Announcements:
• Preflight 5 was due at noon
• Problem Set 5 out, due next Friday

Last time: began massive stars

Main sequence:
• burn $p \rightarrow ^4\text{He}$ via CNO cycle
when H exhausted:
• homologous contraction
• H shell burning begins $\rightarrow$ supergiant
• heat core $\rightarrow$ ignite...
He burning: via $3\alpha \rightarrow ^{12}\text{C}$ $Q$: how might this work
The Triple-Alpha Reaction

$3\alpha \rightarrow ^{12}\text{C}$ in two steps:

(1) $\alpha + \alpha \leftrightarrow ^{8}\text{Be}$ establishes (small) $^8\text{Be}$ equilibrium

\[ 2\mu_\alpha = \mu_8 \]
\[ \Rightarrow n_{^8\text{Be}}^{\text{eq}} \sim n_\alpha^2/(mT)^{3/2} e^{-Q/T} \]
\[ Q = 0.092 \text{ MeV} \sim 10^9 \text{ K} \Rightarrow \text{small abundance!} \]

(2) $^8\text{Be} + \alpha \rightarrow ^{12}\text{C} + \gamma$

\[ \text{rate} \sim \langle \sigma v \rangle n_\alpha n_{^8\text{Be}}^{\text{eq}} \sim \langle \sigma v \rangle n_\alpha^3/(mT)^{3/2} e^{-Q/T} \]

but: He$\rightarrow$C burning too slow if cross section really, astrophysical $S(E)$, is constant or slowly varying

$Q$: and so?
He→C burning too slow if $S(E)$ is constant
Fredy Hoyle: reaction must pass through resonance
$^8\text{Be} + \alpha$ lied just at excited state of $^{12}\text{C}$

Hoyle predicted existence of state, soon confirmed by nuke experiment!

www: $^{12}\text{C}$ energy level scheme
→ early example of cosmos as poor woman’s accelerator

Along with $^{12}\text{C}$ production, also $^{16}\text{O}$ production via $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
Initially: $3\alpha \rightarrow ^{12}\text{C}$ dominates
Then: $^{12}\text{C}$ source $\propto n_\alpha^3$ low $\rightarrow ^{16}\text{O}$ made

key rate: $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
• sets ejected $^{12}\text{C}/^{16}\text{O}$ ratio
• determines later stellar evolution
• uncertain (but getting better!)
When He exhausted, begin cycles:
• contract
• ignite new shell burning
• ignite ash → fuel in core
• burn core to exhaustion
repeat...

develop “onion skin” structure: www: pre-SN favors “α-elements”: tightly bound

\[
\begin{align*}
\text{C burning:} & \quad 12C + 12C & \rightarrow & & 20Ne + \alpha \\
\text{Ne burning:} & \quad 20Ne + \gamma & \rightarrow & & 16O + \alpha \\
& \quad 20Ne + \alpha & \rightarrow & & 24Mg + \gamma \\
& \quad 24Mg + \alpha & \rightarrow & & 28Si + \gamma \\
\text{O burning:} & \quad 16O + 16O & \rightarrow & & 28Si + \alpha \\
& & & \rightarrow & & 32S + \gamma
\end{align*}
\]
Neutrino Cooling

At $T \gtrsim 5 \times 10^8$ K (C burn):
neutrinos produced via $e^+ e^- \rightarrow \nu \bar{\nu}$
much slower than $e^+ e^- \rightarrow \gamma \gamma$ yet still crucial
$Q$: why?

neutrino production rate per volume:

$$q_\nu = \langle \sigma v n_e^2 \rangle \sim T^2 \times (T^3)^2 \sim T^8$$

(1)

$\nu$ escape $\rightarrow$ dominate $E$ loss: **neutrino cooling**

neutrino $E$ loss rate per vol: $\varepsilon_\nu = E_\nu q \sim T^9$
equilibrium: $\varepsilon_{\text{emit,}\nu} = \varepsilon_{\text{released,nuc}}$
$\rightarrow L_\nu \sim (1 - 10^6)L_\gamma$ for C thru Si burning: neutrino star!
shortens burning phases
final stages: months, days
Si Burning

\( T \sim 4 \times 10^9 \text{ K} \rightarrow n_\gamma \sim T^3 \) large

photodisintegration \( ^{28}\text{Si} + \gamma \rightarrow p, n, \alpha \)

rate \( \lambda_\gamma \propto e^{-Q/T} \), \( Q = \text{BE of } p, n, \alpha \) in nucleus

1. \( \gamma \)'s take \( p, n, \alpha \) from weakly bound nuclei
2. these recombine with all nuclei
3. flow \( \rightarrow \) more tightly bound

Net effect: redistribute nucleons to most tightly bound

www: Brad Meyer movie

Driven to **nuclear statistical equilibrium (NSE)**

for \( \boxed{\text{Ni}n + \text{Zi}p \leftrightarrow \text{Ai} } \)

chem eq: \( \text{Ni}\mu_n + \text{Zi}\mu_p = \mu_i \)

\[
Y_i = \frac{n_i}{n_B} \sim \left( \frac{\rho}{(mT)^{3/2}} \right)^{A_i-1} Y_n^{N_i} Y_p^{Z_i} e^{B_i/T}
\]

(2)

with \( B_i = \text{binding energy max} \sim \text{largest } B_i \)

Q: namely?
NSE parameters: $T, \rho, Y_n, Y_p$
but $Y_n, Y_p$ related via charge conservation (“neutron excess”):

$$\eta = \frac{\sum_i (N_i - Z_i) n_i}{\sum_i (N_i + Z_i) n_i} = \sum_i (N_i - Z_i) Y_i = 1 - 2Y_e$$

where $Y_e \in (0, 1)$ is the “electron fraction” (PS1)

After H burn $\rightarrow \ ^4\text{He}$: $\eta \simeq 0$
If no $\beta$ decays later, $\eta$ unchanged
At $\eta = 0$, NSE max not at $\ ^{56}\text{Fe}$ but at
double magic $N_i = Z_i = 28$: $\ ^{56}\text{Ni}$
...but $\ ^{56}\text{Ni}$ unstable outside SN core!
then decays $\rightarrow$ crucial for light curve!

end with “iron core”

$M_{\text{core}} \sim 1.4M_\odot = M_{\text{Chandra}}$
max BE: fusion no longer exoergic!
Core Collapse

Why collapse?

(1) can’t burn Fe $\rightarrow$ degenerate core support: thermal, $\epsilon$ degen pressure but do burn Si in overlying shell $\rightarrow$ increase Fe core mass when $M_{\text{core}} > M_{\text{Chandra}} \rightarrow$ collapse

(2) Fe core photodisintegrated
e.g., $^{56}\text{Fe} \rightarrow 13\alpha + 4n$
electron capture $e^- + p \rightarrow n + \nu_e$
and $e^- + Z_A \rightarrow Z - 1_A + \nu_e$
“neutronization” or “deleptonization” $\Rightarrow$ removes $e$, reduced degen. pressure also: releases $\nu_e$s
Freefall timescale for material with density $\rho$:

$$\tau_{ff} \sim 1/\sqrt{G\rho} \sim \frac{446}{\sqrt{\rho_{cgs}}} \lesssim 1 \text{ sec}$$

but pre-supernova star very non-uniform density

$Q$: what does this mean for collapse?

inner core: homologous collapse $v \propto r$

outer core: quickly becomes supersonic $v > c_s$

outer envelope: unaware of collapse
**Bounce and Explosion**

core collapses until $\rho_{\text{core}} > \rho_{\text{nuc}} \sim 3 \times 10^{14} \text{ g/cm}^3$

repulsive short-range nuclear force dominates: “incompressible”

details depend on equation of state of nuke matter

1. core bounce $\rightarrow$ proto neutron star born
2. shock wave launched
3. a miracle occurs
4. outer layers accelerated
   
   *Demo: AstroBlaster™*

5. successful explosion observed
   $\rightarrow v_{\text{ej}} \sim 15,000 \text{ km/s} \sim c/20!$
**Why step 3?** What’s the miracle?

“prompt shock” fails:

**do** launch shock, but

- overlying layers infalling
  
  → ram pressure $P = \rho v_{in}^2$

- dissociate Fe → lose energy

shock motion stalls → “accretion shock”

“prompt explosion” mechanism fails

**Q: what needed to revive explosion?**
Delayed Explosion Mechanisms

“delayed explosion” to revive: neutrinos, 3-D hydro/instability, rotation effects? some models not work, but controversial

Energetics:

\[ E_{\text{ejecta}} \sim M_{\text{ej}} v^2 \sim (10M_\odot)(c/20)^2 \sim 10^{51} \text{ erg} \equiv 1 \text{ foe} \]

but must release grav binding

\[ \Delta E \sim -GM_\star^2/R_\star - (-GM_{\text{NS}}^2/R_{\text{NS}}) \]
\[ \approx GM_{\text{NS}}^2/R_{\text{NS}} \sim 3 \times 10^{53} \text{ erg} = 300 \text{ foe} \]

Q: Where does the rest go?
\[ \Rightarrow \text{SN calculations must be good to } \sim 1\% \]
to see the minor optical fireworks