Nucleosynthesis processes:
s-process,
p-process,
r-process.

Advisor-Seminar Astrophysics, TUM, SS2004:
Forged in Thermonuclear Fire: The Making of Chemical Elements

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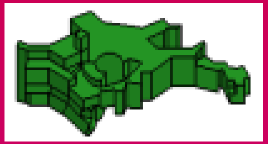


Burbige,E.M., Burbidge,G.R., Fowler,W.A., & Hoyle,F. 1957, Rev.Mod.Phys.,29,547

"What has been the history of the matter, on which we can make observations, which produced the elements and isotopes of that matter in the abundance distribution which observation yields? The history is hidden in the abundance distribution of the elements."

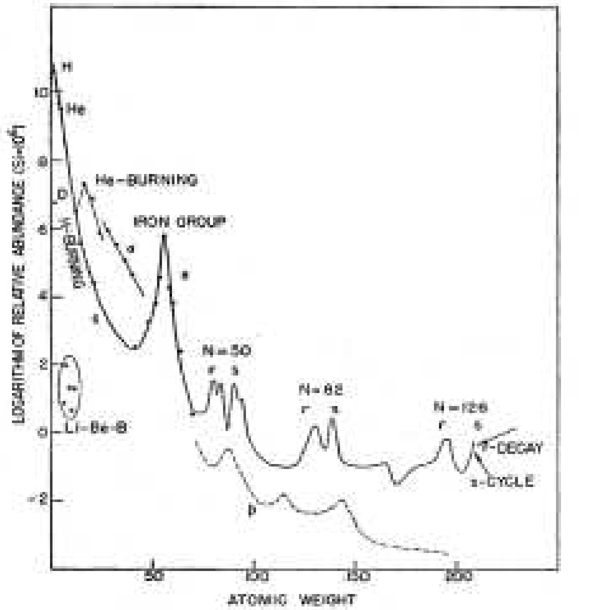


FIG. I,1. Schematic curve of atomic abundances as a function of atomic weight based on the data of Suess and Urey (Su56). Suess and Urey have employed relative isotopic abundances to determine the slope and general trend of the curve. There is still considerable spread of the individual abundances about the curve illustrated, but the general features shown are now fairly well established. These features are outlined in Table I,2. Note the overabundances relative to their neighbors of the alpha-particle nuclei $A=16, 20, \cdots 40$, the peak at the iron group nuclei, and the twin peaks at $A=80$ and 90, at 130 and 138, and at 194 and 208.

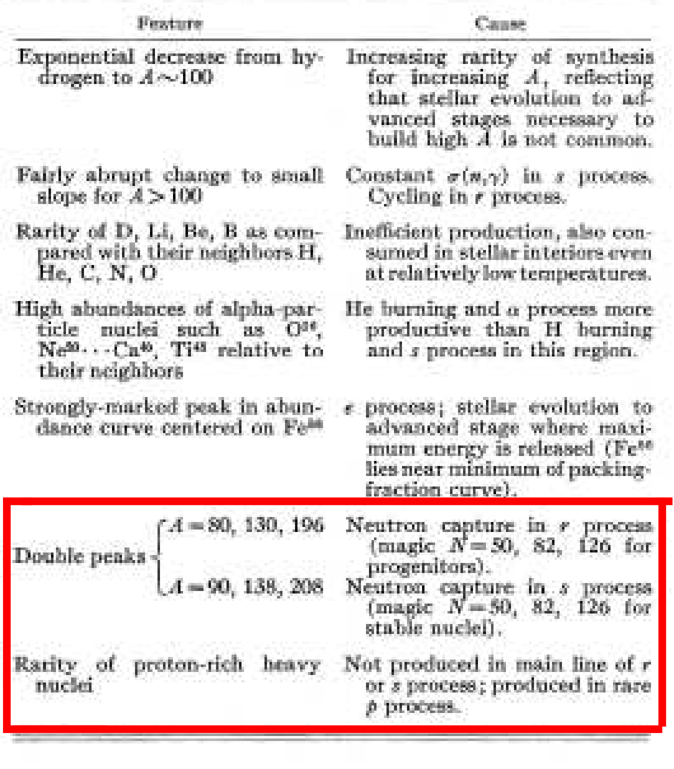
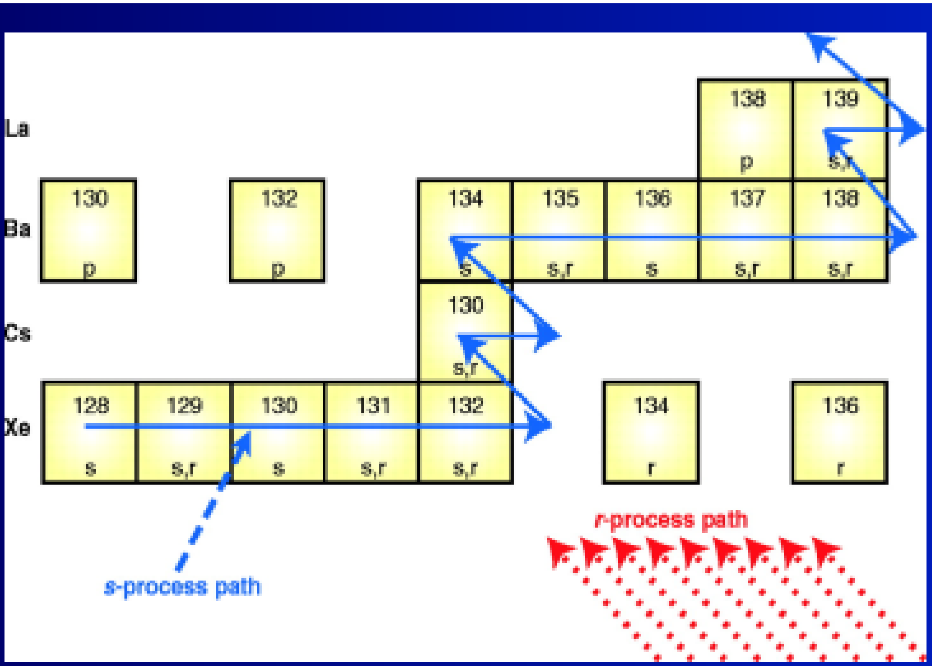


TABLE I,2. Features of the abundance curve.

Feature	Cause
Exponential decrease from hydrogen to $A \sim 100$	Increasing rarity of synthesis for increasing A, reflecting that stellar evolution to advanced stages necessary to build high A is not common.
Fairly abrupt change to small slope for $A > 100$	Constant $\sigma(n,\gamma)$ in s process. Cycling in r process.
Rarity of D, Li, Be, B as compared with their neighbors H, He, C, N, O	Inefficient production, also consumed in stellar interiors even at relatively low temperatures.
High abundances of alpha-particle nuclei such as O^{16}, $Ne^{20} \cdots Ca^{40}$, Ti^{48} relative to their neighbors	He burning and α process more productive than H burning and s process in this region.
Strongly-marked peak in abundance curve centered on Fe^{56}	e process; stellar evolution to advanced stage where maximum energy is released (Fe^{56} lies near minimum of packing-fraction curve).
Double peaks $A=80, 130, 196$	Neutron capture in r process (magic $N=50, 82, 126$ for progenitors).
Double peaks $A=90, 138, 208$	Neutron capture in s process (magic $N=50, 82, 126$ for stable nuclei).
Rarity of proton-rich heavy nuclei	Not produced in main line of r or s process; produced in rare p process.

What are r,p,s-processes?



Sneden, C., & Cowan,J.J. 2003, Science, 299, 70

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

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

$(Z,A+1) \rightarrow (Z+1,A) + \beta + \nu$

- s - process: $N_n \sim 10^8$ cm^{-3}

  $\tau_{n\gamma} \gg \tau_\beta$

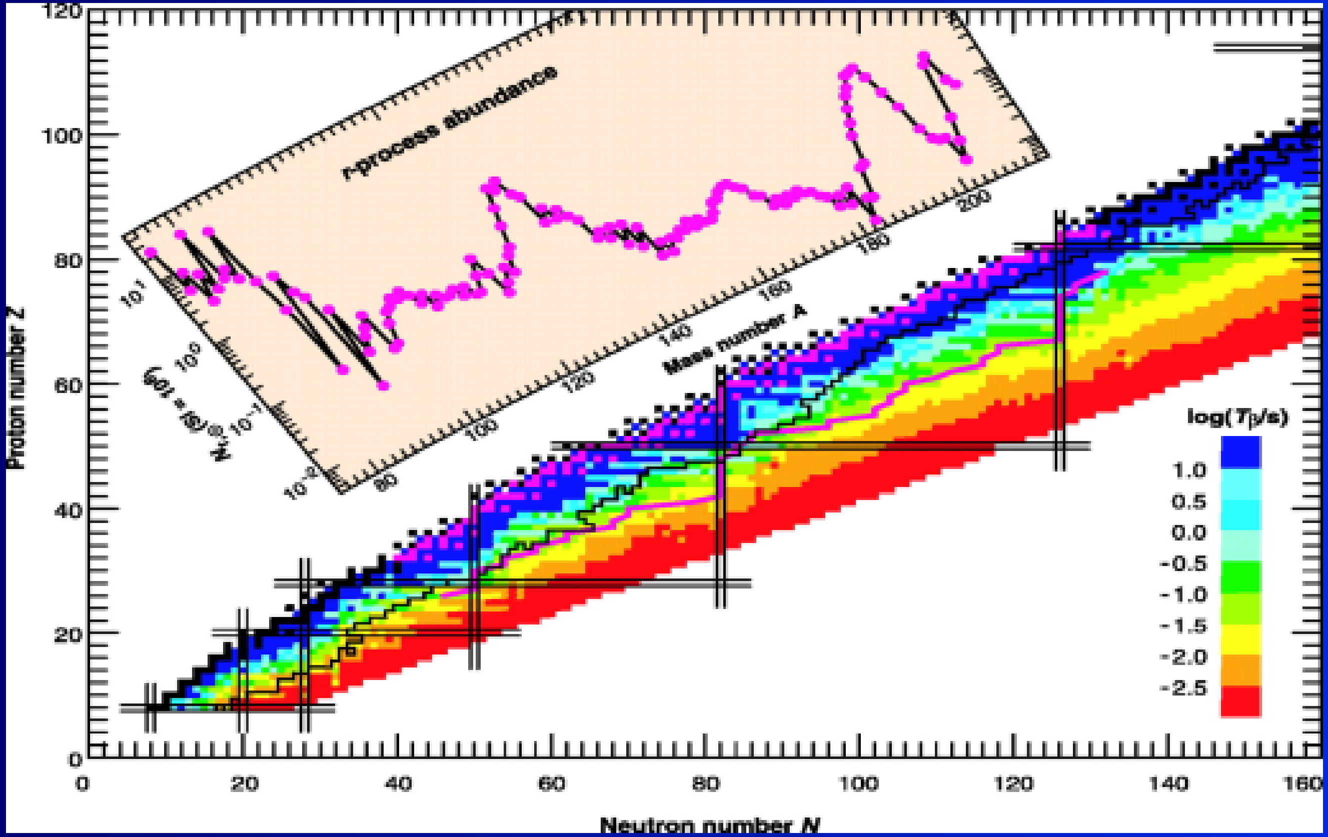
- r - process: $N_n \sim 10^{23}$ cm^{-3}

  $\tau_{n\gamma} \ll \tau_\beta$

- p - process: 10^2 -10^3 less abundant. e^+ capture and production, p capture, and (γ,n) or (p,n) reactions.

What are r,p,s-processes?

Sneden, C., & Cowan,J.J. 2003, Science, 299, 70



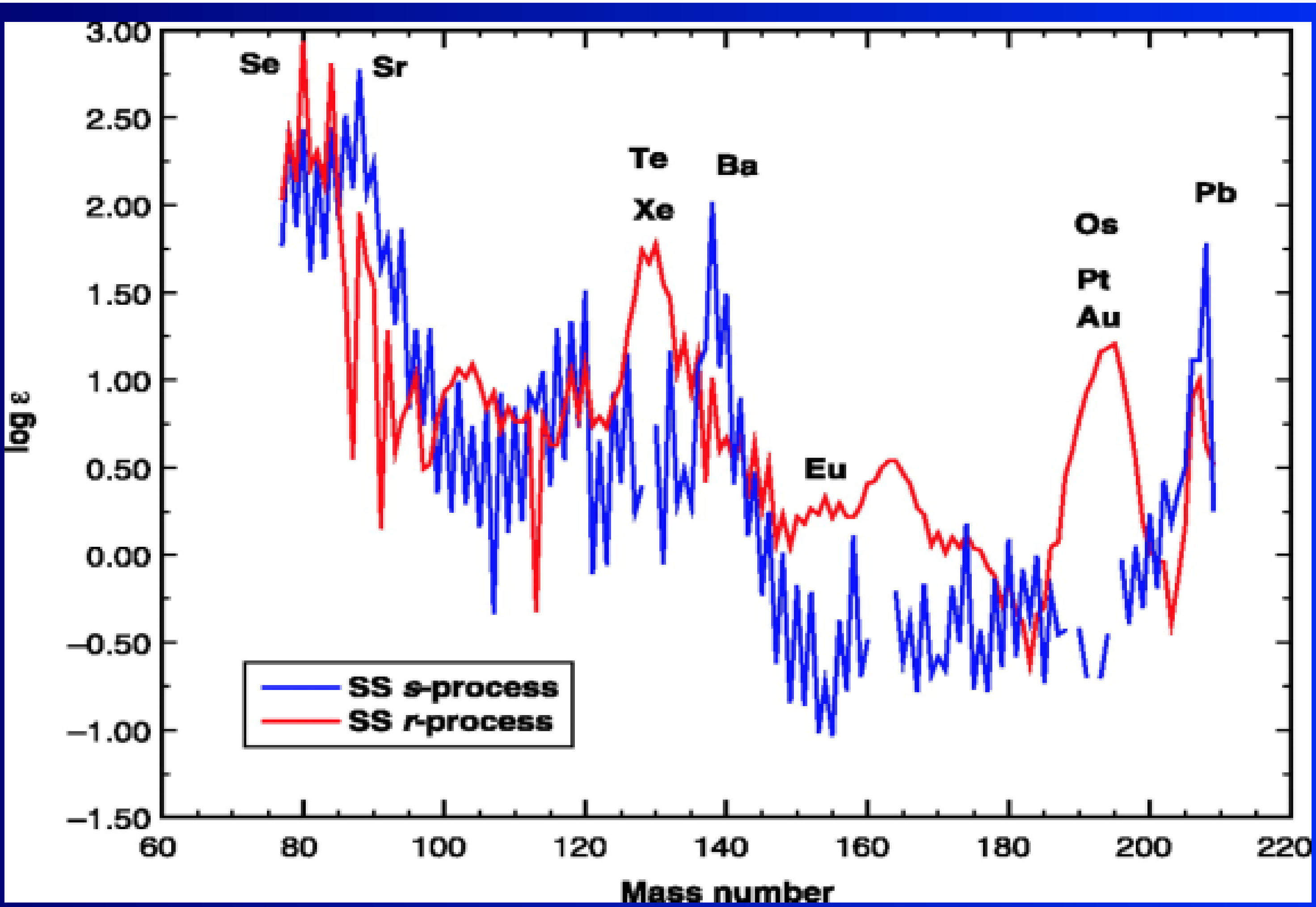
■ stable nuclei

— r-process path

— limit of experimentally determined properties of nuclei

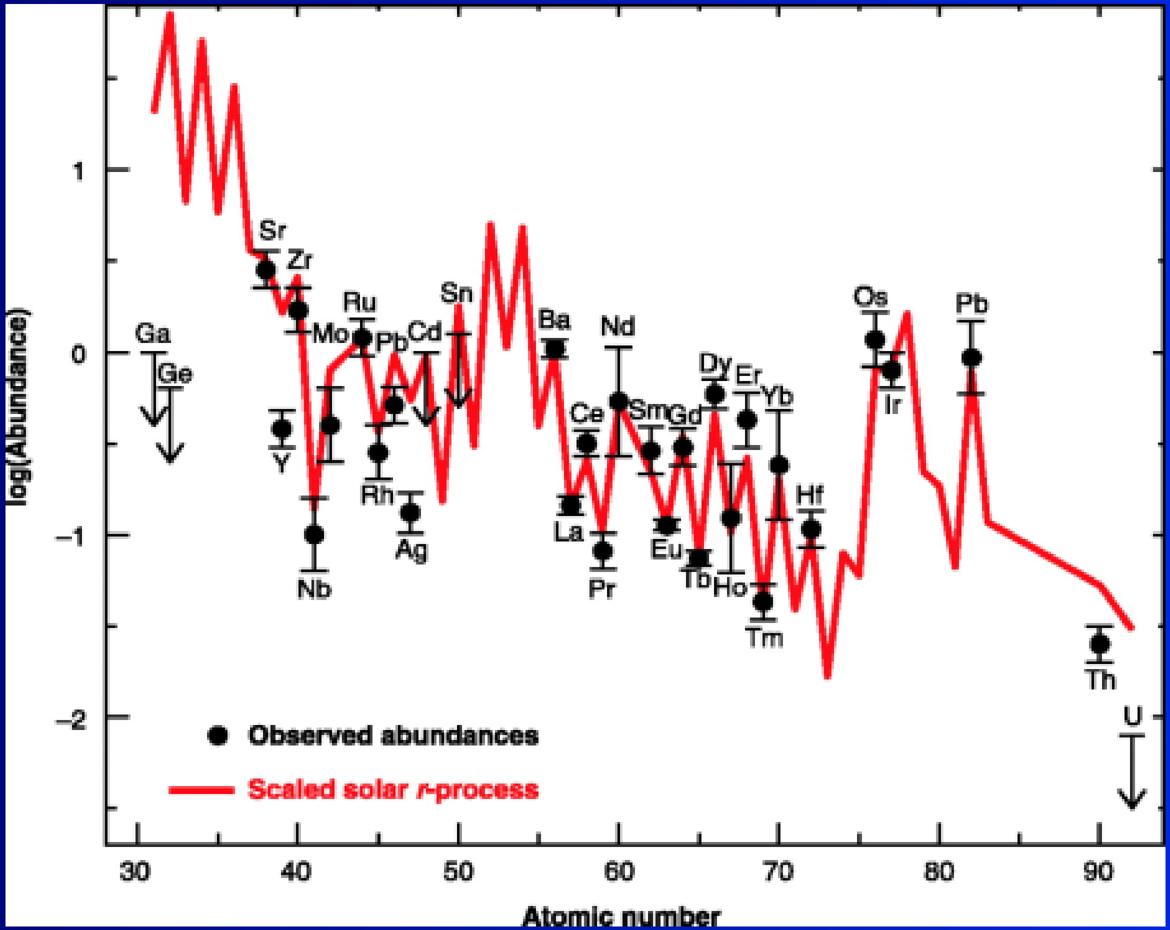
Observations

Sneden, C., & Cowan,J.J. 2003, Science, 299, 70



Observations

Ultra-metal-poor (UMP) giant star: CS 22892-052



Sneden, C., & Cowan,J.J. 2003, Science, 299, 70

[Fe/H] = -3.1

s-Process

- The nuclei follow the valley of β-stability
- Neutron capture occurs all way from ^{56}Fe (the seed nuclei) on up to ^{209}Bi (the last stable nucleus)
- The time dependence of the abundacies is:

$$\frac{\mathrm{d}N_A}{\mathrm{d}t} = N_n(t)N_{A-1}(t)\langle\sigma v\rangle_{A-1} - N_n(t)N_A(t)\langle\sigma v\rangle_A - \lambda_\beta(t)N_A(t)$$

- Analytic approach:

  1) $\tau_{n\gamma} \gg \tau_\beta$: radioactive nuclei decay quickly ➜ neglected abundancies

  $\tau_{n\gamma} \ll \tau_\beta$: radioactive nuclei ~ stable nuclei

  2) T const. during the s-process ➜ $<\sigma v> = \sigma_A v_T$

- Neutron exposure: $\tau = v_T \int_0^t N_n(t)\mathrm{d}t$ ➜ $\frac{\mathrm{d}N_A}{\mathrm{d}t} = \sigma_A N_A - \sigma_{A-1}N_{A-1}$

$$\sigma_A N_A = \int_0^\infty \rho(\tau)N(\tau)\mathrm{d}\tau$$

$$\rho(\tau) = f\frac{N_{56}^{\odot}}{\tau_0}e^{-\frac{\tau}{\tau_0}}$$

mean neutron exposure

mmm

s-Process: possible sites

Good fit of the σN curve:

$\tau_0 \simeq 0.3\,\mathrm{mb}^{-1} \Rightarrow 90<A<204$ Main component

$\tau_0 \simeq 0.06\,\mathrm{mb}^{-1} \Rightarrow A \lesssim 90$ Weak component

$\tau_0 \simeq 7.0\,\mathrm{mb}^{-1} \Rightarrow A=204\text{-}209$ Strong component

- Weak component: He burning in the cores of massive stars ($\gtrsim 15 M_\odot$)
- Main component:

1. Massive AGB stars: He-burning shell + H rich envelope. But the mixing is complicated
2. Low mass AGB ($\lesssim 3 M_\odot$). Convection and diffusion could cause the mixing of p with ^{12}C

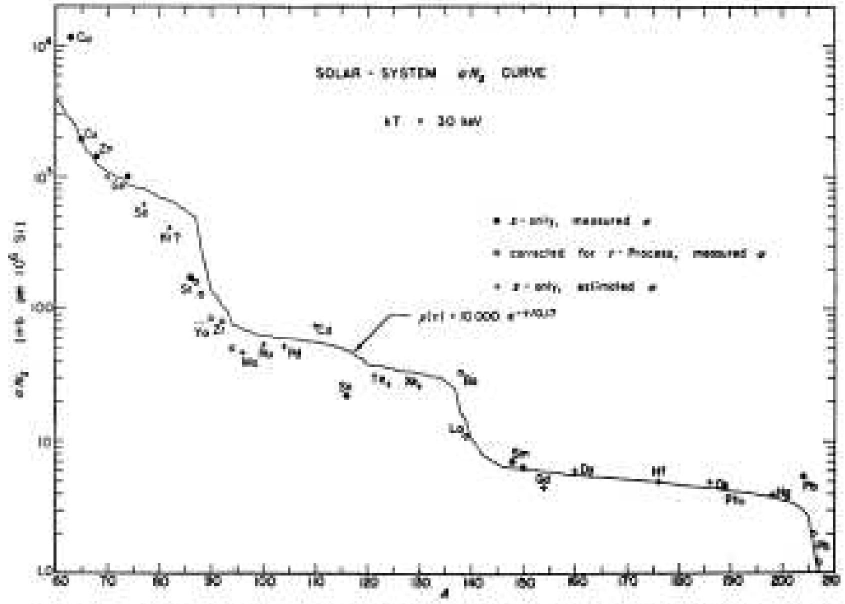
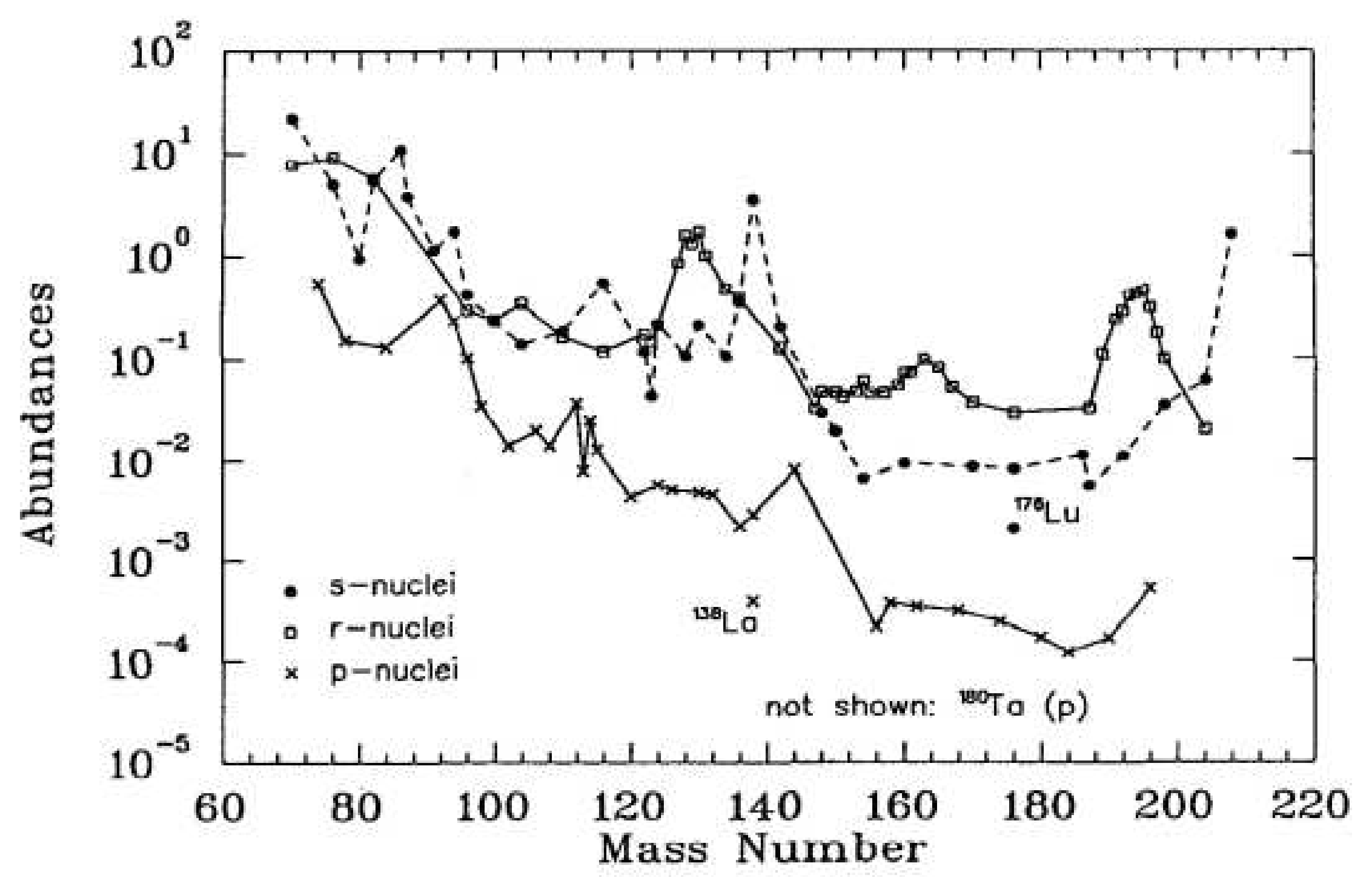


FIG. 1.—Solar-system σN_s-curve. The product of the neutron-capture cross-section at $kT = 30$ keV (in mb) times isotopic abundance (Si = 10^6) is plotted versus atomic mass number A. The solid line is a calculated curve corresponding to an exponential distribution of integrated neutron flux.

Where do the neutrons come from?

$^{13}C(\alpha,n)^{16}O$, $^{17}O(\alpha,n)^{20}Ne$, $^{21}Ne(\alpha,n)^{24}Mg$, $^{22}Ne(\alpha,n)^{25}Mg$

p-Process

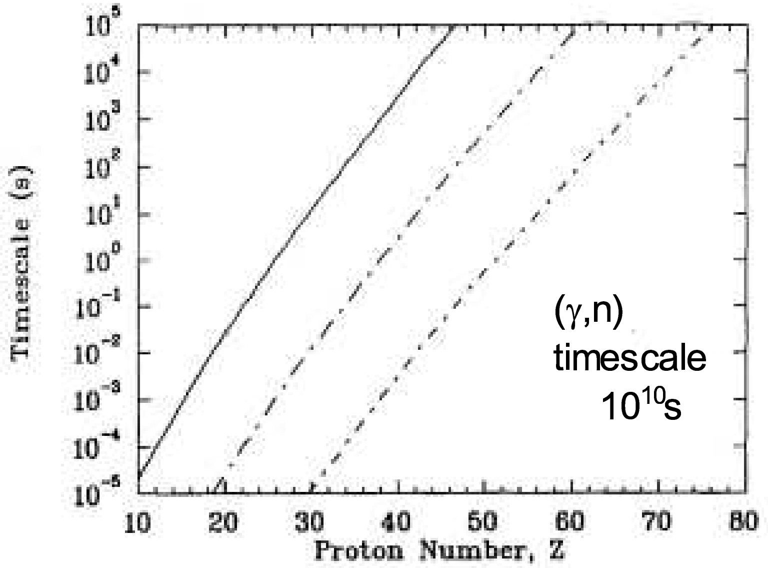


^{92}Mo

^{144}Sm

Meyer,S.M. 194, Ann. Rev. A&A, 32,153

p-Process



(γ,n) timescale 10^{10}s

Figure 9 Timescales for proton capture on the most proton-rich isotope of each element at the fixed temperature of $T_9 = 1$. The curves are for mass densities in protons of $\rho Y_p = 1\ \mathrm{g\ cm^{-3}}$ (*solid curve*), $10^{3}\ \mathrm{g\ cm^{-3}}$ (*long dashed-dotted curve*), and $10^{6}\ \mathrm{g\ cm^{-3}}$ (*short dashed-dotted curve*). The rates are computed from expressions in Woosley et al (1975).

Meyer,S.M. 194, Ann. Rev. A&A, 32,153

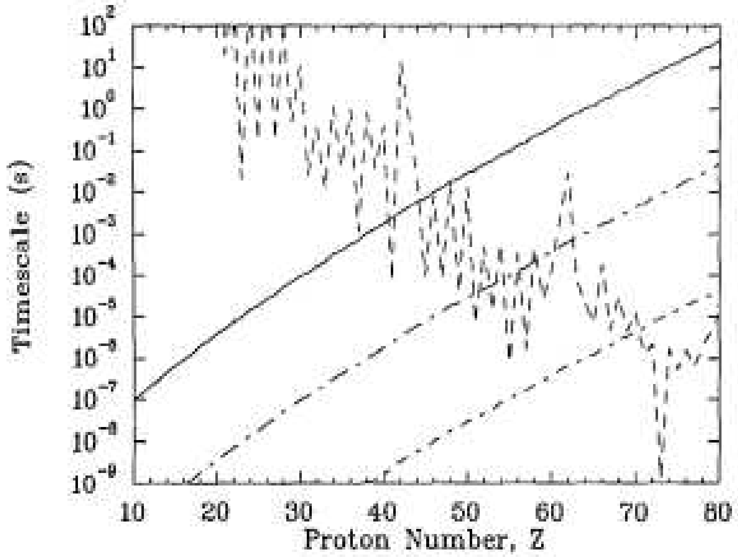


Figure 10 Same as Figure 9 but for $T_9 = 3$. The short-dashed jagged curve shows the timescale for (γ, n) reactions on these nuclei. The (γ, n) rates are computed from neutron-capture cross sections in Woosley & Hoffman or Cowan et al (1991) and neutron-separation energies are derived from Möller & Nix (1988).

- Proton capture.
  - low T ➜ no disintegration, but it is needed a large supply of p for long time
  - high T ➜ shorter capture timescale, but disintegration (γ,n) reaction will dominate
- Disintegration reaction: first (γ,n) reaction produces quite proton-rich nuclei, and then (γ,p) and (γ,α) reactions. The nuclei "melt" towards iron. T drops and the melting is incompleted.

^{92}Mo (Z=42, N=50)

^{144}Sm (Z=62, N=82)

p-Process: possible sites

- B^2HF: proton capture: Supernova shock passing through the hydrogen-rich envelope in massive stars

- Woosley & Howard (1978): gamma-process, disintegration. O/Ne shell in type II supernovae. It underproduces light p-nuclei and it is necessary to superimpose several abundance distributions to get a realistic distribution of p-nuclei.

- Howard et al. (1991): outer layers of the carbon-oxigen white dwarf star suffering a type Ia supernova explosion. s-Process builds up the abundances of A=90 nuclei. Light p-nuclei are produced by proton capture while the normal gamma-process made heavier p-nuclei. But later calculations have not been successful in producing light p-nuclei.

r-Process

Condition required :

- $T \sim 1 - 3 \cdot 10^9$ K
- $N_n > 10^{20}$ cm^{-3}
- n/p ~ 7 - 8 (≳ 100 free neutrons per seed nuclei (A~240))
- timescale ~ 1s

Secondary sites: seed nuclei already exist from synthesis in previous generations of stars.

Primary sites: the r-process seed nuclei are built up during the r-process event itself . NSE:mass fraccion of nucleus ^AZ

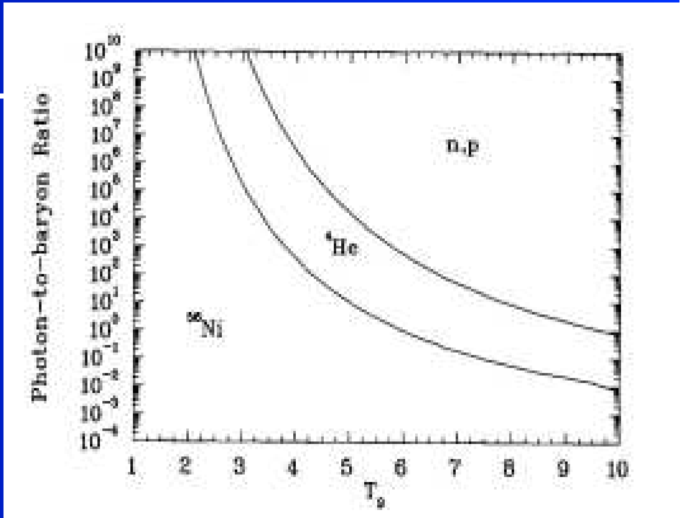
$$X(Z,A) = G(Z,A)\left[\zeta(3)^{A-1}\pi^{\frac{(1-A)}{2}}2^{\frac{(3A-5)}{2}}\right]A^{5/2}\left(\frac{KT}{m_N c^2}\right)^{\frac{3(A-1)}{2}}\phi^{1-A}X_p^Z X_n^{A-Z}e^{\frac{B(Z,A)}{KT}}$$

$$\phi = \frac{n\gamma}{\rho N_A} = \frac{1}{\pi^2}\frac{g_\gamma}{(\hbar c)^3}\frac{\zeta(3)(KT)^3}{\rho N_A}$$

$$S \simeq \frac{4}{3}a\frac{(KT)^3}{\rho N_A}$$

$\phi \sim 1$ ➔ iron-group: large binding energies

ϕ large ➔ dissociated gas of nucleons and α-particles



material in NSE at high T, ρ

↓

it expands and cools

↓

reactions fall of equilibrium(charge-current reactions)

↓

freeze out

↓

it leaves nuclei and free neutrons

↓

r-process=neutron capture in equlilbrium with the reverse reaction

↓

it drops out of the equlibrium and freezes out

Clasical r-process: $\phi \lesssim 1$

- Charge-particle reactions freeze out: protons are bound into iron-group nuclei
- n/p ~ 7 -8 and Y_e ~ 0.1: neutron-rich material ➜ outer layers of proto-neutron star
- Hillebrandt, Takahashi & Kodama (1976): realistic supernova model used to follow the ejected neutronized material
- Problems:
  - the fit to the solar system abundance curve had the A=130 and A=195 peaks shifted
  - overproduction of the r-process material
- Posible solutions:
  - the material accretes back onto the protoneutron star
  - only certain rare supernova (1in 1000) can eject the neutron-rich matter (rotation, magentic fields). But, the presence of short-lived radioactive r-process nuclei in the early solar system indicates that the site may not be that rare

r-Process

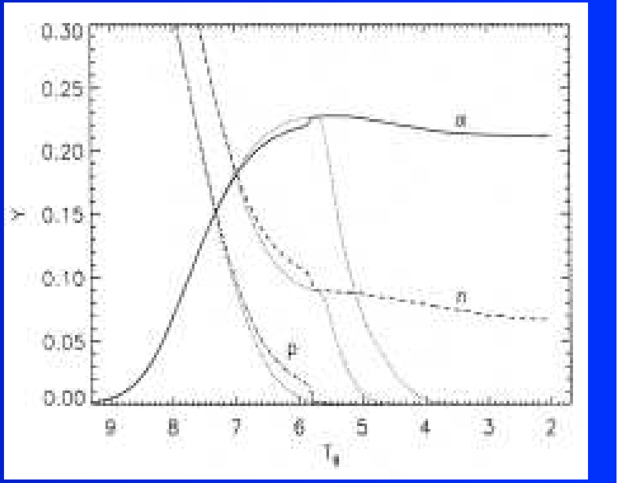
Neutrino wind / hot bubble (high S)

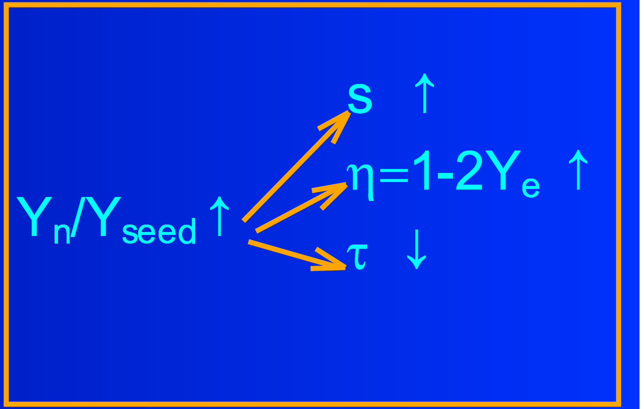
ϕ large (high entropy): at high T NSE favors α-particles and free neutrons. T falls and NSE evolves towards heavier nuclei. The high-entropy neutrino-energized wind provides a natural site.

- Early phase of expansion: close to neutron star, NSE forms free neutrons and protons, the disociation of nuclei is nearly complete.
- Wind material moves away, α-particles are the main component at $T \simeq 7 \cdot 10^9$K. Recombination:

  $3\alpha \rightarrow {}^{12}C$

  $\alpha + \alpha + n \rightarrow {}^{9}Be$ followed by ${}^{9}Be(\alpha,n){}^{12}C(n,\gamma){}^{13}C(\alpha,n){}^{16}O(\alpha,\gamma){}^{20}Ne$
- Low density ➜ three-body reactions are slow ➜ NSE breaks down at $T\sim 7\text{-}5 \cdot 10^9$K
- α-particles build up heavier elements until it is impeded by Coulomb barrier or photo-disintegration= α-process
- There are a small amount of heavy nuclei and sufficient number of free neutrons at the freeze-out of α-particles
- r-process starts on these heavy "seed" nuclei





$Y_n/Y_{seed} \uparrow$

$s \uparrow$

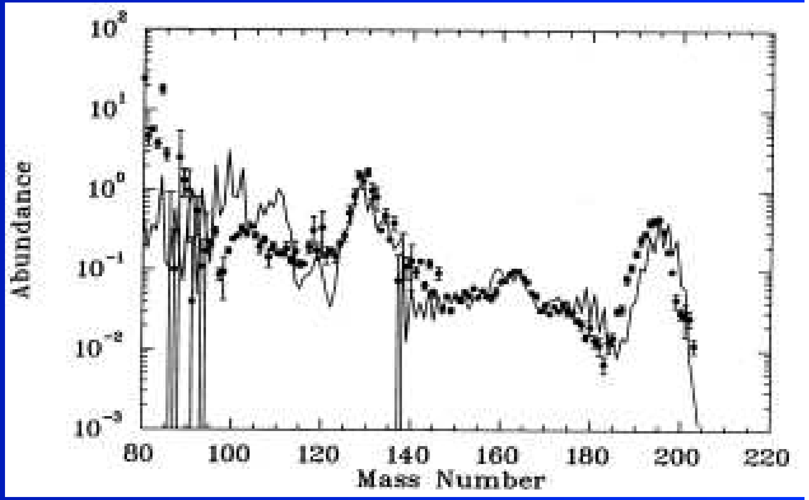
$\eta = 1-2Y_e \uparrow$

$\tau \downarrow$

r-Process Neutrino wind / hot bubble

Woosley,S.E., Wilson,J.R., Mathews,G.J., Hoffman,R.D., & Meyer,B.S., 1994, ApJ,433,229

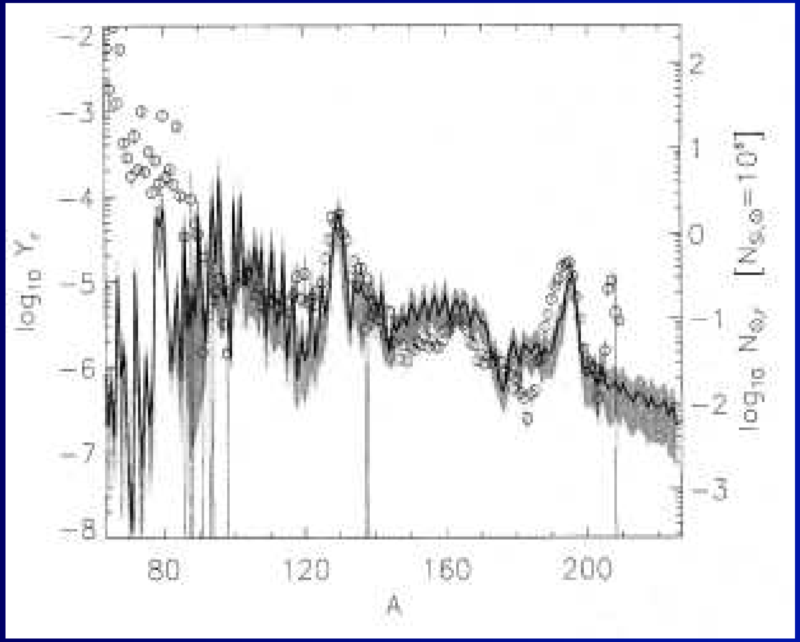
- Initial model: Wilson & Mayle, 20M$_\odot$ star, ~ 3s after bounce
- Composition of the ejecta agrees with the solar r-process abundances
- Problems:
  - they explored only a single supernova model
  - not taken into account a reverse shock
  - no multidimesional treatment
  - initial model has too high entropies



r-Process

Neutrino wind / hot bubble

Witti,J., Janka, H.-Th., & Takahashi,K., 1994, A&A, 286,841
Takahashi,K., Witti,J., & Janka, H.-Th., 1994, A&A, 286,857



- Initial model of Wilson, 25 $M_\odot$ star, ~0.6 s after bounce
- α-process: seed nuclei with A $\leq$90, but low entropy and too few neutrons at the end of the freeze-out
- r-process: they scale the denstities of the initial model down by a factor constant in space and in time.
- Reduction factor of 5.5 led to an abundance distribution similar to that of the solar system
- Problems:
  - artifitial factor for increasing the entropy
  - one supernova model
  - not good agreement for A<80

r-Process

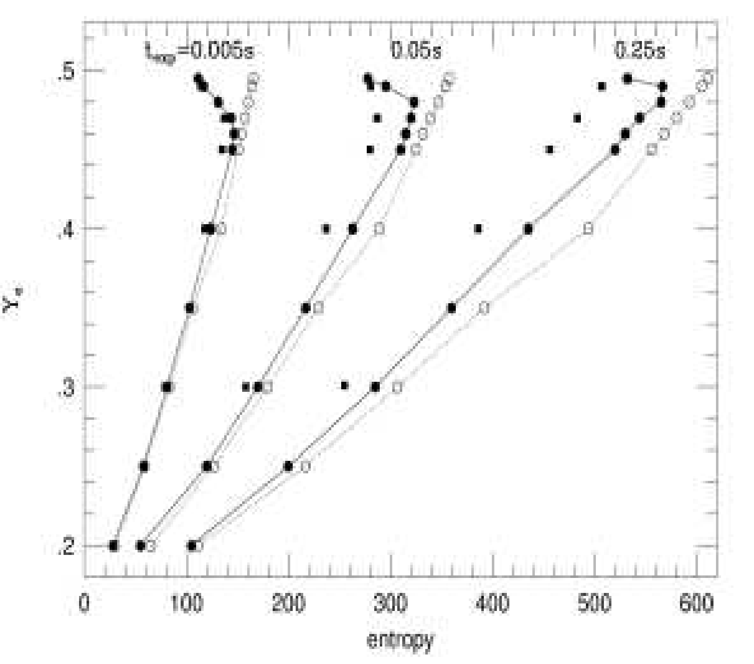
Neutrino wind / hot bubble

Qian,Y.-Z. & Woosley,S.E. 1996, ApJ, 471,331
Hoffman,R.D., Woosley,S.E., & Qian,Y.-Z., 1997, ApJ, 482,951

- Analytic and numeric methods to derive the conditions relevant for heavy nuclei synthesis in the wind: s, Y_e, τ, and $\dot{M}$

- The dynamic timescale is important: for given Y_e, the neutron-to-seed ratio increases when:
  - reaction rates of α-particles into heavy nuclei decrease (increase of S)
  - the time during which these reactions can operate is reduced

- Effective way of accelerating the expansion and increasing S, is to provide an additional source of energy (violent vibration, rapid rotation, magnetic fields,...)

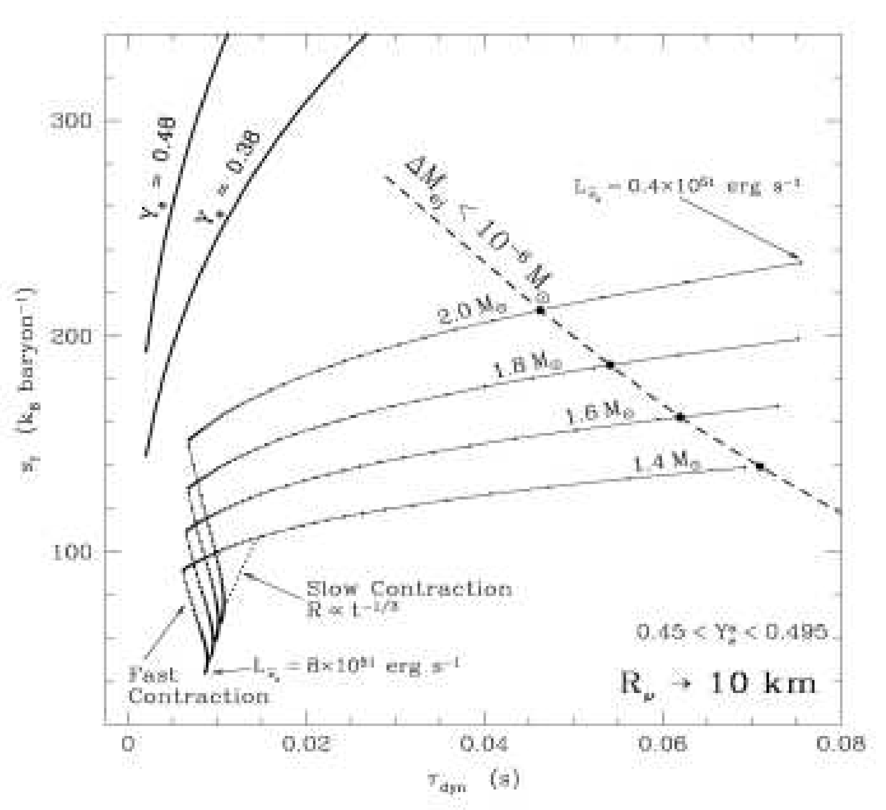


- □ high S scenario (S $\gtrsim$350 and 0.495 $\gtrsim Y_e \gtrsim$ 0.40) corresponds to longer expancion times ($t_{exp} \gtrsim$ 0.1s)

- ○ low entropy scenario (S $\lesssim$ 200 and $Y_e \lesssim$ 0.40) requires shorter expansion times ($t_{exp} \lesssim$ 0.025) ➞ jets

Neutrino wind / hot bubble

Thompson,T.A., Burrows,A., & Meyer,B.S., 2001, ApJ, 563,887
Thompson,T.A. [astro-ph/0309111]



- Reviews the fundamental and general equation for time independent energy-deposition-driven winds
- netron-to-seed ratio depends on: entropy, neutron richness (Y_e) and dynamical timescale (τ_{dyn})
- Some modification to the physics it might:

  Y_e ↘ s ↗ τ_{dyn} ↘

Problems to be solved:

- initial supernova model
- not detailed simulations for different initial parameters
- reverse shock
- neutrino transport
- convection: two, three dim model
- magnetic fields
- nuclear data (β decay, (n,γ) rates,....)
- ....

Other sites

- O/Ne/Mg cores of stars in the mass range 8-10$M_\odot$
- Jets
- Neutron star mergers

To be a major source for the r-process, an enviroment must satisfy two criterions:

- reproducing the solar r-process abundance pattern
- supplying the total amount of r-process material in the present Galaxy

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