Effects of beta–delayed proton emission on the rp–process

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EFFECTS OF β-DELAYED PROTON EMISSION ON THE rp-PROCESS

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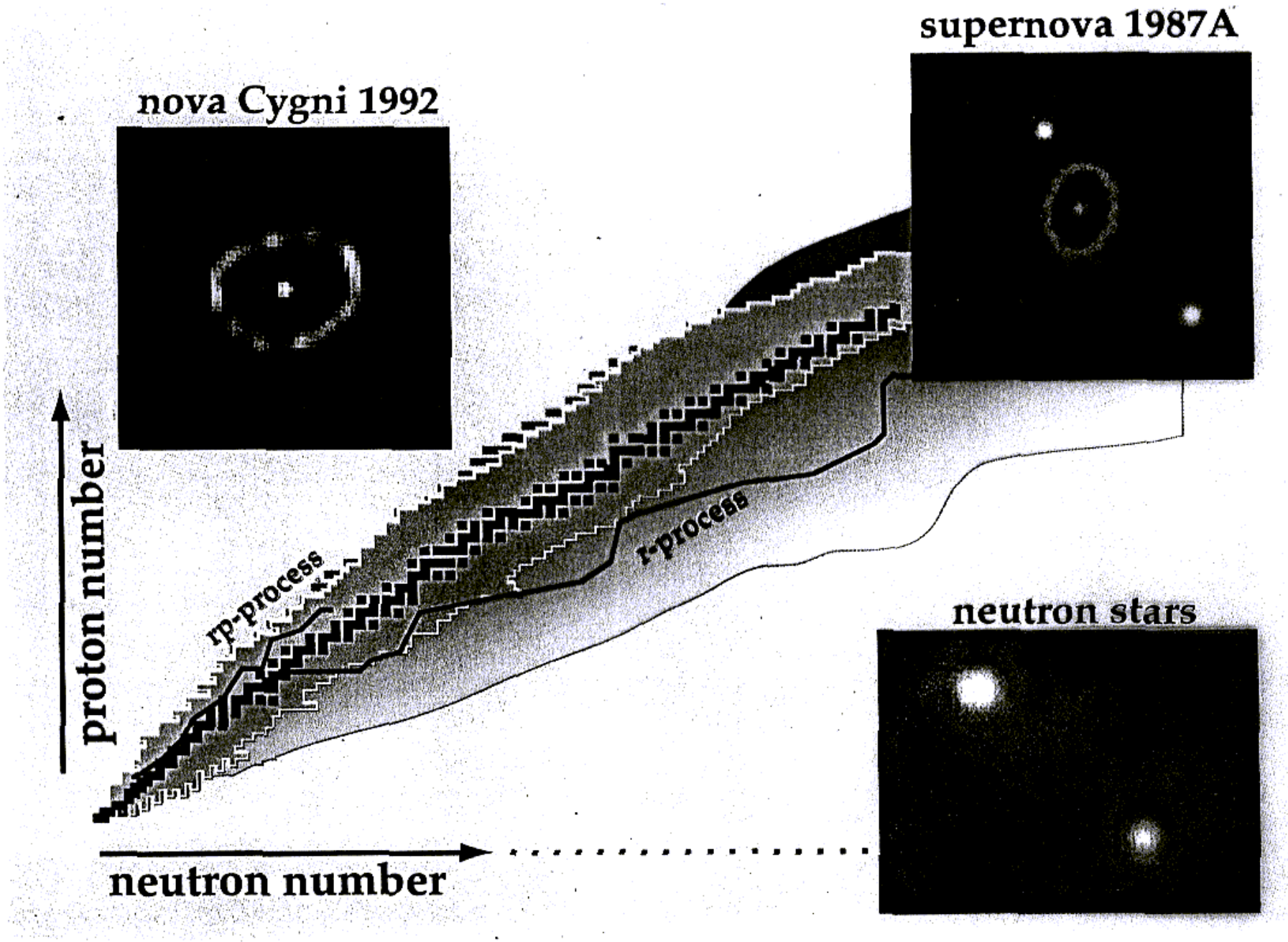
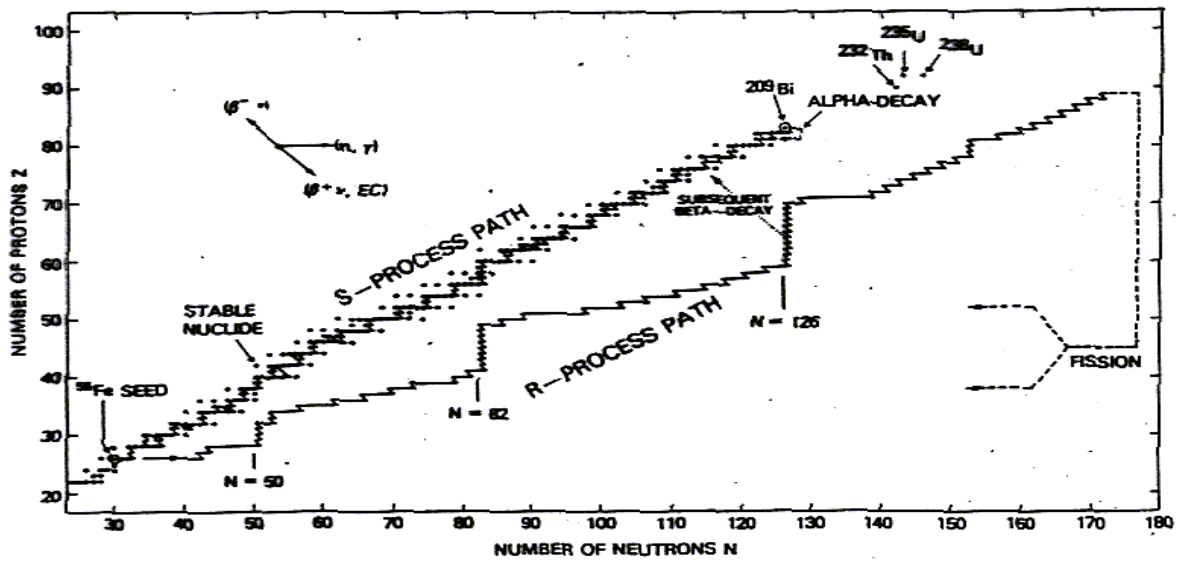

supernova 1987A
nova Cygni 1992
rp-process
r-process
neutron stars
proton number
neutron number

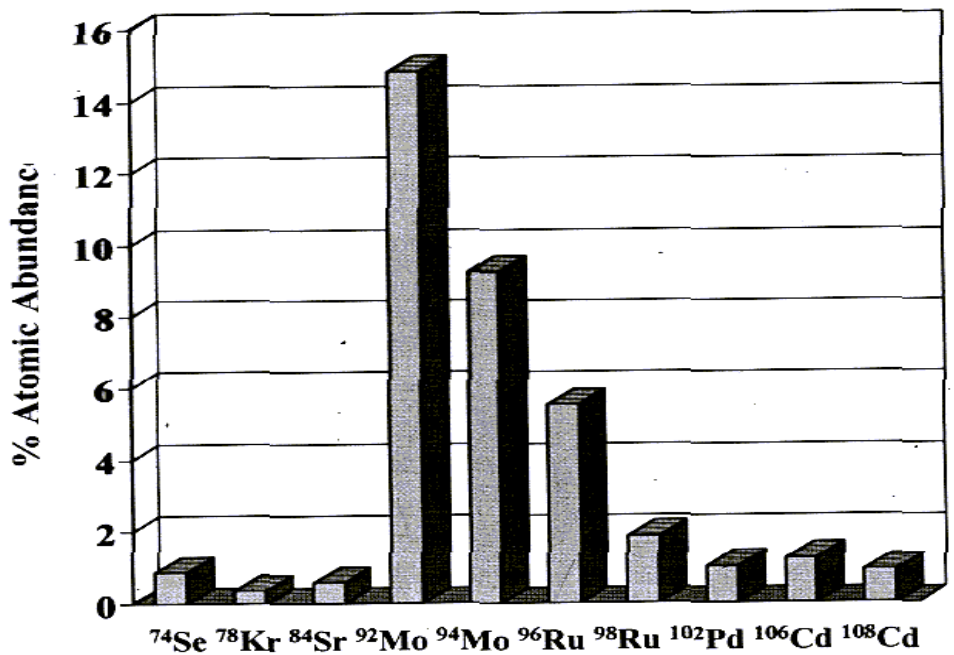
REFERENCE TEMPERATURES

Center of Sun:	**15×10^6 K**
H-burning, massive star	**30×10^6 K**
He-burning	**200×10^6 K**
rp-process on W.D.	**300×10^6 K**
rp-process on n-star	**1.5×10^9 K**

(p,γ) reaction rates are *very* temperature dependent.


NUMBER OF PROTONS Z
NUMBER OF NEUTRONS N
S—PROCESS PATH
R—PROCESS PATH
STABLE NUCLIDE
^{56}Fe SEED
N = 50
N = 82
N = 126
^{209}Bi
ALPHA-DECAY
^{232}Th
^{235}U
^{238}U
SUBSEQUENT BETA-DECAY
FISSION
(n, γ)
(β⁺ ν, EC)

p-Nuclide Abundances



APPROACHES TO SYNTHESIZING p-NUCLIDES

rp-Process:

Creates heavier nuclides from lighter ones via (p,γ) reactions. Abundance builds up at waiting points (long $T_{1/2}$, weak (p,γ)).

γ-Process:

Synthesizes heavy p-nuclides from even heavier ones via (γ,p) and (γ,α) reactions. Also (inevitably) operates on lighter nuclei during rp-process.

α-Rich Freezeout:

Operates in nuclear statistical equilibrium, starting at high T. Does make some p-nuclei.

Repetitive rp-process:

rp-Process with short repetitive bursts separated by times >> decay times. Makes some hard-to-make p-nuclides.

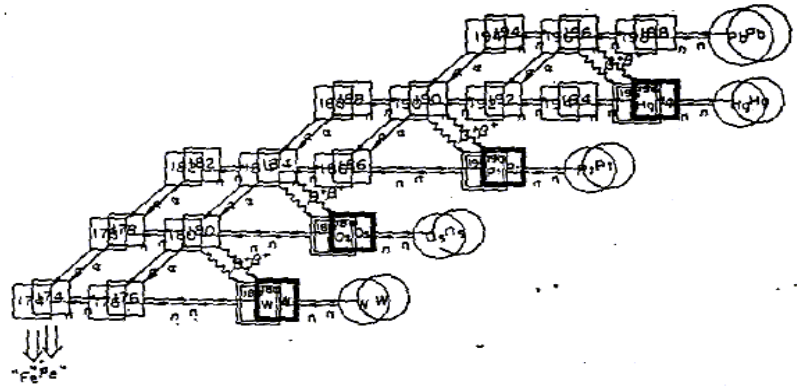


FIG. 1. Photodisintegration flows in the vicinity of the heavy p-nuclei (double squares). The circles labeled with elemental symbols represent all the stable isotopes of the given element. Arrows labeled with "n" or "α" represent photoneutron and photoalpha flows, respectively. In this mass region the α and β interactions of the p-nuclei are primarily produced as photonuclear progenitors which decay by positron emission (arrows labeled "β^+") after the explosion.

The Astrophysical rp-Process

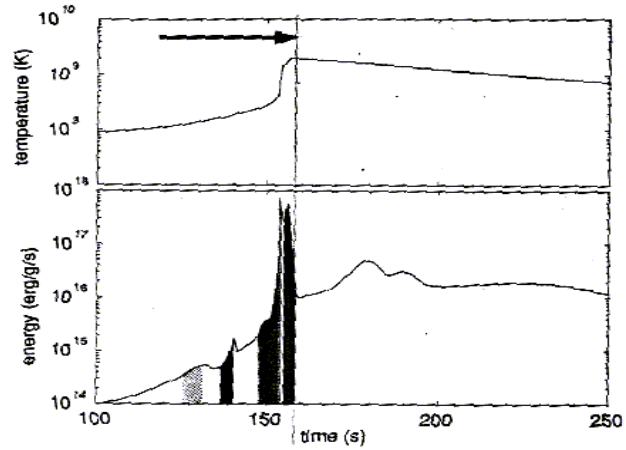
The rp-process occurs at high temperature in a H-rich environment. Such conditions never exist in the core of a star during one of the phases of normal stellar evolution.

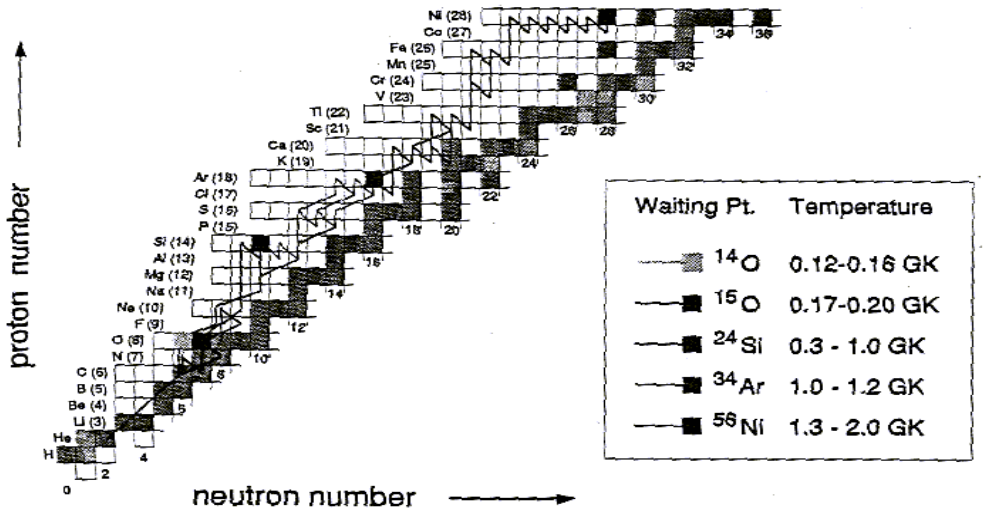
Thus the rp-process occurs only in special situations, e.g., accretion of matter from the periphery of a star onto a compact companion, e.g., white dwarf or black hole.

The (proton rich) accreted matter achieves a high temperature as it falls into the deep gravitational potential well of the compact object, satisfying the rp-process conditions.

The rapid burning produces thermonuclear runaway, and a transient phenomenon: a nova or an x-ray burst.

- *temperature:*
- energy production:





PUSHING THE rp-PROCESS TO ITS LIMITS

Schatz, Wiescher, Thielemann, Kratz 1997:

Push T, density, and burning times to herioc values.
And, include "two proton captures".
So circumvent rp-process termination point at ^{68}Se by:

a) Long burning times allow ^{68}Se to decay.

b) 2p-captures bypass unstable ^{69}Br, to ^{70}Kr.

T_9 = 1.5, density = 10^6 g cm^{-3}, burning times of many 10's of seconds, OP factors of order 10^7 to 10^8 for 80-100 u p-nuclei.

Are these the conditions of x-ray bursters? Are these produced by accretion onto a neutron star or a black hole? Could anything get out of such a gravitational trap?

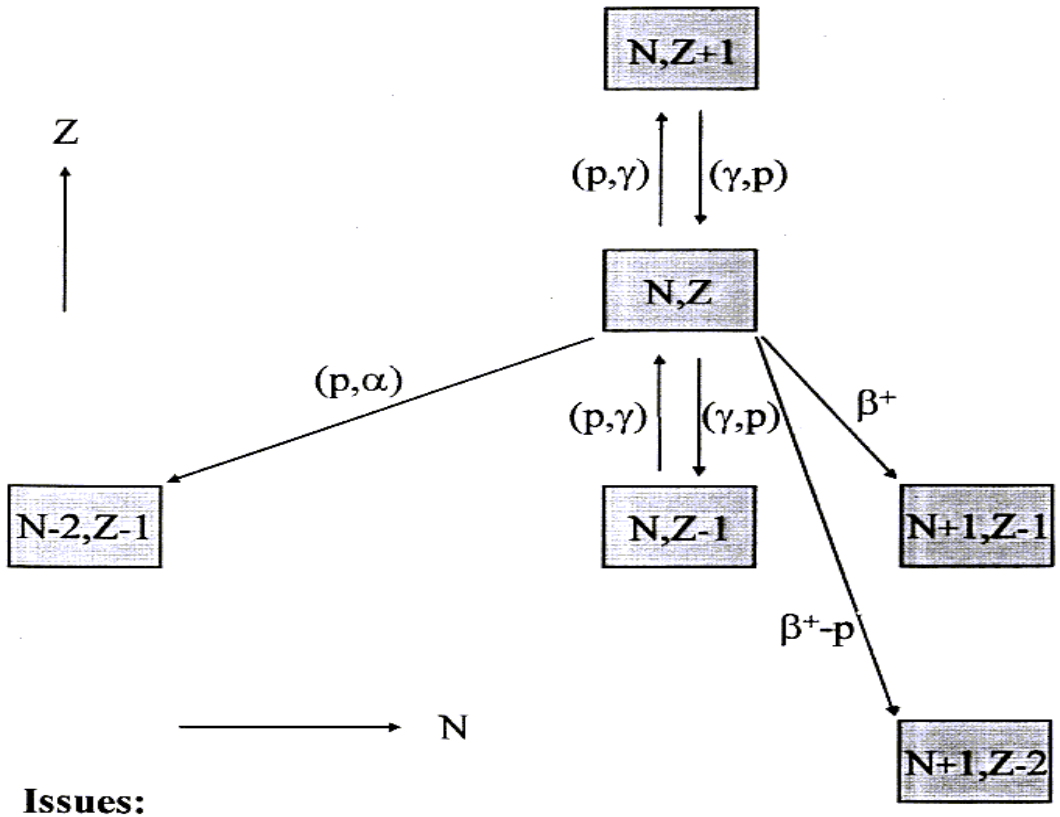
And, a nucleosynthesis problem: **WAY** too much light p-nuclide, e.g., ^{80}Kr, production.

OP determined by masses and halflives. Some critical halflives:

^{84}Mo, ^{85}Mo, ^{92}Pd, ^{96}Cd, and especially ^{80}Zr.

POSSIBLY IMPORTANT: β-DELAYED PROTON EMISSION?

REACTIONS OF THE rp-PROCESS



Issues:

Proton unstable nuclei?

Waiting points?

Requirements for (p,α)?

Processing times vrs. decay half-lives?

FOR β-p TO LEAVE NUCLEO-SYNTHETIC SIGNATURES FROM rp-PROCESSING:

Most obvious signatures will occur for nuclei that are difficult to make in any other way.

So pay special attention to p-process nuclides.

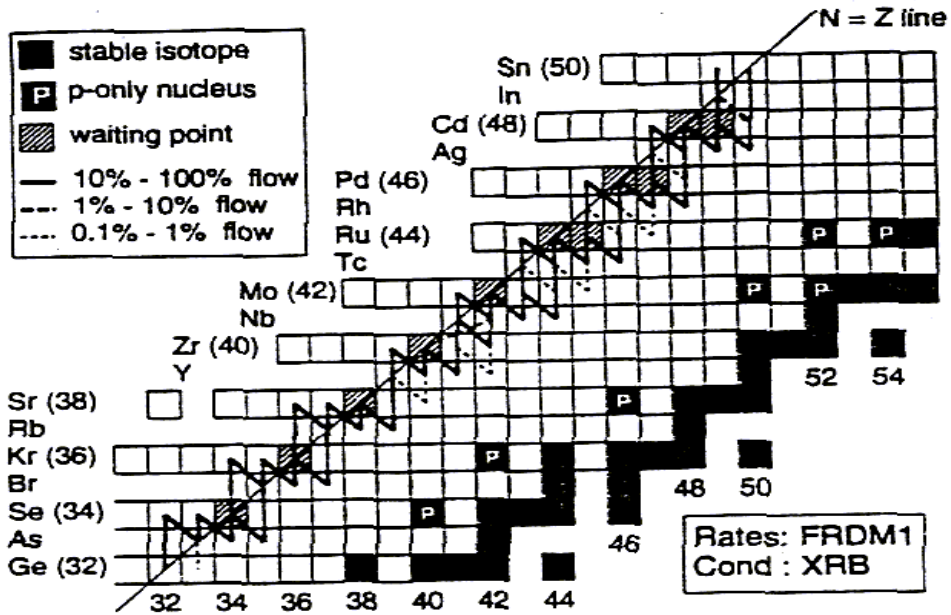
In the rp-process (and γ-process!), long-lived waiting point nuclides will achieve large abundances. Prompt β-p *moves nuclides much closer to stability, from which* they'll continue to be processed.

So need nuclides that undergo β-p that have half-lives long enough to outlast the rp-processing. ($T_{1/2}$ is usually very short for such nuclides!)

Fraction of β-p decay need not be very large if natural abundance of stable (ultimate) daughter is tiny.

***But "most interesting cases" (e.g., ^{92,94}Mo, ^{96,98}Ru) DO* have large abundances.**

And, isomeric states of neutron-poor isotopes could have long half-lives AND decay by β-p.



From Schatz et al.
Physics Reports 1998.

Path of the rp-process

Waiting points — abundance buildup

p-process nuclei

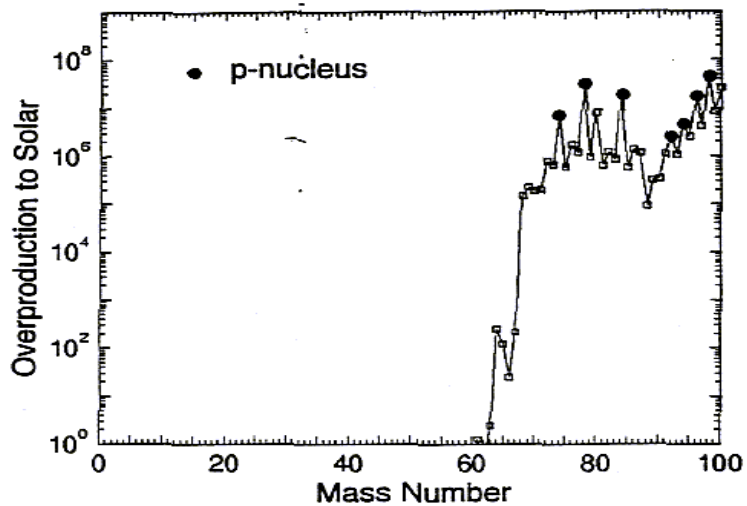


Figure 17. The abundance distribution after the thermonuclear runaway of a single X-ray burst.

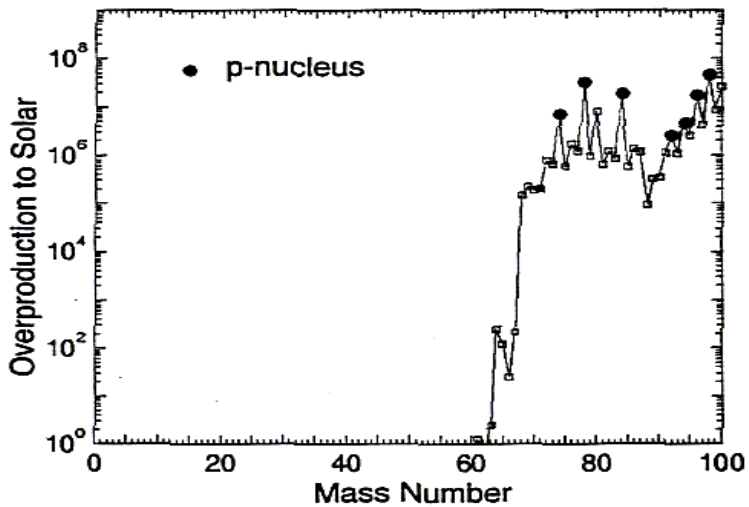


Figure 18. The ratio of the produced abundances and the initial solar abundances after the thermonuclear runaway of a single X-ray burst. The light p-nuclei are marked as black dots, their overabundance is about one to two orders of magnitude larger than the of other isotopes. The abundances of the last two mass numbers are not reliable because they correspond to the end of the network.

RePetitive rp-Process: the $(rp)^2$-Process

Brad Meyer, Mike Hencheck, RNB

Process solar seeds at "high" T for one second (exponential fall off), cool for one year, process for one second, cool ...

Use up to 50 repetitions

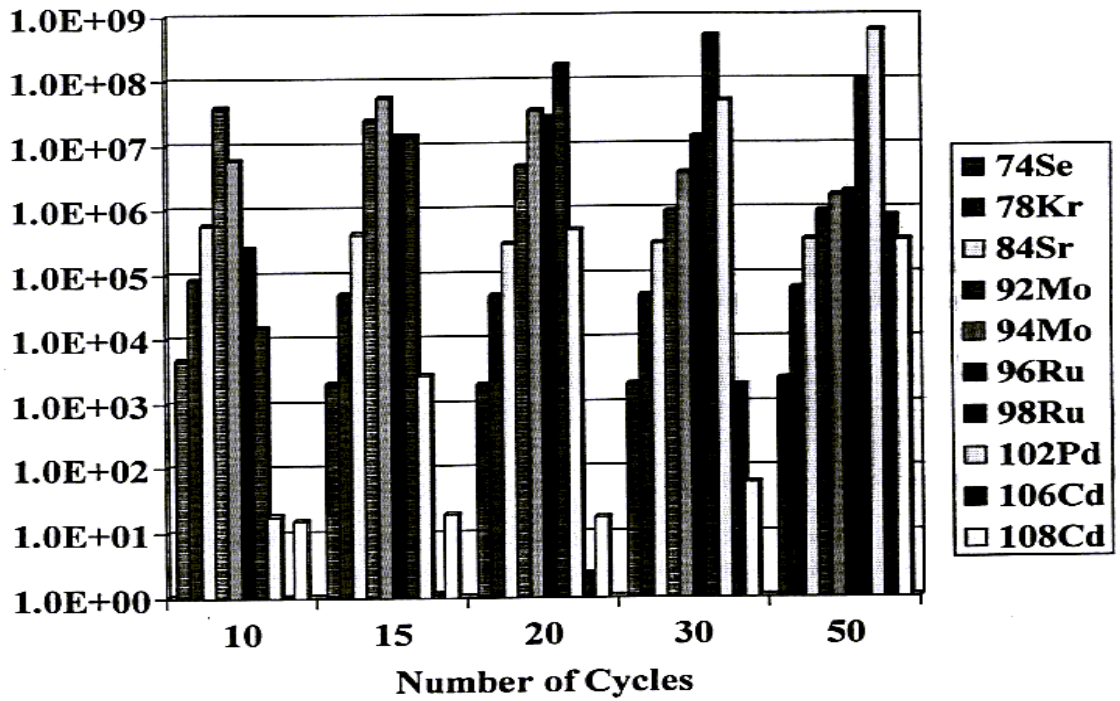
$T_9 = 1.0, 1.5, 2.0$

Seeds for each processing cycle are the products of the previous cycle; no rp-process "termination point".

Can make LOTS of difficult to make p-nuclei: ^{92,94}Mo and ^{96,98}Ru. Production is peaked over a few amu. But beware, e.g., ^{93}Nb.

OVERPRODUCTION FACTORS FROM $(rp)^2$-PROCESSING

$T_9 = 1.0$, Quiescent Time = 1 y



A Simple Model of $(rp)^2$-Process Nucleosynthesis

Assume that in each accretion event, mass M is added, and that identical processing scenarios occur each time.

Assume also that the amount of matter being expelled after the nth event, $\delta(n)$, by the explosion is a small fraction η of the total matter being processed (reasonable for a neutron star!).

Then $\delta(n) = \eta \Sigma_{j=1}^{n} M(j)$,
where $M(j)$ *is the amount of matter that has been* processed j times.

(Note that the H is never close to being used up.)

Thus the total amount of expelled material after N events would be

$\Sigma_{j=1}^{N} \delta(j) = \eta \Sigma_{j=1}^{N} (N+1-j)M(j)$.

For small N, this favors slightly processed material. But for large N, the material expelled will tend toward its $(rp)^2$-process saturation abundances.

Temperature, Density, and the Path of the rp-Process.

What conditions are required for the rp-process path to go through the β-delayed *proton emitters around 95 u?*

(Schatz et al.) At $T_9 = 1.5$, $\rho = 10^6$ g/cm^3, the path DOES go through the β-delayed proton emitters.

However, at $T_9 = 1.5$, $\rho = 10^5$ g/cm^3 or less, it apparently doesn't.

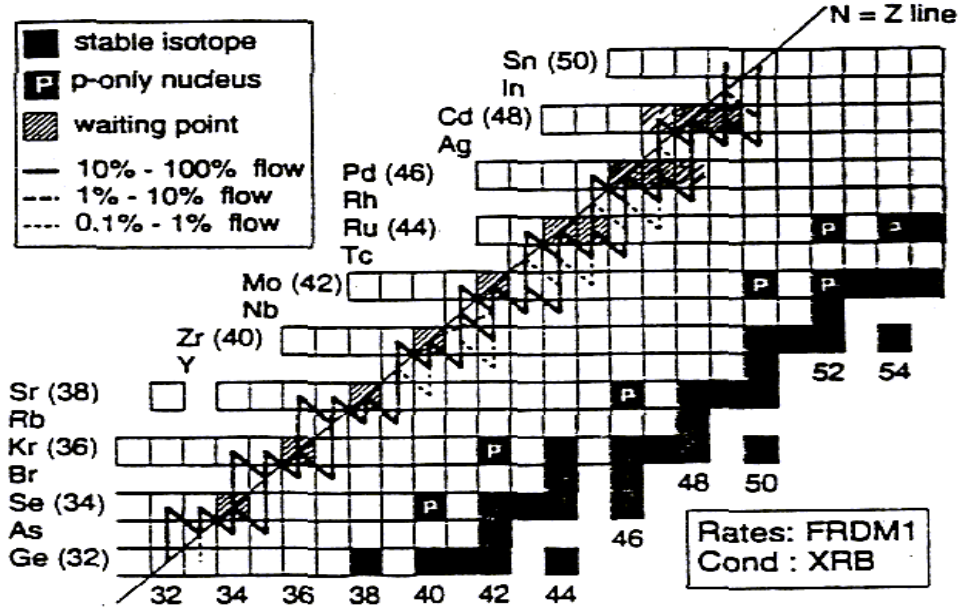
The rp-process populates a group of nuclei *with roughly equal overproduction factors,* so dramatic odd/even effects would only be seen if its path went through the β-delayed proton emitters, i.e., if T and ρ were high enough.

So the Mo-Ru abundances can serve as a very sensitive barometer/thermometer!

^{92}Pd (^{94}Pd) would be a progenitor of ^{92}Mo (^{94}Mo). But ^{92}Pd has a short $T_{1/2}$? However, ^{93}Pd and ^{94}Pd both have long $T_{1/2}$ (60 s, 9 s), so are waiting points at $T_9 \sim 1$ to 1.5. Thus, if ^{93}Pd ALSO decayed by β-p (it's energetically VERY favorable), the ^{92}Mo and ^{94}Mo puzzles might be solved.

^{97}Cd has a small (or negative) Q-values for (p,γ); it's also a *waiting point, and has a fairly long* (3 s) $T_{1/2}$. So abundance will build up there. If it decayed by β-p, it would produce ^{96}Ru, possibly solving that abundance question.

rp-process simulations often make too much ^{93}Nb and ^{97}Ru; β-p branching would help those problems.


stable isotope
p-only nucleus
waiting point
10% - 100% flow
1% - 10% flow
0.1% - 1% flow
N = Z line
Sn (50)
In
Cd (48)
Ag
Pd (46)
Rh
Ru (44)
Tc
Mo (42)
Nb
Zr (40)
Y
Sr (38)
Rb
Kr (36)
Br
Se (34)
As
Ge (32)
32
34
36
38
40
42
44
46
48
50
52
54
Rates: FRDM1
Cond : XRB

CONCLUSIONS

β-delayed proton emission might affect the path of the rp-process, but it would be difficult to tell, if the half-lives involved were fast (they usually are!).

More promising might be the possibility that β-delayed proton emission might affect abundances. This appears to be quite possible for the neutron poor Mo and Ru isotopes.

However, we need MORE DATA. And maybe even a bit more theory.

Long rp-process times, or multiple rp-process pulses, seem able to produce the Mo-Ru p-nuclide yields.

And, rp-process yields could define density and temperature of rp-process environment!