

Astro 596/496 NPA

Lecture 29

Oct. 30, 2009

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*

$$2\mu_\alpha = \mu_8$$

$$\Rightarrow n_8^{\text{eq}} \sim n_\alpha^2 / (mT)^{3/2} e^{-Q/T}$$

$$Q = 0.092 \text{ MeV} \sim 10^9 \text{ K} \Rightarrow \text{small abundance!}$$

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

$$\text{rate} \simeq \langle \sigma v \rangle n_\alpha n_8^{\text{eq}} \sim \langle \sigma v \rangle n_\alpha^3 / (mT)^{3/2} e^{-Q/T}$$

but: He \rightarrow C burning too slow if cross section

really, astrophysical $S(E)$, is constant or slowly varying

\sim

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 → ${}^{16}\text{O}$ made

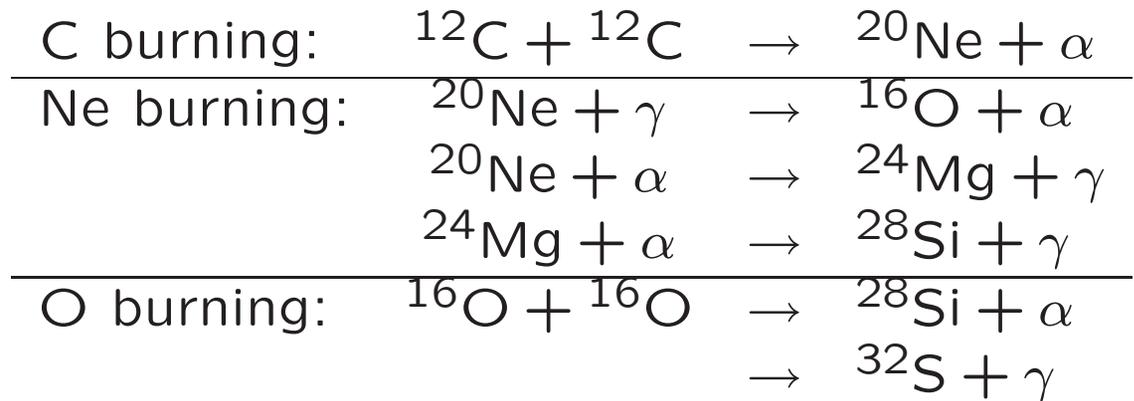
key rate: ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$

- 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 \rightarrow fuel in core
 - burn core to exhaustion
- repeat...

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



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:

$$q_\nu = \langle \sigma v n_e^2 \rangle \sim T^2 \times (T^3)^2 \sim T^8 \quad (1)$$

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

1. γ s take p, n, α 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 $N_i n + Z_i p \leftrightarrow A_i$

chem eq: $N_i \mu_n + Z_i \mu_p = \mu_i$

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

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

Q : namely?

NSE parameters: T, ρ, Y_n, Y_p

but Y_n, Y_p related via charge conservation (“neutron excess”):

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

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

After H burn \rightarrow ${}^4\text{He}$: $\eta \simeq 0$

If no β decays later, η 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*”

\checkmark $M_{\text{core}} \sim 1.4 M_{\odot} = M_{\text{Chandra}}$

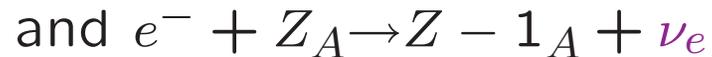
max BE: fusion no longer exoergic!

Core Collapse

Why collapse?

(1) can't burn Fe \rightarrow degenerate core
support: thermal, e 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



“neutronization” or “deleptonization”

\Rightarrow removes e , reduced degen. pressure

also: releases ν_e s

Collapse Dynamics

Freefall timescale for material with density ρ :

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

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 nuclear matter

1. *core bounce* → proto neutron star born
2. *shock wave* launched
3. a miracle occurs
4. outer layers *accelerated*

Demo: AstroBlaster™

5. successful *explosion* observed
→ $v_{\text{ej}} \sim 15,000 \text{ km/s} \sim c/20!$

Why step 3? What's the miracle?

“prompt shock” fails:

do launch shock, but

- overlying layers infalling

→ ram pressure $P = \rho v_{\text{in}}^2$

- 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:

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

but must release grav binding

$$\begin{aligned} \Delta E &\sim -GM_{\star}^2/R_{\star} - (-GM_{\text{NS}}^2/R_{\text{NS}}) \\ &\simeq GM_{\text{NS}}^2/R_{\text{NS}} \sim 3 \times 10^{53} \text{ erg} = 300 \text{ foe} \end{aligned}$$

Q: Where does the rest go?

⇒ SN calculations must be good to $\sim 1\%$

to see the minor optical fireworks