Cosmic Thermonuclear Reactors

How stars burn fuel to shine and make new elements

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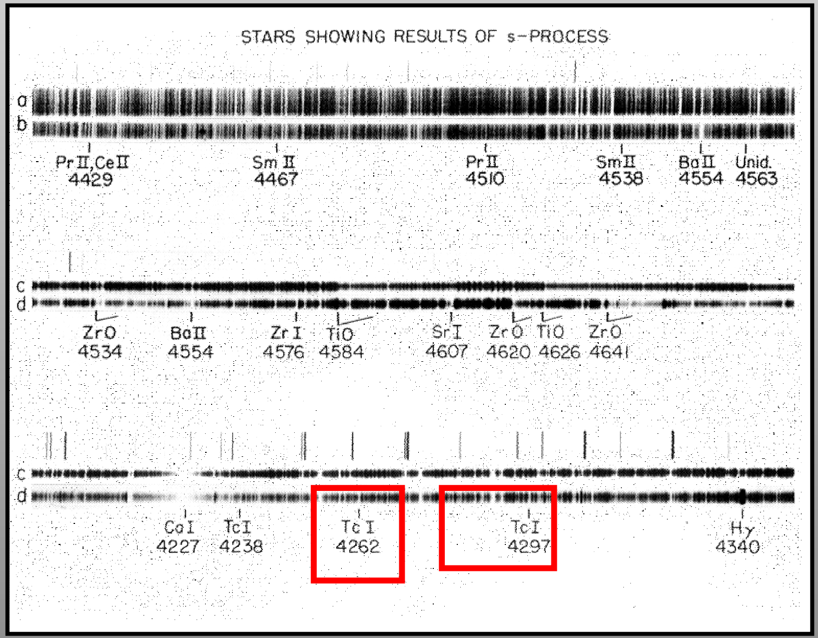
Evidence for nucleosynthesis

- **Discovery of Technicium in stars (Merril 1952)**
  - Synthesised nuclei from the interior are mixed into the photosophere.
  - Tc 99 has half-life of 2.1×10^5 yrs & lies on s- nucleosynthesis path.
  - Decay rate enhanced at high interior temperatures due to thermally populated excited mother nuclear states
  - half life becomes ~few yrs at 300 million Kelvin (Takahashi &Yokoi 1987).

Pagel Fig 1.8



proof for ongoing nucleosynthesis in stars !

Why do stars burn so slowly?

Stellar nuclear reactions can be:

- **Charged particle reactions**
- **Neutral particle (neutron) induced**

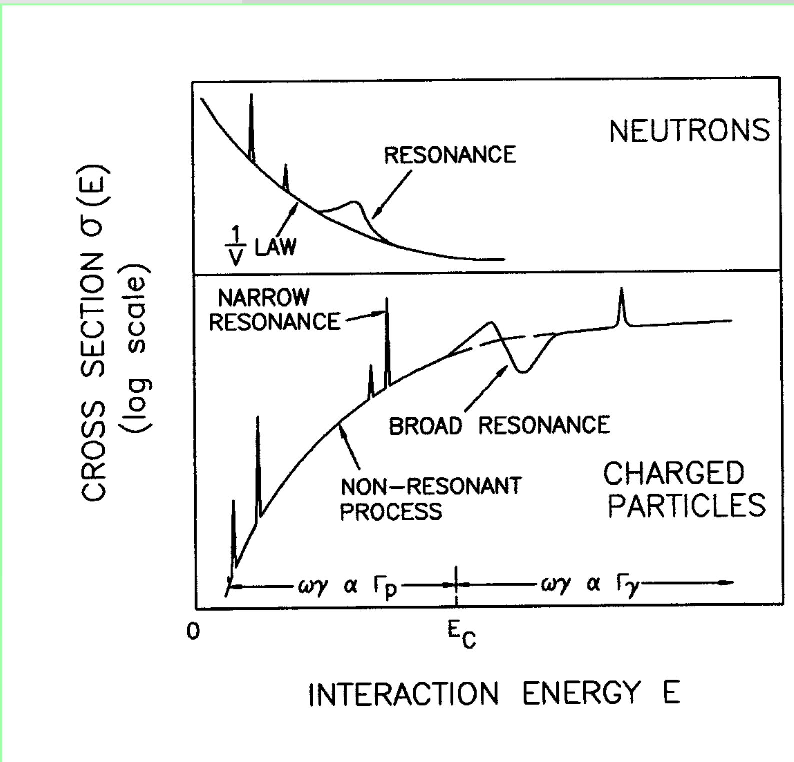
"what is possible in the Cavendish laboratory may not be too difficult in the sun"
(A.S. Eddington 1920 while referring to Sir Ernest Rutherford)

Charged particle reaction cross sections drop rapidly with decreasing energy due to the Coulomb barrier.

At the low energies relevant for thermal plasma in stars,
The cross sections become miniscule. They are therefore
Difficult to measure for the stellar conditions in the lab.

Contrast the case of neutron rexns..

Neutron and charged particle cross sections



- **Neutron cross-sections are large and increase with decreasing energy. These cross-sections can be measured in lab for stellar energies if such long lived nuclei**

  can be generated.

Charged particle cross-sections decrease rapidly with decreasing energy due to Coulomb barrier. The probability that the incoming particle penetrates the barrier simplifies at the low energy limit: E • E_c , (classical turning point R_c being much larger than the nuclear radius R_n) :--

$$P = \exp(\bullet 2 \bullet\ Z_1 Z_2\, e^2/(hv))$$
$$= \exp[\bullet 31.3\ Z_1 Z_2\ (\mu/ E)^{1/2}]$$

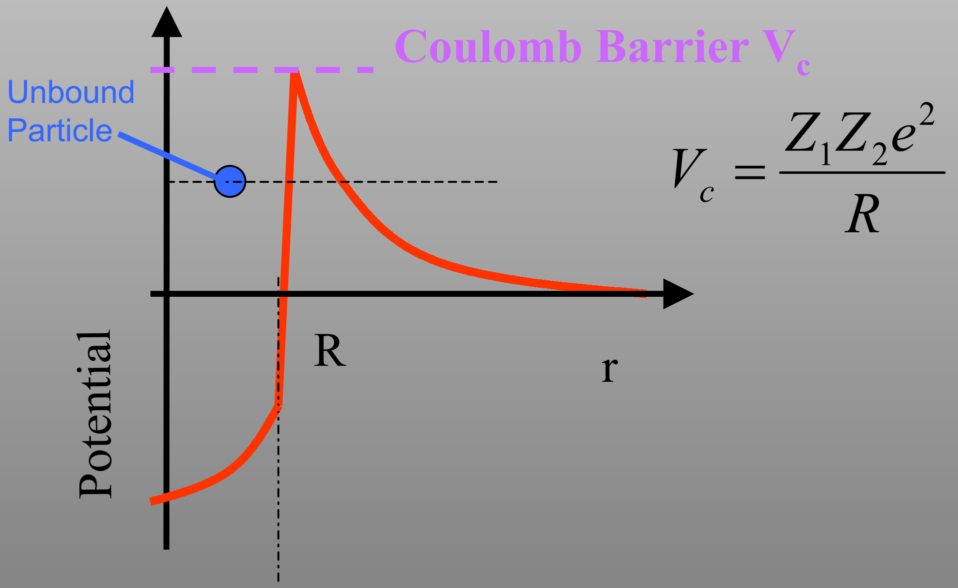
$$\sigma \cong \ \bullet\ (\lambda / h)^2 \quad \alpha \quad (1/E)$$

$$= \exp(-\,2 \bullet\ \eta)\ \ S(E) / E$$

Barrier penetration: charged particles

Coulomb barrier too high
For heavy nuclei to have the
Charged particle **(blue dot)**
Penetrate into classically
“forbidden” region and drop
To a bound state at E < 0.

Neutrons do not suffer the
Coulomb barrier



The s- and r- processes

H. Reeves 1968

- In the Z-N chart, the stable elements are represented by black squares.
- Many isobars have 3 stable members.
- If we raise a vertical axis M above the Z-N plane, we have a diagonal valley.
- Diagram to the right is a section along a line A=Z+N= even.
- The elements at the bottom of valley are the s- elements; they form a nearly continuous sequence.
- The isobars to the right of the valley (so-called r- elements) are comparatively richer in neutrons than s-elements. Their total abundance are nearly comparable to the s-elements.

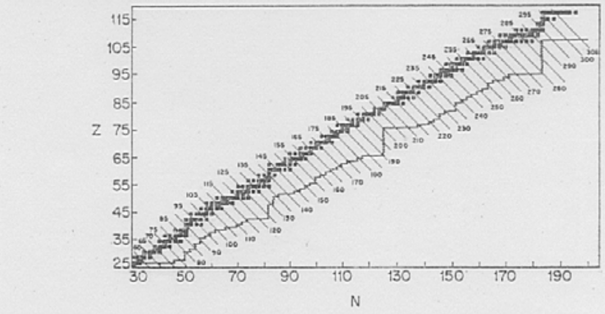
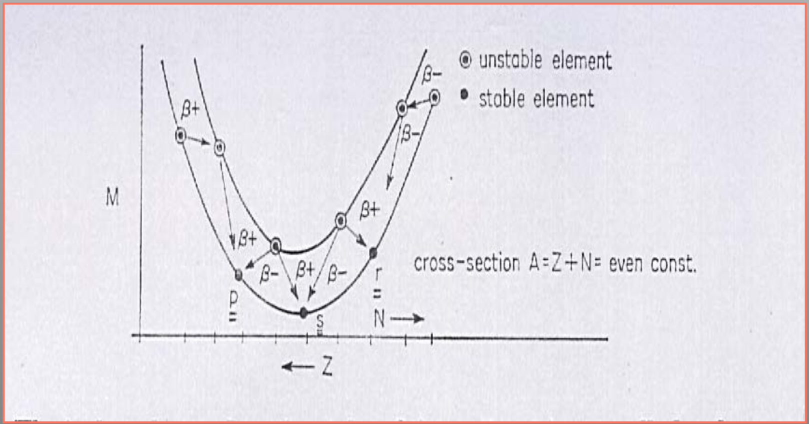


FIG. IV–3. The Z–N plane of the heavy elements. The black squares are the stable elements; we have a valley of nuclear stability. At the bottom of the valley (nearly continuous line), the s elements. To the right and to the left (isolated squares) the p and r elements. Further to the right, the thin line represents the path of the r process (Clayton, 1962).



Neutron captures Slow and Rapid compared to Beta-decays

process	conditions	timescale	site
s-process (n-capture, ...)	**T~ 0.1 GK** **τ_n~ 1-1000 yr, n_n~10^{7-8}/cm^3**	**10^2 yr and 10^{5-6} yrs**	**Massive stars (weak)** **Low mass AGB stars (main)**
r-process (n-capture, ...)	**T~1-2 GK** **τ_n ~ μs, n_n~10^{24} /cm^3**	**< 1s**	**Type II Supernovae ?** **Neutron Star Mergers ?**
p-process ((γ,n), ...)	**T~2-3 GK**	**~1s**	**Type II Supernovae**

The s-process:

- **When neutron captures are much slower than typical beta decay rate, 1) the weak reactions maintain the Z-N equilibrium; every time a neutron is captured and the A+1 nucleus beta decays to a nucleus of greater stability; 2) rate of synthesis and the "mass flow" to heavier nuclei is proportional to the rate of neutron capture; 3) the path of nucleosynthesis sticks to the valley of beta stability.**

The s-process path in (N,Z) plane

Rolfs and Rodney 1988

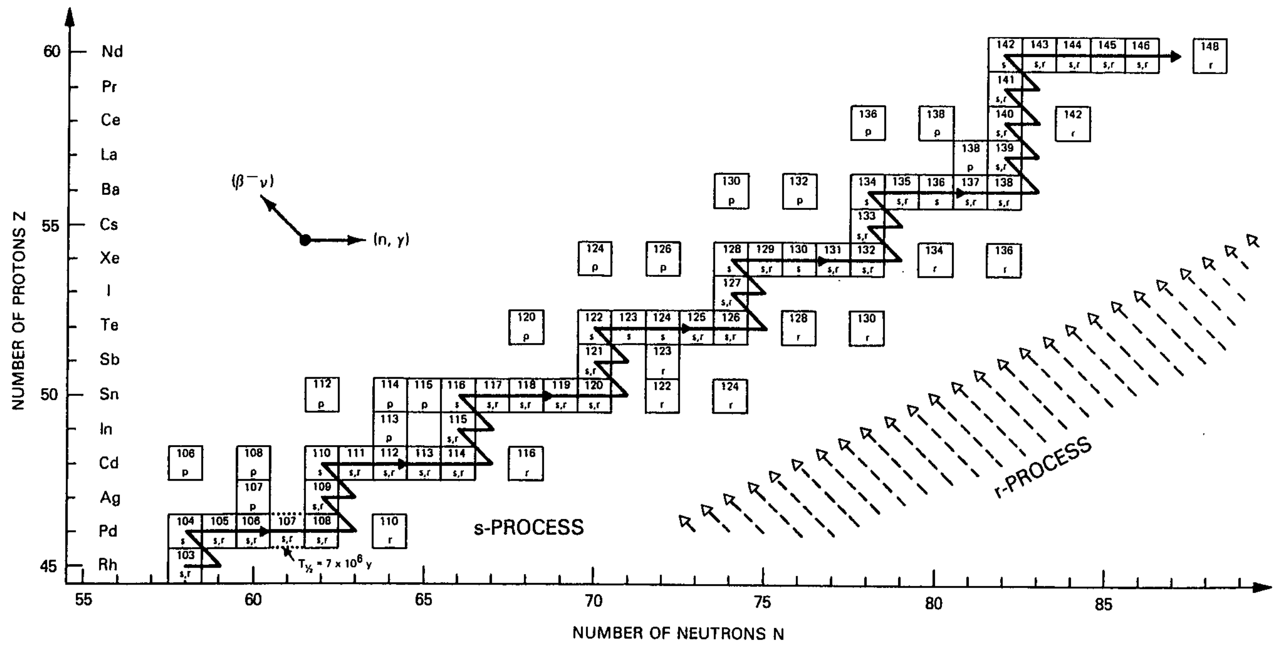
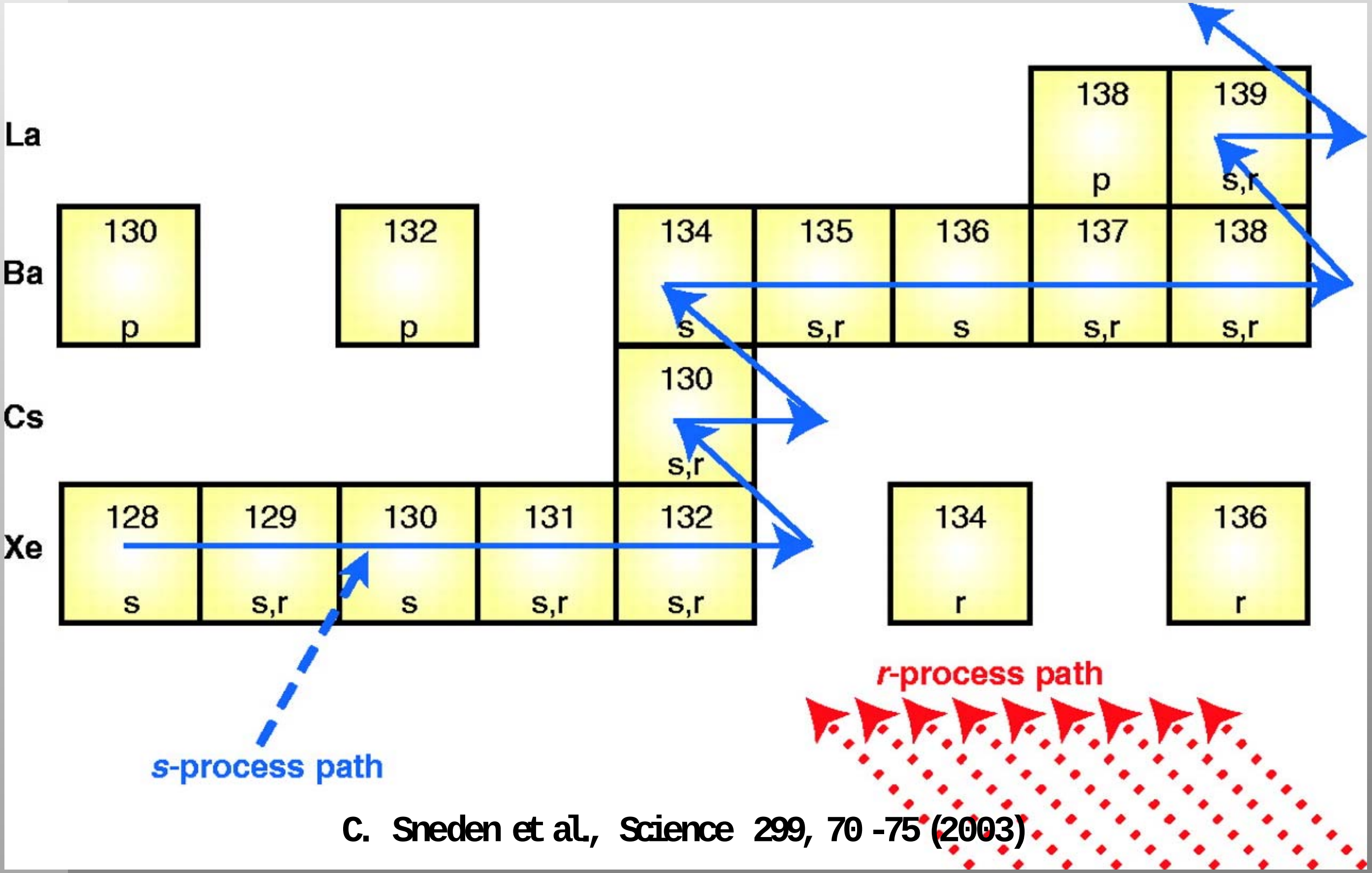


FIGURE 9.7. A section of the chart of nuclides and the *s*-process path through the elements in this mass region. Note that the path bypasses the *p*- and *r*-process nuclei. The *r*-process nuclei are the end products of an isobaric β-decay chain, the flow of which is indicated by the inclined arrows, from neutron-rich progenitors produced in an intense neutron flux. When this flux ceases, the progenitors "rain" down to the valley of stability via β-decay.

S-only, r-only and s r-nuclei

- A nucleus can be in general be synthesised by a combination of s- and r-processes (usually at different sites, stars etc).
- Some nuclei can be due only to s-process or r-process, since they are shielded by other nuclei from the alternate process' path. E.g. in the next figure, ^{134}Ba (s-only nucleus) is shielded from the r-process path by ^{134}Xe. Similarly, ^{134,136}Xe (r-nuclei) are shielded from s-process path.

s- and r-process paths near Xe-Cs-Ba-La



C. Sneden et al., Science 299, 70-75 (2003)

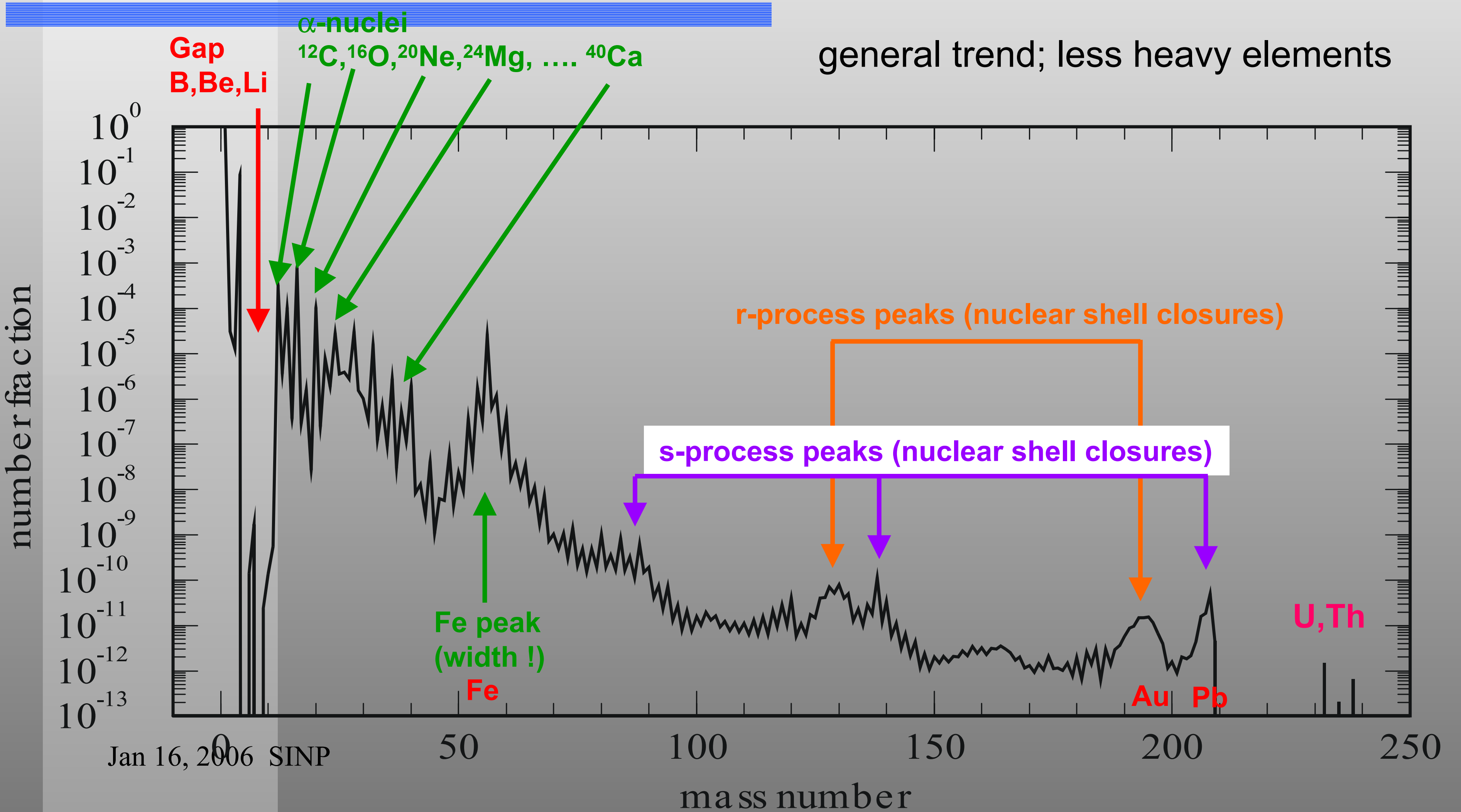
The r-process

The plot of the s-process path in the (N,Z) plane shows that certain Nuclei on the neutron rich side of the valley of stability will be missed by the s-process. A second mechanism for synthesizing heavy nuclei also proposed by Burbidge et al (1957) is the r-process in which:

- **An equilibrium is maintained in $(n,\gamma) \Leftrightarrow (\gamma,n)$ reactions. Neutron capture Fills up the available bound levels in the nucleus until this equilibrium sets in.**
- **The nucleosynthesis path is along exotic neutron-rich nuclei that would Be highly unstable in the laboratory.**
- **The rate of nucleosynthesis is controlled by the beta-decay rate. Each beta-decay converting $n \rightarrow p$ opens up a hole in the Fermi sea allowing another neutron to be captured. The r-process abundance is : $A(Z,N) \propto [\omega_\beta (Z, N)]^{-1}$.**
- **The neutron capture is fast comapred to beta-decay rates.**

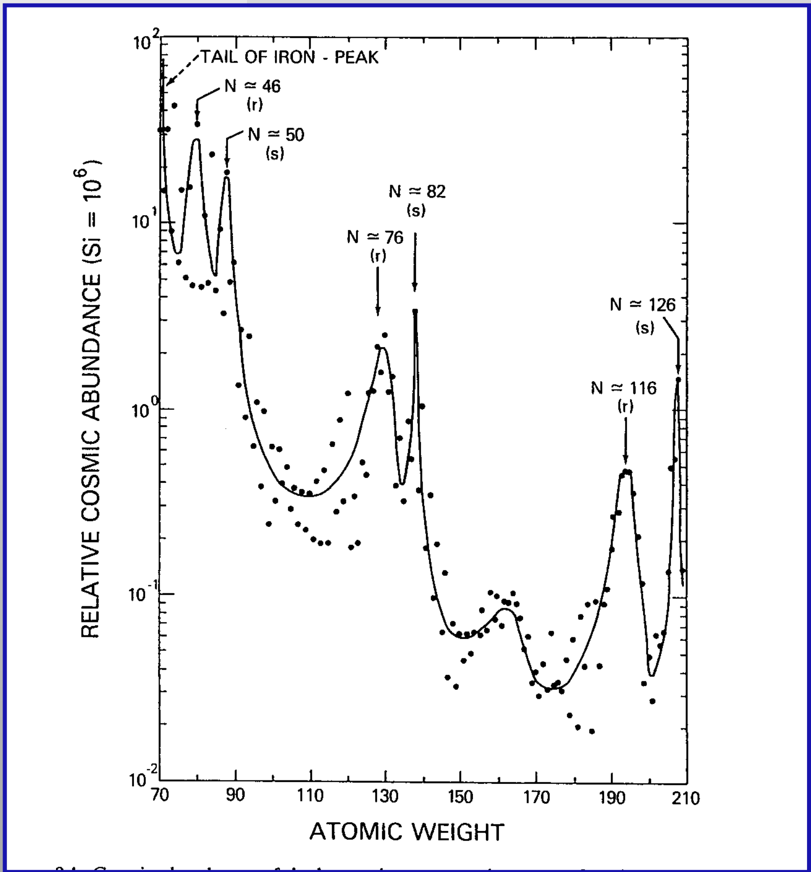
H.Schatz 2004

Hydrogen mass fraction	**X = 0.71**
Helium mass fraction	**Y = 0.28**
Metallicity (mass fraction of everything else)	**Z = 0.019**
Heavy Elements (beyond Nickel) mass fraction	**4E-6**



Element Abundance and neutron capture cross sections

Rolfs and Rodney1988



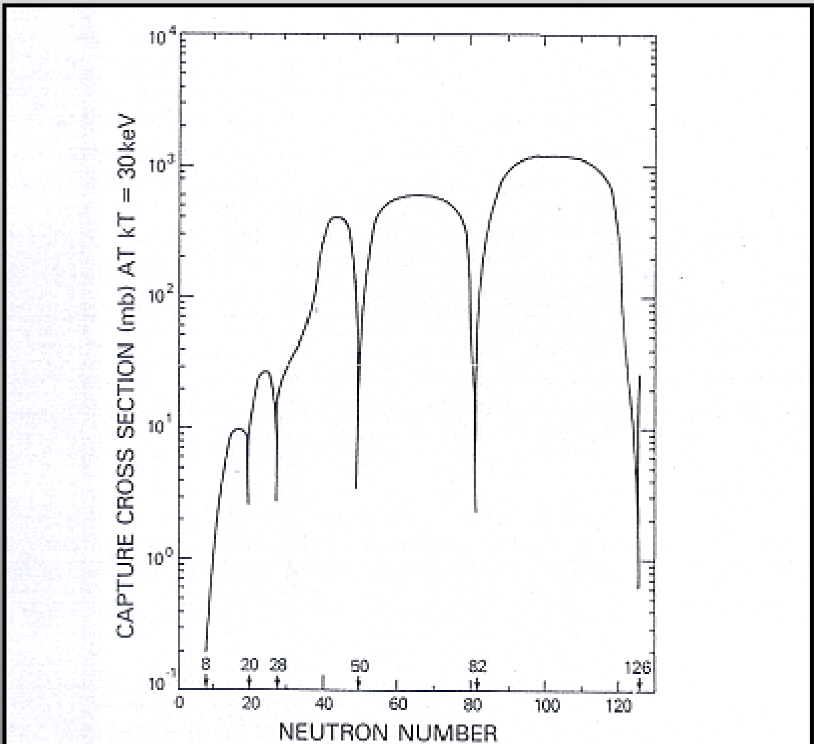


FIGURE 9.6. The measured average neutron-capture cross sections $\langle \sigma \rangle$ at 30 keV are shown schematically as a function of neutron number N of the nuclei (All71, Ulr82, Käp82, Alm83). Note the large dips near the neutron closed shells at N = 8, 20, 28, 50, 82, and 126.

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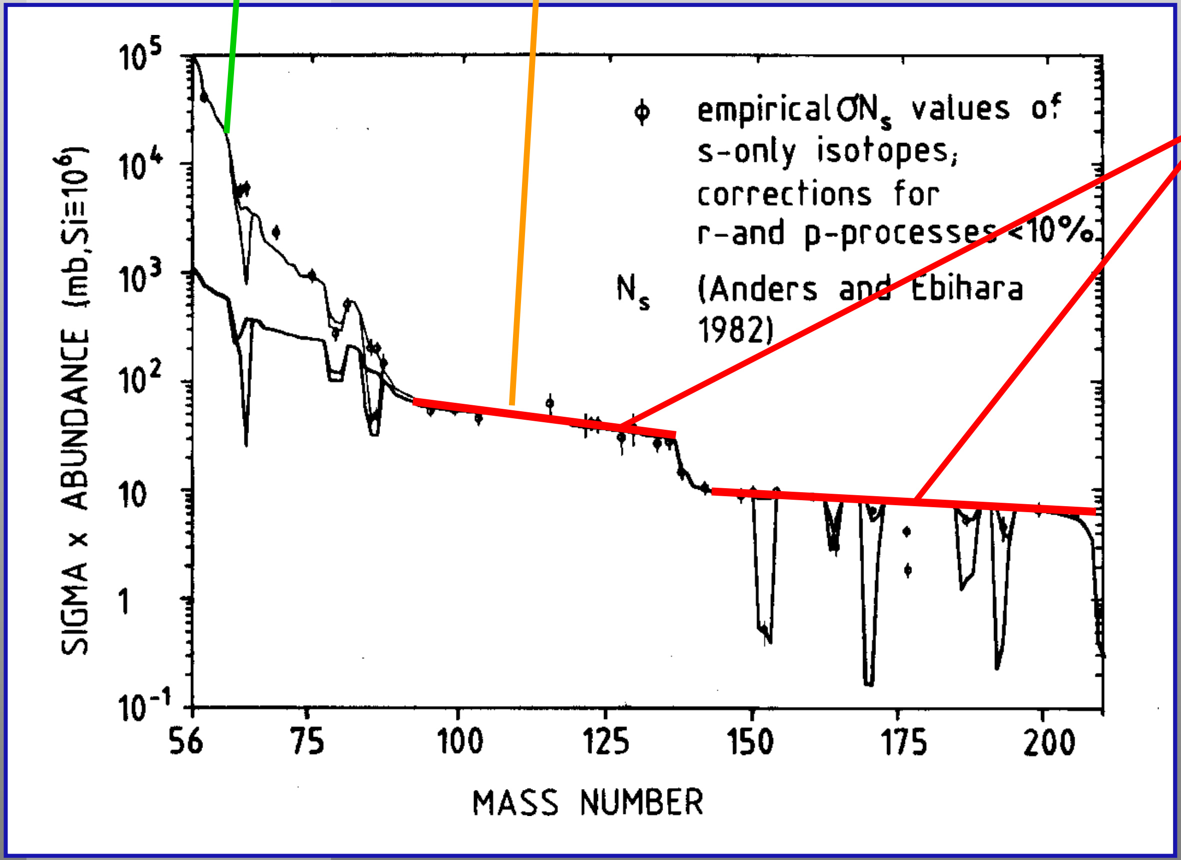
The sites of the s-process

weak s-process: **core He/ shell C burning in massive stars**

main s-process: **He shell flashes in low mass TP-AGB stars**



approx. steady flow

$$Y\lambda \propto Y\sigma_{(n,\gamma)} \approx \text{const}$$

↓

can easily interpolate s-contribution for s+r-nuclei **if neutron capture cross sections are known**

The weak s-process and its neutron source

In massive stars (e.g. 25 Msun) during core Helium burning and Shell C-burning, ^{14}N is rapidly burnt to ^{22}Ne by successive alpha Captures and a beta+ decay.

He burning core contains ^{14}N initially.

The product ^{22}Ne then acts as a neutron source in the reaction $^{22}Ne(\alpha, n)^{25}Mg$ towards the end of Helium burning when Temperature is about $3 \cdot 10^8$ K .

Iron group nuclei serve as seed nuclei for a secondary s-process

The main s-process

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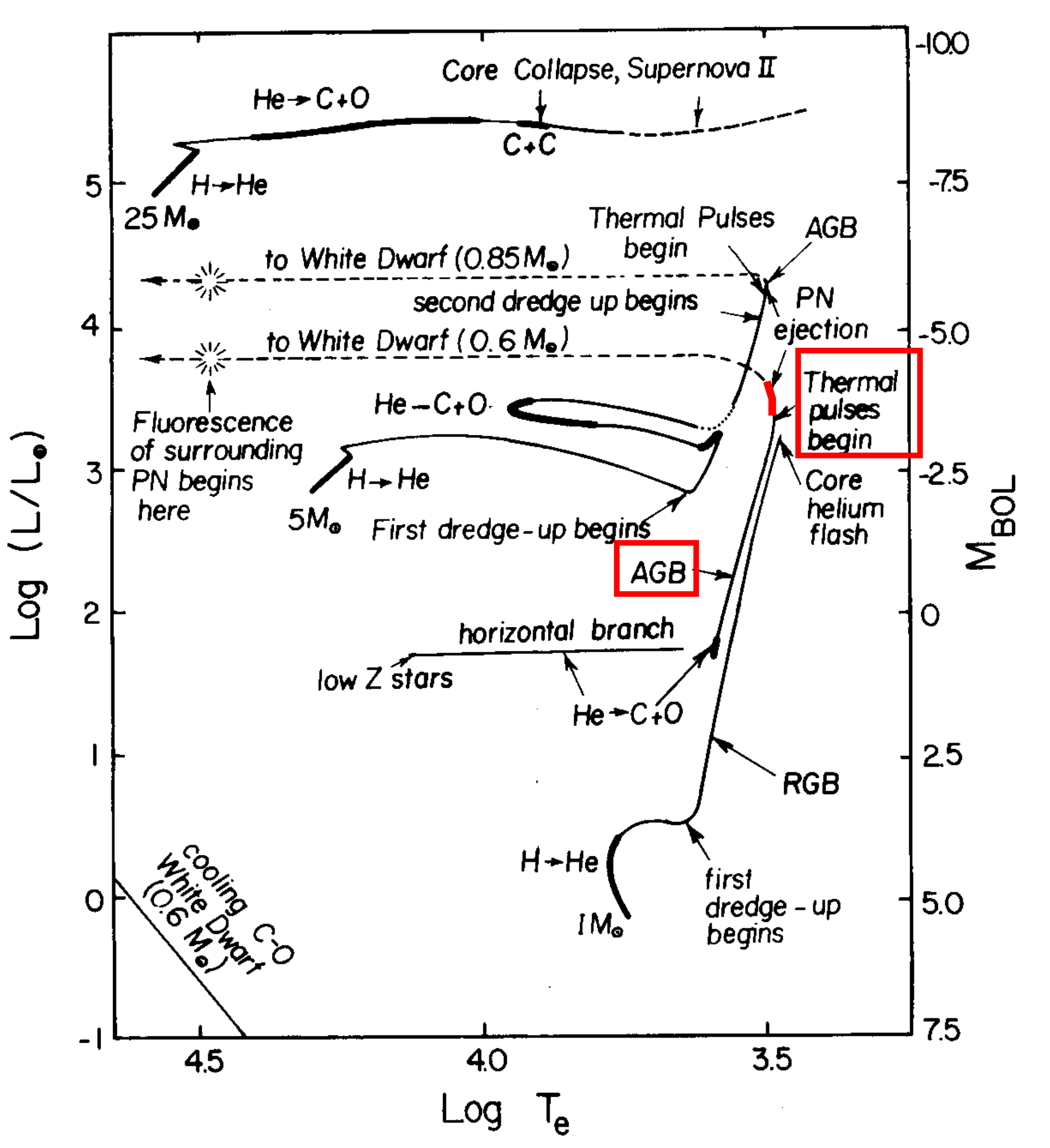
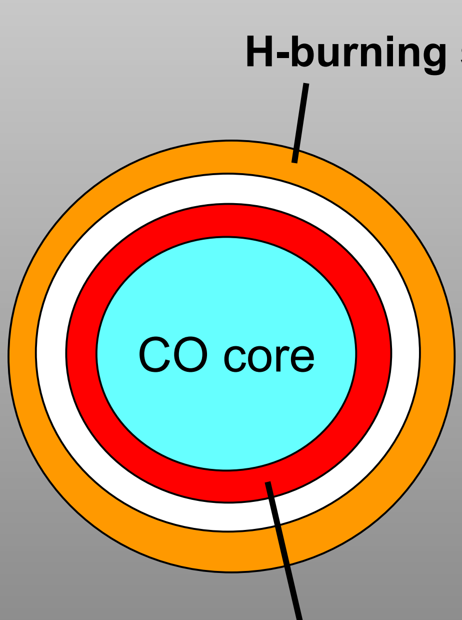
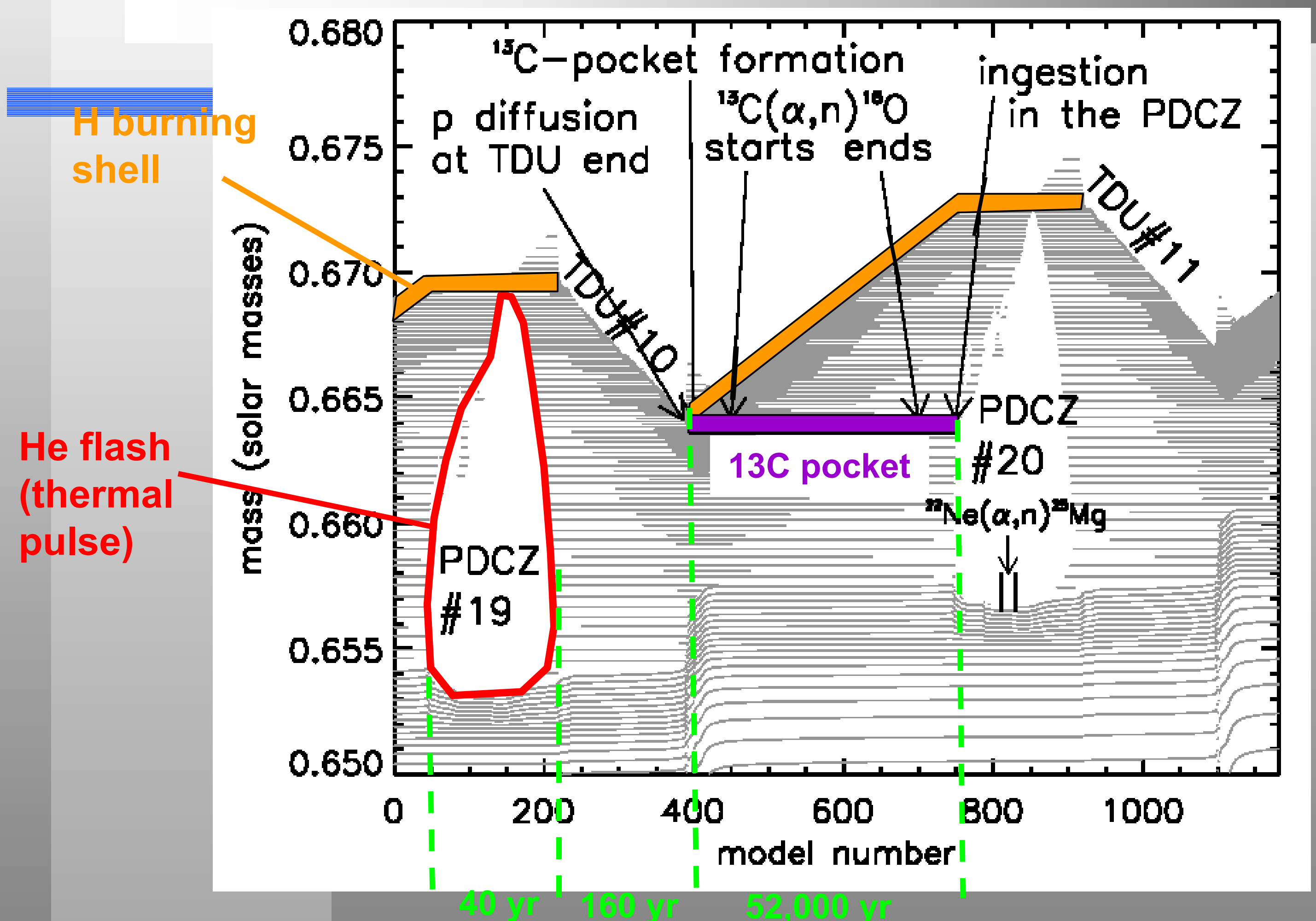


Site: low mass TP-AGB stars
(thermally pulsing stars on the asymptotic giant branch in the HR diagram, 1.5 - 3 solar masses)



unstable - burns in flashes
(thin shell instability)

• number of He flashes in stars life: few – 100
• period of flashes: 1000 – 100,000 years



s-process in:

- He flash via $^{22}Ne(\alpha,n)$
- ^{13}C pocket via $^{13}C(\alpha,n)$

(Lugaro et al. ApJ586(2003)1305)
Adopted by H. Schatz

Neutron sources in s-process

Conditions during the main s-process

	$^{13}C(\alpha,n)$ in pocket	$^{22}Ne(\alpha,n)$ in He flash
Temperature	**0.9×10^8 K**	**2.7×10^8 K**
Neutron density	**7×10^7 cm^{-3}**	**10^{10} cm^{-3}**
Duration	**20,000 yr**	**few years**
Neutron exposure τ *)	**0.1 / mb**	**0.01 / mb**

weaker but longer main contribution (90% of exposure)

short, intense burst slight modification of abundances (branchings !)

s-process……

The time dependence of abundance N_A of An s-only isotope of A is given by:

$$dN_A/dt = N_n(t)\, N_{A-1}(t) \langle\sigma v\rangle_{A-1} - N_n(t)\, N_A(t) \langle\sigma v\rangle_A - \lambda_\beta(t)\, N_A(t)$$

The destructive terms in above equation can be combined into: $N_A(t)\,(\lambda_n + \lambda_\beta)$.

When the beta-decay rate is much faster than the capture rate $\lambda_\beta >> \lambda_n$, the radioactive nuclei decay quickly to their adjacent isobars of higher Z and their own abundances can be completely neglected.

In the other extreme case when $\lambda_\beta << \lambda_n$, the radioactive nuclei are treated as stable nuclei. This is ok except in the s-process branching points.

More on s-process

- Stellar temperature is constant during s-process. Can therefore write:

$<\sigma v> = \sigma_A v_T$, where the σ_A is the Maxwellian averaged neutron capture cross section and v_T is thermal velocity. Then the equation:

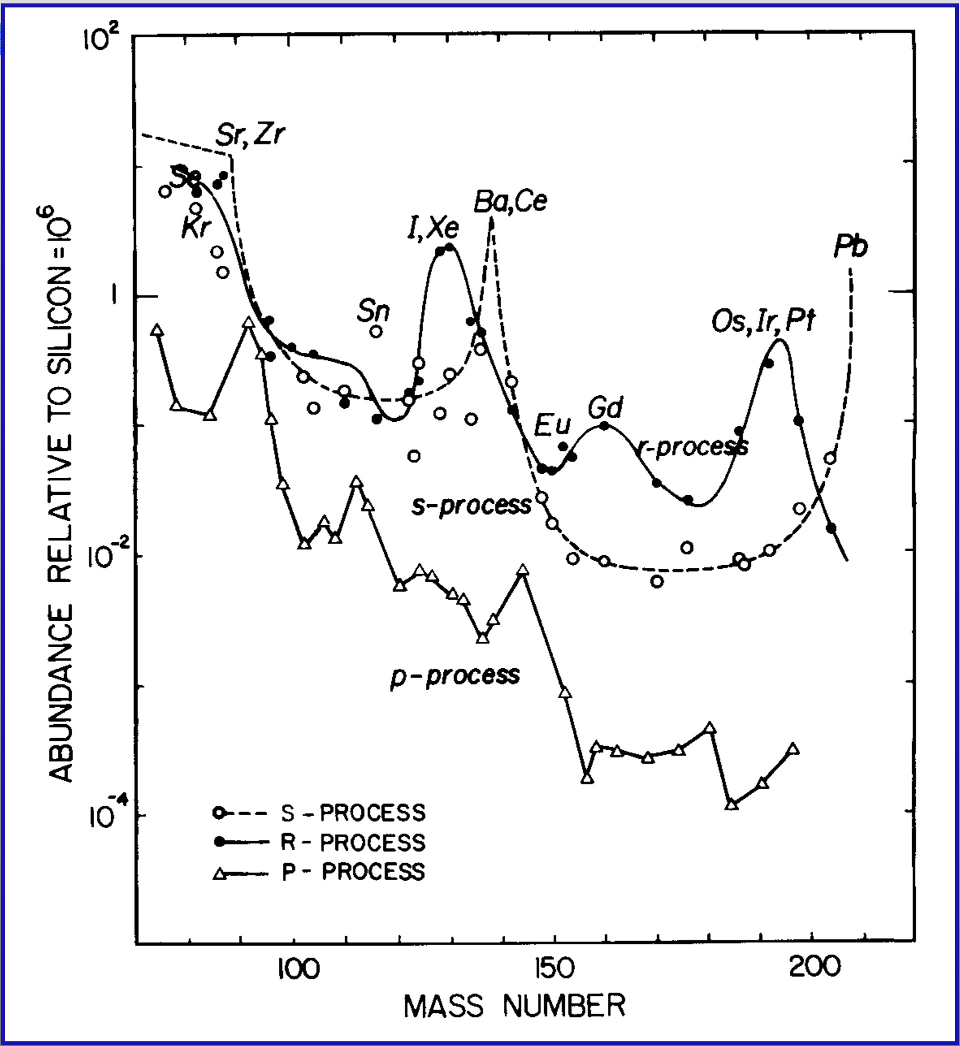
$$dN_A/dt = v_T N_n(t) (\sigma_{A-1} N_{A-1} - \sigma_A N_A)$$

The coupled terms are self-regulating. I.e., the effect is to minimize the difference between the terms on the R.H.S. and to reach an equilibrium state where the LHS = 0. In the mass region between neutron magic numbers, we there get:

$$\sigma_A N_A = \sigma_{A-1} N_{A-1} = \text{constant}$$

Heavy elements in the solar system

The Fig. on the right from Pagel shows contribution of several processes to the Abundance of each element. In turn each process can be a mixture of several events.

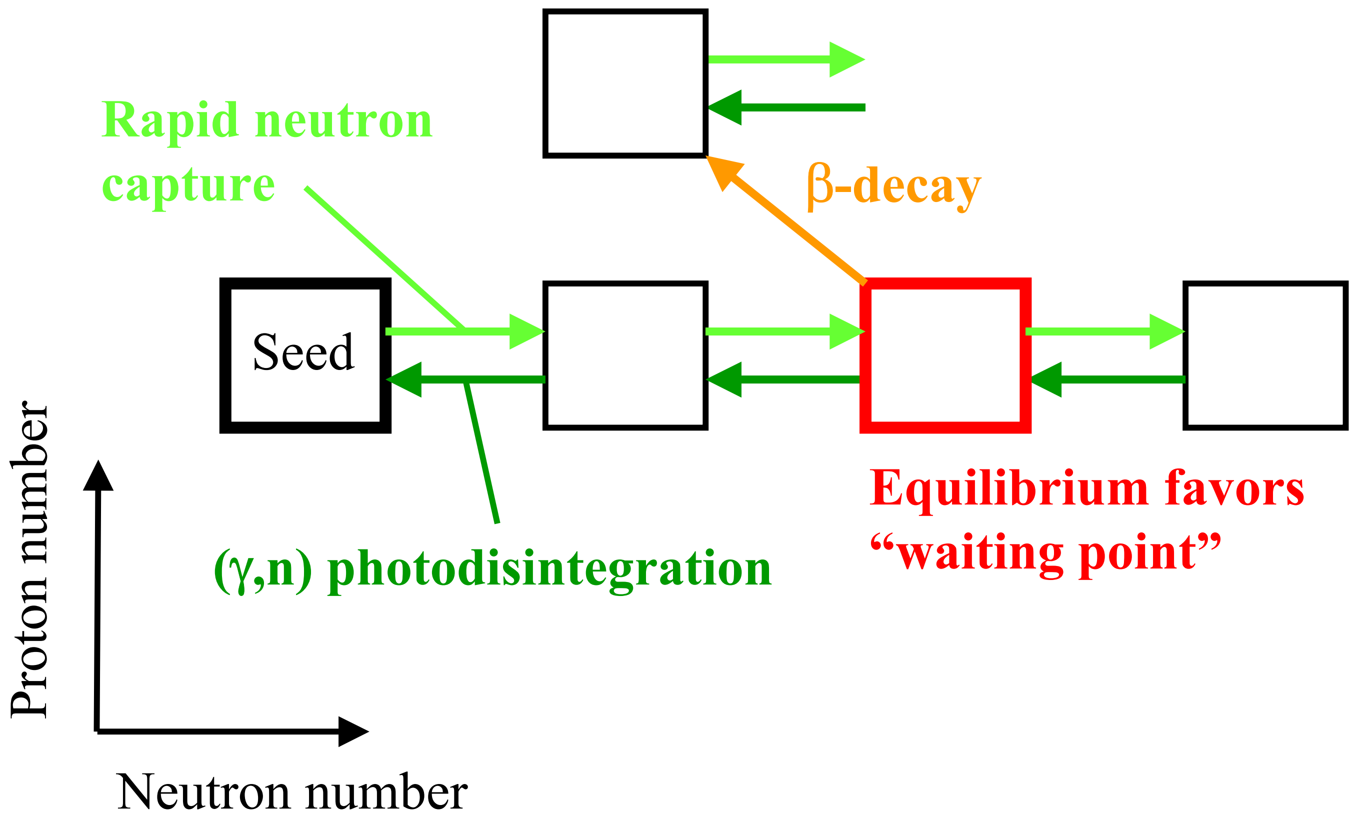


The r-process

Temperature: ~1-2 GK

Density: 300 g/cm3 (~60% neutrons !)

neutron capture timescale: ~ 0.2 μs



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(n, γ) Equilibrium in r-process nucleosynthesis

As the neutron number density increases, the neutron binding energy Q_n decreases and rapid neutron addition stops when Q_n approaches zero energy. This happens when the (γ, n) photodisintegration rate balances out the neutron capture rate. The (n,γ) reaction is an exothermic reaction and the thermally averaged reaction has:

$$\langle \sigma v \rangle_{(n,\gamma)} = \left(\frac{2\pi}{\mu k T} \right)^{3/2} \frac{\Gamma_n \Gamma_\gamma}{\Gamma} e^{-E/KT}$$

Here E ~ 0 is the resonance energy.

(n,γ) reactions (continued)

$$r_{(n,\gamma)} = N_n N_A \left(\frac{2\pi}{\mu kT} \right)^{3/2} \frac{\Gamma_\gamma \Gamma_n}{\Gamma}$$

Compare this with the reverse (γ, n) reaction rate with the photon number density in the high energy tail (2 slides later)

$$\approx \frac{1}{N_\gamma \pi^2} \varepsilon^2 e^{-\varepsilon / kT} d\varepsilon$$

$$\text{with : } N_\gamma \approx \frac{\pi}{13} (kT)^3$$

(n, γ) equilibrium (contd.)

- Use resonant cross section in the (γ,n) direction with photon wavenumber proportional to the energy:

$$\sigma_{(\gamma,n)} = \frac{\pi}{\varepsilon^2} \frac{\Gamma_\gamma \Gamma_n}{(\varepsilon - E_r)^2 + (\Gamma/2)^2}$$

and with $c = 1$,

$$\langle \sigma v \rangle = \frac{1}{\pi^2 N_\gamma} \int_0^\infty \varepsilon^2 e^{-\varepsilon/kT} d\varepsilon \frac{\pi}{\varepsilon^2} \frac{\Gamma_\gamma \Gamma_n}{(\varepsilon - E_r)^2 + (\Gamma/2)^2}$$

Here, $N_\gamma \sim \pi (kT)^3/13$ is the photon normalization factor.

(n,γ) reaction (contd..)

For a sharp resonance, the integral over The numerator yields: $(2\pi/\Gamma)$. Thus,

$$\langle \sigma v \rangle \approx \frac{\Gamma_n \Gamma_\gamma}{N_\gamma} e^{-(E_r/kT)} \frac{2}{\Gamma}$$

The (γ,n) rate is then:

$$r_{(\gamma,n)} \approx 2N_{A+1} \frac{\Gamma_\gamma \Gamma_n}{\Gamma} e^{-E_r/kT}$$

Neutron density for (n,γ) equilibrium

Equate (n,γ) and (γ,n) rates with $N_A \sim N_{A+1}$

$$N_n \approx \frac{2}{(\hbar c)^3}\left(\frac{\mu c^2 kT}{2\pi}\right)^{3/2} e^{-E_r/kT}$$

The above neutron density requires the neutron Binding energy E_r and neutron reduced mass with a A~150 nuclear target.

R-process and neutron binding energy

- With typical r-process conditions, $T_9 \sim 1$

And $N_n \sim 3 \times 10^{23}$ cm^{-3}, we get:

$$E_r \sim 2.4 \text{ MeV}$$

The neutrons are thus bound by about 30 times the kT, a value that is still small compared to a typical binding energy of 8 MeV for a normal nucleus near the valley of beta stability.

What is the site of r-process?

(has been debated over many years and remains still tentative:)

- **The r-process requires exceptionally explosive conditions: $\rho \sim 10^{20}$ cm^{-3}, T ~ 0.1 MeV, t ~ 1 sec.**
- **Both primary (requiring no pre-existing metals) and secondary sites (neutron capture on seeds) have been proposed and leads to different evolution with galactic metallicity.**

Sites of r-process …..

- **Primary sites include:**

  1) neutronized atmosphere above proto neutron star in a Type II SN

  2) neutron rich jets from supernovae or neutron rich mergers

  ……

Sites of r-process …..

- Secondary sites (where the ρ (n) can be lower):

  1)He/C zones in Type II SNe

  2) Red Giant Helium flash

  3) ν-spallation neutrons in the Helium zones

  ……

R-process site

- Balance of evidence favours primary sites: (see W. Haxton, Chap 5)
- Ultra Metal Poor (UMP) stars ([Fe/H] ~ -1.7 to -3.1) in the galactic halo (Sneden et al 2003) show an r-process element distribution v. similar to Sun for Z > 55. It appears that in the early galaxy, all of the elements, even those like Ba that are now being formed in s-process, were in fact synthesised then in a unique process: the main r-process. But discrepancies below Ba (Z=56) between solar and UMP abundances suggest a weak r-process.
- Also the iron content is variable. These old stars must have then formed within ages short compared to galactic mixing times. Thus the r-process material in these stars must be from one or a few local SNe.

Scenario for r-process primary sites

R-process conditions realized in a type II SN

As the material just above the proto-neutron star boundary is blown off, the very hot neutron rich material containing neutrons and protons cools and at first assembles to α-particles in a freeze-out, locking up all the protons. Then triple alpha and (α, α, n) rexns bridge the A = 5, 8 gap and alpha captures continue till heavy nuclei "seeds" of A ~ 80 – 100.

The net result is a small number of heavy seed nuclei, and left over excess neutrons and alphas. The excess neutrons preferentially capture on the heavy seeds to go further producing r-process nuclei. The models of supernovae have the required conditions "almost happen". (The devil is in the details).

The role of neutrinos in r-process nucleosynthesis ?

- Recall r-process requires: (1-3) x 10^9 K; Freeze-out radius is about 600-1000 km from the proto-neutron star in a SN;
  $L\nu \sim (0.015 - 0.005) 10^{51}/(100\text{km})^2$sec; $\tau \sim 3$ sec.
- r-process material ejection occurs in an intense neutrino flux. Post-processing by neutrinos can alter the nuclear distribution after the r-process is completed.
- In the Neon-zone where Flourine production was due to 1/300 of the nuclei interacting with neutrinos, and since relevant neutrino-nucleus cross-section scale as A, the probability of an r-process nucleus interacting with the neutrino flux is approximately unity.
- This scenario can be altered if ν oscillations ($\nu e \Leftrightarrow \nu\tau$) lead to an anomalously hot νe spectrum via ($\nu e + n \rightarrow e + p$) which converts the soup back towards the proton rich side.

Neutrino capture reactions

$$\nu_e + n \rightarrow p + e^-$$

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

On free nucleons

$$\nu_e + (Z, A) \rightarrow (Z+1, A) + e^-$$

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

On nuclei

Matrix elements

$$|M_F|^2 = |\langle \psi_f | C_V \sum_{i=1}^{A} \tau(i) | \psi_i \rangle|^2$$

$$|M_{GT}|^2 = |\langle \psi_f | C_A \sum_{i=1}^{A} \sigma(i)\tau(i) | \psi_i \rangle|^2$$

For very neutron rich nuclei the antineutrino capture direction is Pauli blocked. In these cases the antineutrino capture rate is negligible compared to the neutrino capture rates (there is no Fermi transition in the $\beta+$ direction).

For the very neutron rich nuclei typical of the r-process, there will be several neutrons emitted after the neutrino induced excitation to the Gamow-Teller or Fermi resonances.

Meyer, McLaughlin & Fuller (1998)

Waiting point approximation

Definition: **ASSUME** (n,γ)-(γ,n) equilibrium within isotopic chain

Consequences

During (n,γ)-(γ,n) equilibrium abundances within an isotopic chain are given by Saha equilibrium:

$$\frac{Y(Z,A+1)}{Y(Z,A)} = n_n \frac{G(Z,A+1)}{2G(Z,A)} \left[\frac{A+1}{A} \frac{2\pi\hbar^2}{m_u kT} \right]^{3/2} \exp(S_n / kT)$$

- **time independent**
  - can treat whole chain as a single nucleus in network
  - only slow beta decays need to be calculated dynamically
- **neutron capture rate independent**

  (therefore: during most of the r-process n-capture rates do not matter !)

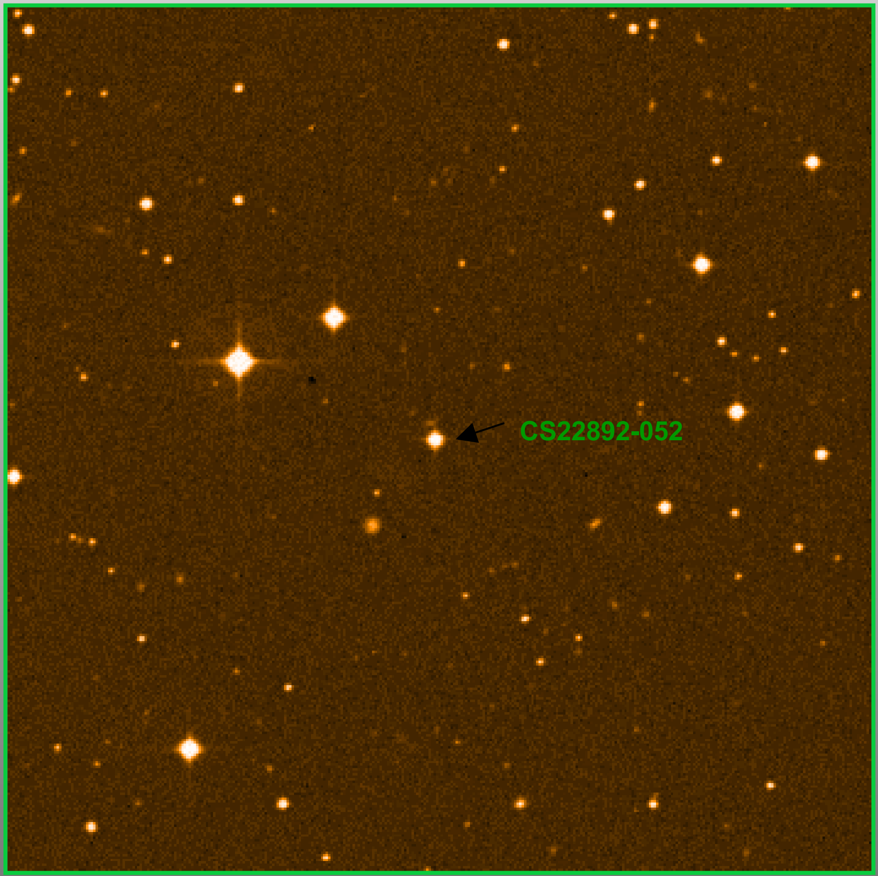
After Schatz 2004

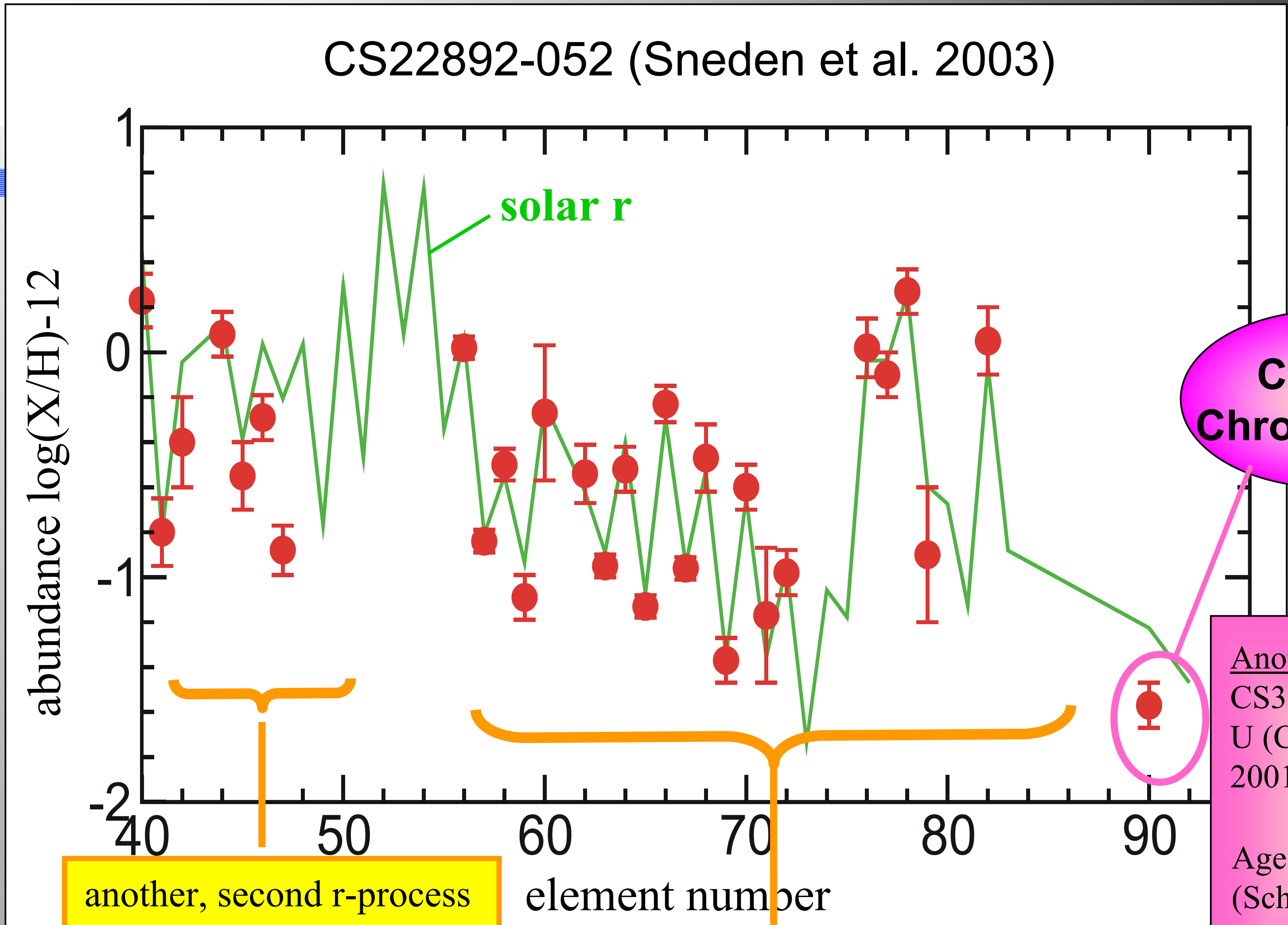
A very old and ultra metal poor star

Sneden 2003

CS22892-052
is a red (K) giant star located in the Halo of the galaxy at a distance: 4.7 kpc and has a mass ~0.8 M_sol.
It is very metal poor:
[Fe/H]= –3.1, [Dy/Fe]= +1.7
Recall that:
$[X/Y]=\log(X/Y)-\log(X/Y)_{solar}$

Old stars formed before the Galaxy was well mixed. They preserve local pollution from individual nucleosynthesis events from the past





another, second r-process to fill this range up ? (weak r-process)

main r-process matches solar r-pattern exactly

Another star CS31082-001 has U (Cayrel etal 2001)

Age 16 +/- 3 Gyr (Schatz etal 2002

Double enhancement of r-process and s-process elements in Carbon-enhanced metal poor stars

- CEMP stars show large enhancement of s-process elements but with lowest [Ba/Eu] ratios (<0.4) disagree with predictions of low metallicity AGB stars and require an additional r-process contribution. Many CEMP stars are in binary systems.
- Such peculiar abundances suggest stellar models in which the double enhancements of s- and r-process elements happen from a 8-10 Msun companion in a wide binary (Wanajo et al 2006).
- The s-processing happens during an AGB phase followed by the r-processing during the subsequent supernova explosion of its inner O-Ne-Mg core, leading to CEMP-r/s stars.

References:

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