Astrophysics I: Stars and Stellar Evolution

AST 4001

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Stars and Stellar Evolution, Fall 2008

Overview

1. Recap
   - EOS
2. Origin of the Heavy Elements
   - Where are the Heavy Elements and How are They Made?
   - r-, p-, and s-Process

Equation of State

- Relates the different thermodynamic quantities, such as
  - pressure
  - temperature
  - density
  - (specific) internal energy
  - entropy
- for a given composition, usually the specification of any two of these is sufficient to compute all the others.
- functional formulation: e.g., $P(\rho, T)$, $S(\rho, P)$, etc.
- differential formulation: e.g.,

$$\frac{\mathrm{d}\rho}{\rho} = \left(\frac{\partial \ln \rho}{\partial \ln P}\right)_T \frac{\mathrm{d}P}{P} + \left(\frac{\partial \ln \rho}{\partial \ln T}\right)_P \frac{\mathrm{d}T}{T}$$

Overview

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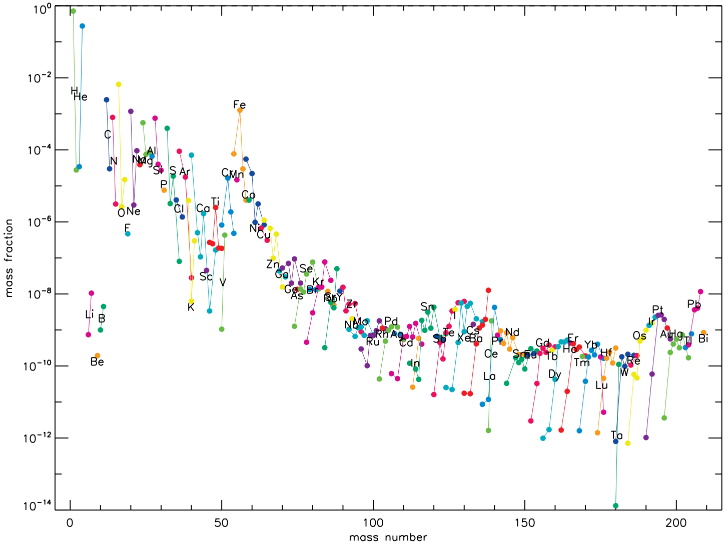
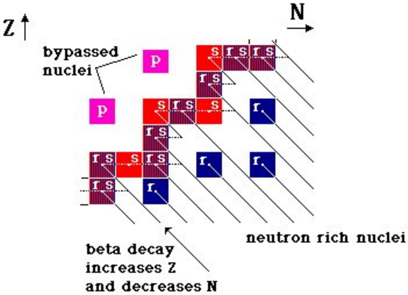
The Composition of the Sun

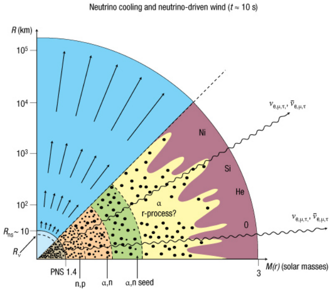


Creation of Heavy Elements



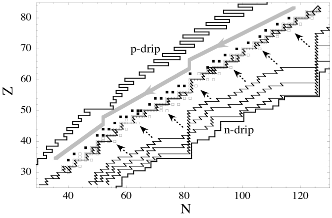
- Beyond iron the mass excess decreases.
- Fusing these heavy nuclei to even heavier does cost energy!
- But fusing a light "nuclei" (mostly neutrons) onto heavier still gives energy.
- Neutrons don't see the coulomb barrier!

r-Process



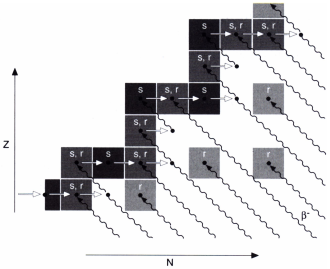
- Typical site: core collapse supernovae, hot neutron-rich environment
- Alternate site I: merger of neutron stars
- Alternate site II: explosive burning in helium shell during supernova explosion
- makes "heavy" nuclei including uranium and thorium (this is where these nuclei are made)
- is the dominant production mechanism for about half (by number) of the heavy isotopes beyond iron

r-Process Mechanism



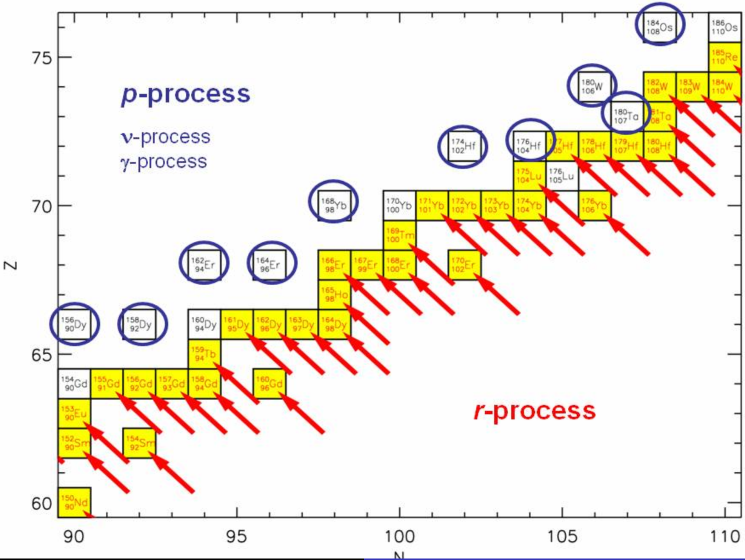
- runs on the neutron-rich side of valley of stability
- very high neutron "exposure"
- (n,γ) $\leftrightharpoons$(γ, n) equilibrium (neutron capture balances photo-disintegration reaction - very fast)
- "wait" for β^- decays to build up heavier nuclei (slower)
- time scale: $1 - 100\,\mathrm{s}$

r-Process Production

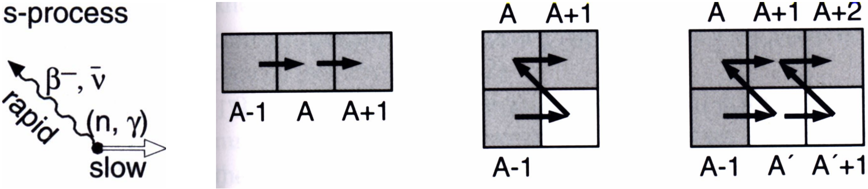


- β^- decays back to line of stability
- makes only nuclei not "shadowed" by other stable nuclei
- $\Rightarrow$ for each mass number A there is only one r-process isotope.

r- and *p*-Process



s-Process

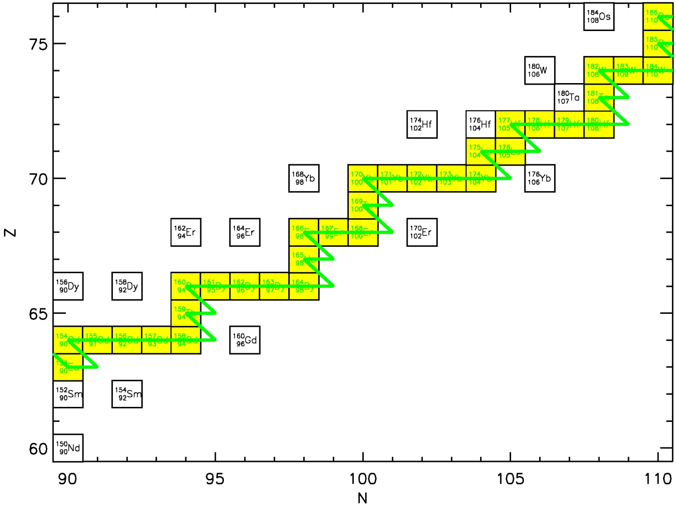


Two major contributions to *s*-process:

Weak component
Mostly in massive stars
weak neutron exposure
not in "equilibrium" - exponential decrease of abundances
Makes nuclei up to $A \sim 90$.

Strong component
Mostly in lower-mass stars, AGB stars
strong neutron exposure
in "equilibrium" - $Y_i \times \sigma_i$ constant (for extended ranges in A) Makes heavy nuclei up to lead (^{209}Bi).

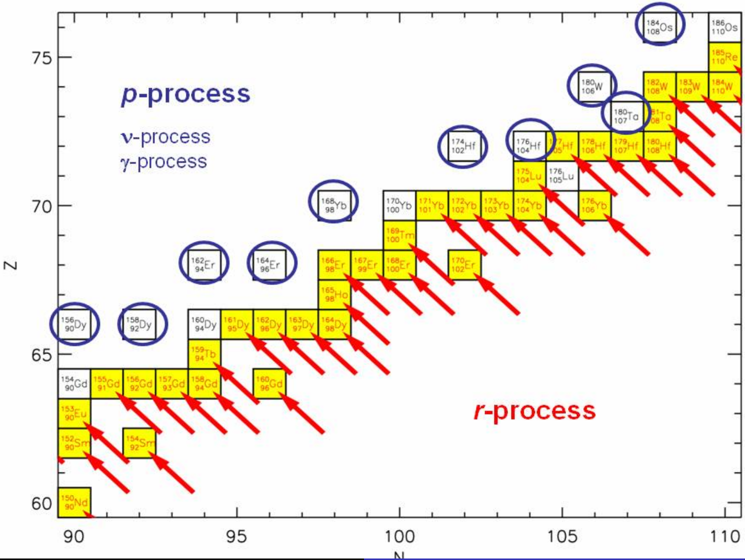
s-Process Path



Neutron Sources for the *s*-Process

- In massive stars:
  $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$
- $^{22}\mathrm{Ne}$ made from
  $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\mathrm{e}^{+}\nu_{\mathrm{e}})^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$
- In low-mass AGB stars (helium shell flashes) also $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$
- $^{13}\mathrm{C}$ made from
  $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}(\mathrm{e}^{+}\nu_{\mathrm{e}})^{13}\mathrm{C}$

r- and *p*-Process



"*p*"-Process (γ-process, ν-process)

- Production of proton-rich nuclei
- Proton-rich heavy nuclei are rare in nature
- Typical site: core collapse supernovae
- Mechanism 1 (γ-process): photo-"evaporation" of neutrons by high-energy photons; (γ,n) reaction;
  at higher energy and for more proton-rich nuclei also (γ,p) and (γ,α) reactions
- Mechanism 2: excitation of nuclei by high-energy neutrinos from hot neutron star; de-excitation by nucleon emission;
  $\mathrm{N}(\nu,\nu')\mathrm{N}^*(\mathrm{n}|\mathrm{p}|\alpha|\ldots)$
- Mechanism 3: conversion of neutrons to protons by electron neutrinos from hot neutron star; $(\nu_\mathrm{e},\mathrm{e}^-)$ reaction
- decay of proton-rich nuclei back to stable nuclei by β^+ decays

"p"-Process (γ-process, ν-process)

- Limitation:
  production of "rare" isotopes from very abundant neighbors.
- light nuclei examples:
  ^{11}B from ^{12}C,
  ^{19}F from ^{20}Ne
- heavy nuclei examples:
  ^{180}Ta from ^{181}Ta
  ^{138}La from ^{138}Ba