Astro 596/496 NPA

Lecture 36

Nov. 18, 2009

Announcements:

- Problem Set 6 posted, due Dec 2 (Wed after break)

Last time: beyond the iron peak

Q: what do solar abundances imply?

Q: what is needed for nucleosynthesis beyond Fe?

Q: what basic competition controls the nuke processes? limiting regimes?

The s-Process: Basic Physics

slow n capture: $\Gamma_{n\gamma} \ll \Gamma_{\beta}$
$\Rightarrow$ path in chart of nuclides:
follow n-rich edge of β-stability
`www:` s`-process path`

for isobar A

$$\frac{dn_A}{dt} = -\langle \sigma v \rangle_A n_n n_A + \langle \sigma v \rangle_{A-1} n_n n_{A-1} \qquad (1)$$

except for seed (e.g., ^{56}Fe)

$$dn_{\text{seed}}/dt = -\langle \sigma v \rangle_A n_n n_{\text{seed}} \qquad (2)$$

Q: what behavior expected for n_A?

put neutron exposure: $d\tau = n_n(t)\ v_T\ dt$
(= time-integrated n flux = n "fluence")
where $v_T = \sqrt{2kT/\mu_n}$, $\mu_n = m_n m_A/(m_n + m_A)$.
Then

$$\frac{dn_A}{d\tau} = -\sigma_A n_A + \sigma_{A-1} n_{A-1} \tag{3}$$

where $\sigma_A = \langle \sigma v \rangle_A / v_T$: thermal n capture cross section

evolution is another example of *self-regulating* equation
→ expect abundance driven to equilibrium, $dn_A/dt = 0$
⇒ $\sigma_A n_A = \sigma_{A-1} n_{A-1}$

$$\frac{n_A}{n_{A-1}} = \frac{\sigma_{A-1}}{\sigma_A} \tag{4}$$

⇒ the "local approximation"
only holds for non-magic nuclei
⇒ good between magic numbers

Solar Abundances and the s-Process

For elements beyond Fe peak:
plot $N_A \sigma_A$ vs A
if *s*-process reaches equilibrium, predict flat curve
Transp: *$N_A \sigma_A$ plot*

for adjacent nuclides, local approximation excellent
between magic N: good
but globally, fails
$\Rightarrow$ need distribution of τ

Roughly: exponential distribution of τ needed
i.e., imagine series of n bursts of different intensities
Q: how does nature do this?

The s-Process: Characteristic Scales

typically, $\langle \sigma v \rangle \sim 3 \times 10^{-17}$ cm^3/s

capture timescale $\tau(n) = 1/(n_n \langle \sigma v \rangle)$

if $\tau(n) > \tau_\beta^{\rm min} \sim 10$ yr shortest lifetime on *s* path

$\Rightarrow n_n < 10^8$ neutrons cm^{-3}

but also must pass through $N = 61$: *no stable nuclei!*

but ${}_{61}{}^{107}$Pd: $\tau_{107} \sim 10^7$ yr

`www: s-process path`

can't decay first:

$\tau(n) < \tau_{107} \;\; \rightarrow \;\; \Rightarrow n_n > 10^2$ neutrons cm^{-3}

cf reactor: $n_n \sim 10^7$ cm^{-3}

Q: Guesses as to astrophysical site?

s-Process: Astrophysical Site

Intermediate mass stars: $\sim 3 - 8\ M_\odot$
recall–after main seq:
1. H shell burn $\rightarrow$ RGB
2. He ignition $\rightarrow$ core He burn
3 He shell burn $\rightarrow$ asymptotically approach RGB again
"asymptotic giant branch" = AGB
HR diagram sketch

On AGB:
two burning shells: H, He
instability $\rightarrow$ thermal pulses (TP)

TP-AGB stars observed to have
- C/O > 1 – "carbon stars"
- high *s*-process! – "S-stars"

s-Process: The Crown Jewel

technetium seen in AGB stars (Merrill 1952)

Transp: *Tc lines*

no stable isotopes!

longest-lived $\tau(^{98}\mathrm{Tc}) = 6$ Myr

$\Rightarrow$ 1st direct evidence for ongoing nucleosynthesis in stars!

$\Rightarrow$ *s*-process must occur in AGB!

s-process occurs in pulsing AGB stars

Q: where did the stars get the neutrons? the seeds?

AGB neutron sources:

- ^{13}C from CNO cycle: $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$
- ^{14}N from CNO cycle burnt to $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$ then $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$

occurs in intershell region

n created during, between pulses

$\Rightarrow$ repeated n exposure of different intensities

$\Rightarrow$ can fit observed exposure distribution

...but now can make detailed, realistic models

in context of stellar evolution

The r-Process: Solar Abundances

for elements above Fe peak
s-process distribution set by theory
so *r*-process is residual:

$$N_r(A, Z) = N_{\text{obs}}(A, Z) - \frac{f(A)}{\sigma_A} \tag{5}$$

where $f(A)$ set by s-theory curve
Transp: r-*process dist'n*
$\Rightarrow$ *r*-process peaks at $A \sim 80, 130, 195$
$\Rightarrow$ at values *below* *s*-process peaks:
$A_{s,\text{max}} - A_{r,\text{max}} \sim 10$
Why?

Also: *s*-process terminates at ^{208}Pb:
$A > 208$ are β-unstable
$\Rightarrow$ ^{232}Th, ^{235}U, and ^{238}U are *r*-process only
demand an *r*-process

The *r*-Process: Basic Physics

Sketch:

- Rapidly add n to seeds (e.g., ^{56}Fe)
- populate n-rich nuclei far from β-stability
- later: decay back to β-stable isotopes

Transp: r-*process path*

In general, heavy nuclei can have both
r-process and *s*-process contributions.

But if have multiple stable states
at fixed A, then bifurcates:
the higher N state gets *r*-process
the lower N is "shielded": *s*-only

`www: s-process path`

$\Rightarrow$ very useful in sorting out processes