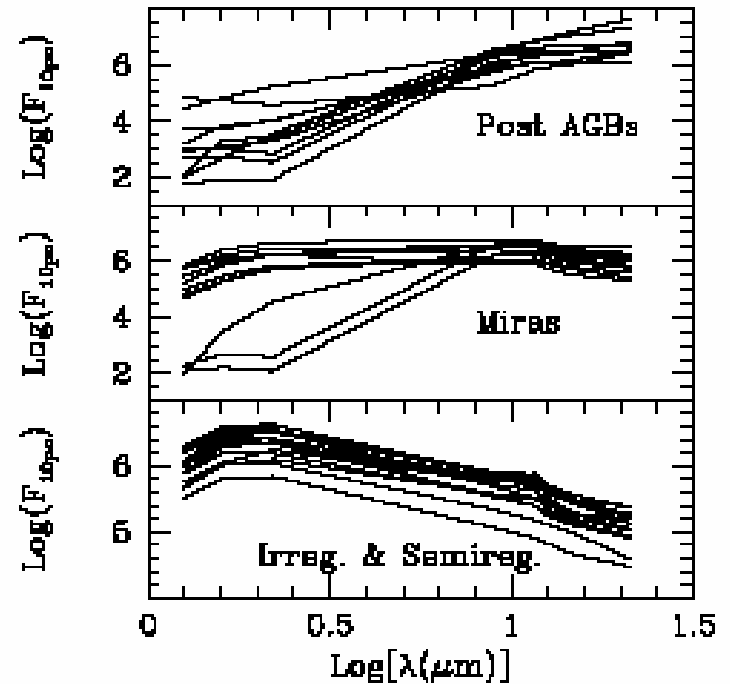


Fig. 3. The Spectral energy distribution up to $21.3 \mu\text{m}$ of a number of sources in our sample, divided according to their type, as constructed with the set of $1\text{-}\mu\text{m}$ -wide filters described in the text.

Observations vs models with no or minimal overshoot

No overshoot needed.

The C-star Luminosity problem does not exist!

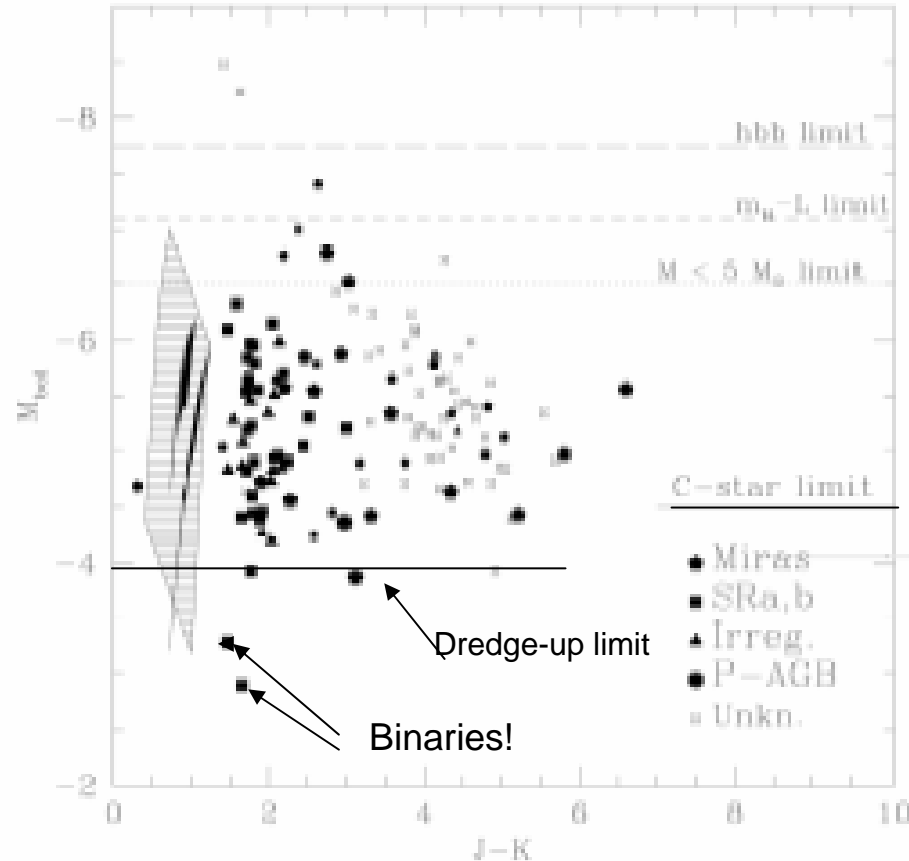
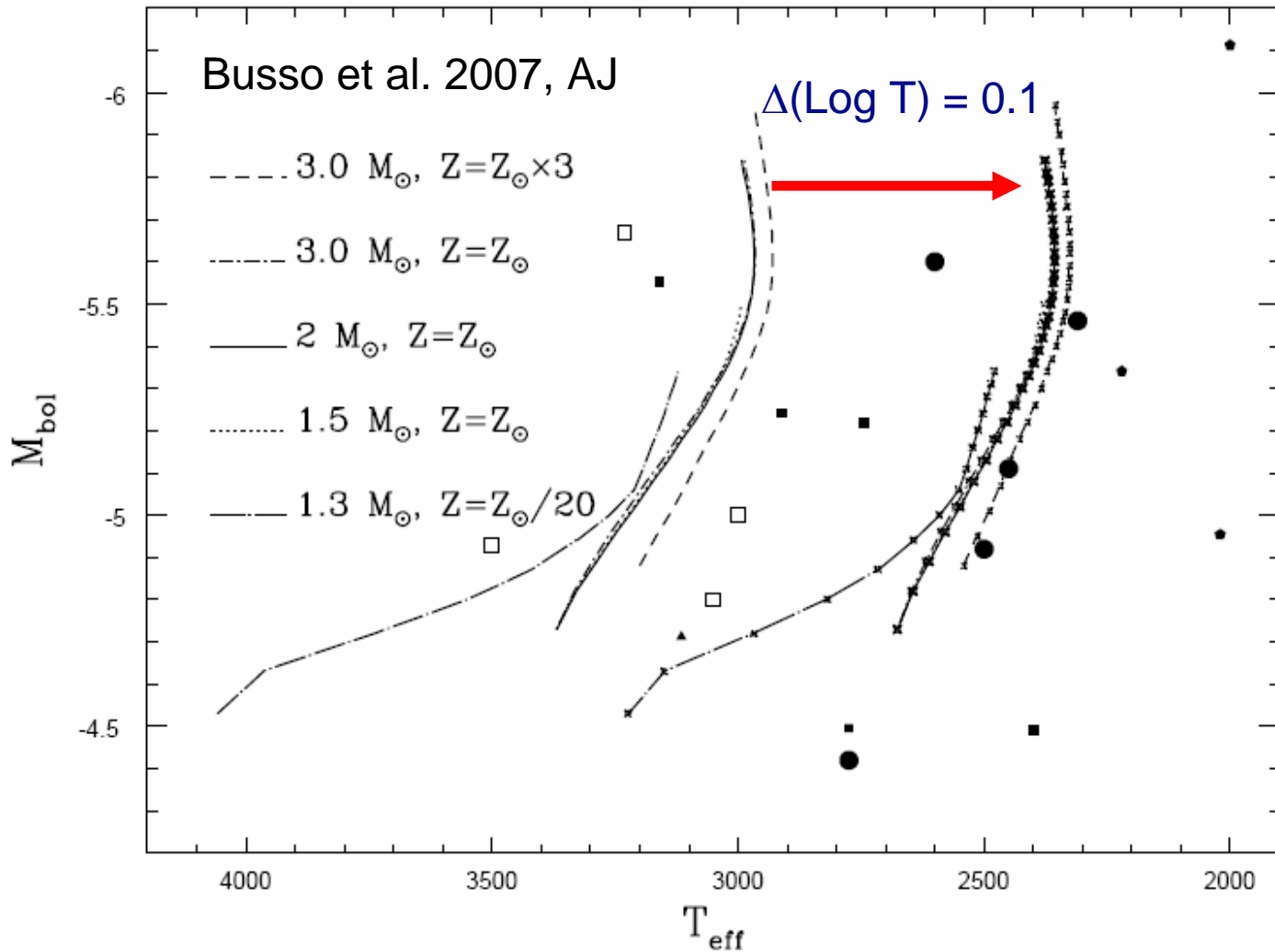


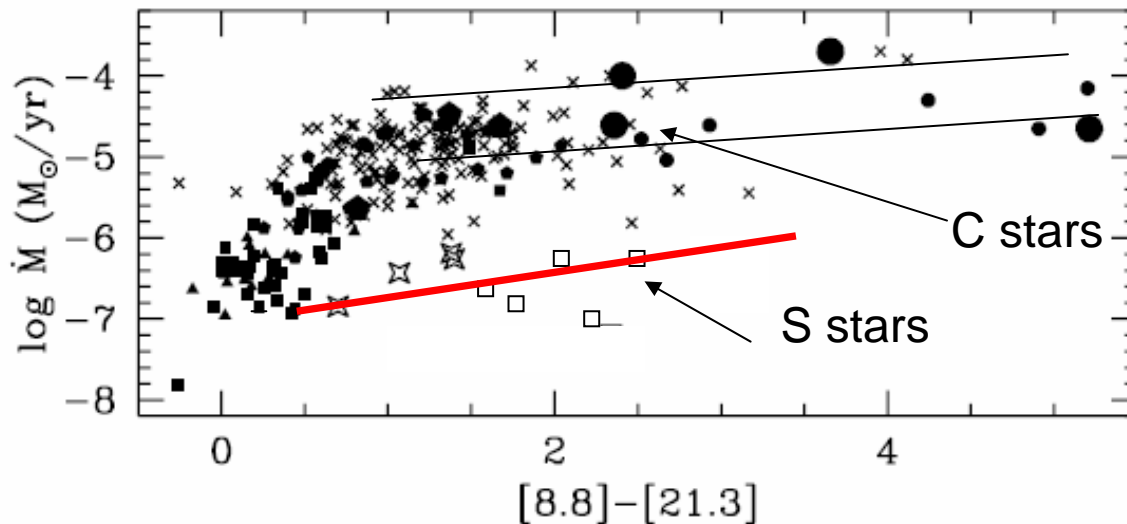
Fig. 7. The HR diagram of observed C stars in near IR, as compared to the area (dashed) covered by canonical stellar models (without hbb). The minimum limit for C star occurrence in the adopted models is indicated

Surface temperatures and opacities



$\Delta(\text{Log } T) = 0.1$ suggested by Marigo (2003) as an effect of wrong molecular opacities

Mass Loss: different history for S stars and C stars



S stars on average less mass-losing
less massive

Slow mixing scheme (parametric!)

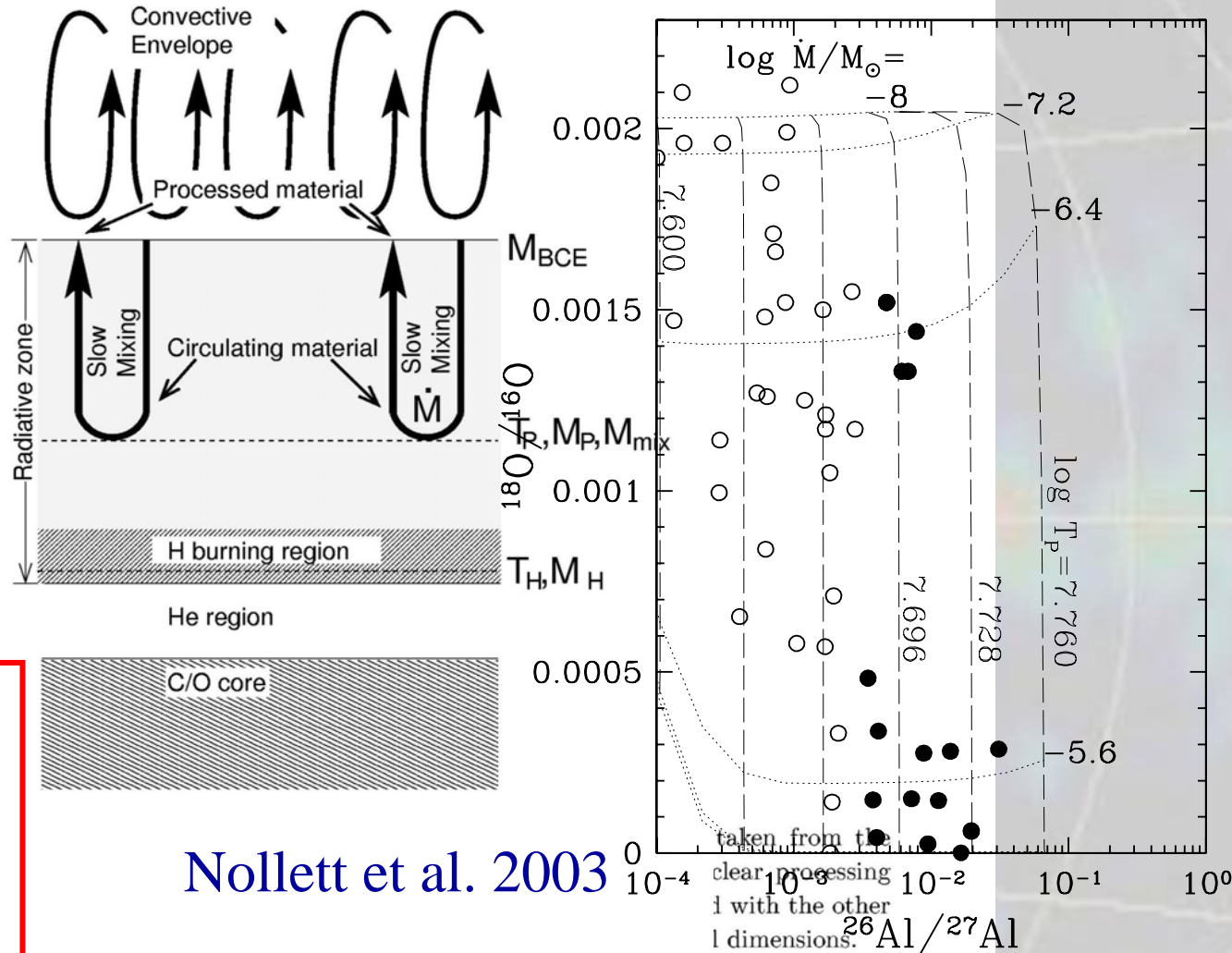
Needed for:

- C isotopes
- O isotopes
- ²⁶Al in grains

BUT:

2 free parameters!

Probably similar phenomena at TDU, below the H shell (extinguished) yield proton mixing and formation of ¹³C



← see also Lugaro et al. 2003

Trento, ECT: May 24-28, 2004

4th Vistars Workshop – Russbach, March 4-10, 2007

N observation in AGB stars

N is known to be enriched in S Stars ($C/O < 1$) compared to normal C(N) Carbon Stars (solar $[Fe/H]$). Nobody could so far explain this: I believe it is the demonstration that very low mass S stars ($M < 1.5 - 1.8 M_{\odot}$) fail to become C stars because C is burnt in cbp, producing N. If true, only above this mass limit does the sequence $M \rightarrow MS \rightarrow S \rightarrow C$ go to its end.

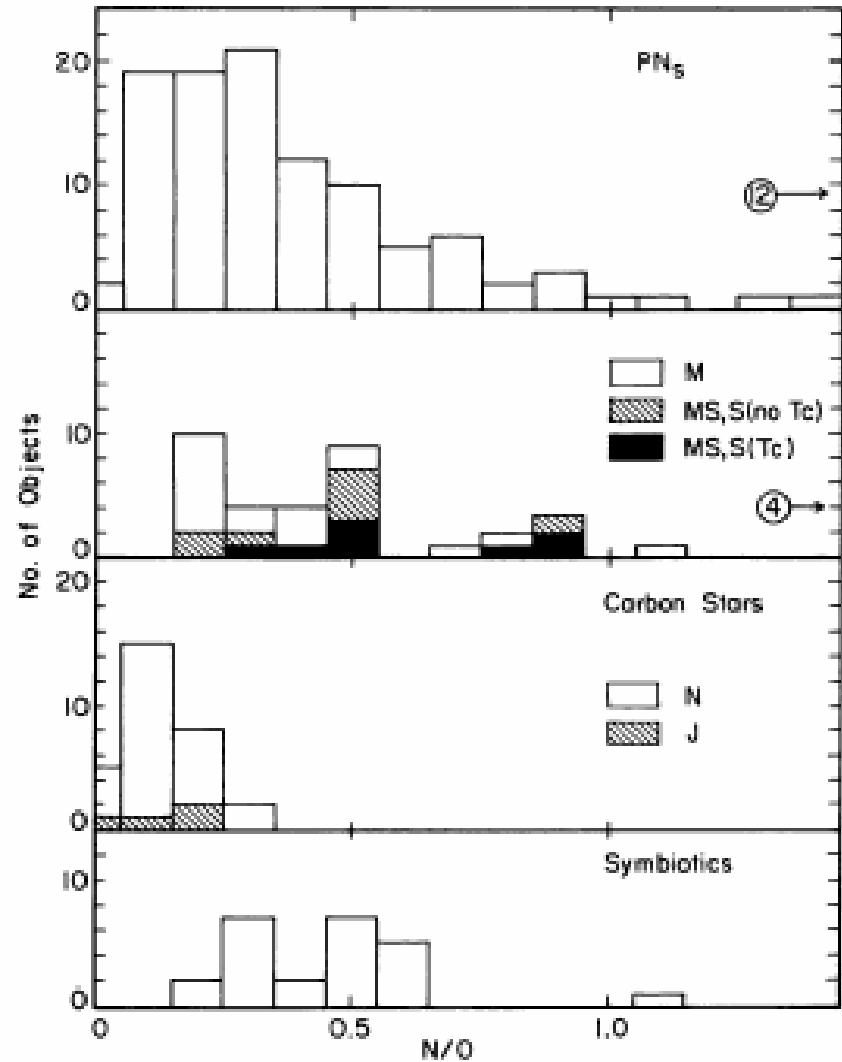


FIG. 15.—Histograms of the N/O ratio for planetary nebulae (PNs); the M, MS, and S stars; the cool carbon stars; and the symbiotic stars.

Current attempts to find physical models of extra-mixing:

Rotational shears (Denissenkov et al. 1998; Charbonnel & Do Nascimento 1998)

Gravitational waves (Denissenkov & Tout 2002)

Rayleigh-Taylor instabilities (Dearborn et al. 2006)

Magnetic buoyancy (Busso et al., in preparation)



CONCLUSIONS

Slow neutron captures occur both in the interiors of massive stars (He, C burning) and in AGB stars: these last produce the main and strong components

Analytical and semi-analytical techniques can help in constraining the stellar model conditions and get a global view of the problem

The neutron flux for the main component is due to neutron produced by α -captures on ^{13}C in the interpulse stages of AGB stars; partial ^{22}Ne burning affects some crucial nuclei.

The main neutron source is not produced self-consistently, but many attempts are made to arrive at a physical model of the extra-mixing required

Other extra-mixing phenomena are responsible for “anomalies” in CNO nuclei (+....?) models include rotation dynamical instabilities, magnetic buoyancy

The C star luminosity problem does not exist: s-process and C-producing stars have the luminosities predicted by canonical models using the Schwarzschild criterion for convection.

IR surveys are disclosing the history of mass loss enriched by s-elements

