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 $p \rightarrow {}^4$He via CNO cycle

when H exhausted:
- homologous contraction
- H shell burning begins $\rightarrow$ supergiant
- heat core $\rightarrow$ ignite...

He burning: via $3\alpha \rightarrow {}^{12}$C *Q: how might this work*

The Triple-Alpha Reaction

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

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

$2\mu_\alpha = \mu_8$

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

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

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

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

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}Be $+\, \alpha$ lied just at excited state of ^{12}C

Hoyle **predicted** existence of state,
soon confirmed by nuke experiment!
`www:` ^{12}C `energy level scheme`
$\longrightarrow$ early example of cosmos as poor woman's accelerator

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

key rate: ^{12}C$(\alpha,\gamma)^{16}$O
- sets ejected ^{12}C/^{16}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: `www: pre-SN`
favors "α-elements" : tightly bound

C burning:	$^{12}\text{C} + {}^{12}\text{C}$	$\rightarrow$	$^{20}\text{Ne} + \alpha$
Ne burning:	$^{20}\text{Ne} + \gamma$	$\rightarrow$	$^{16}\text{O} + \alpha$
	$^{20}\text{Ne} + \alpha$	$\rightarrow$	$^{24}\text{Mg} + \gamma$
	$^{24}\text{Mg} + \alpha$	$\rightarrow$	$^{28}\text{Si} + \gamma$
O burning:	$^{16}\text{O} + {}^{16}\text{O}$	$\rightarrow$	$^{28}\text{Si} + \alpha$
		$\rightarrow$	$^{32}\text{S} + \gamma$

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

$T \sim 4 \times 10^9$ K $\to n_\gamma \sim T^3$ large
photodisintegration $^{28}\mathrm{Si} + \gamma \to p, n, \alpha$
rate $\lambda_\gamma \propto e^{-Q/T}$, $Q =$ BE of p, n, α in nucleus
1. γs take p, n, α from weakly bound nuclei
2. these recombine with all nuclei
3. flow $\to$ more tightly bound

Net effect: redistribute nucleons to most tightly bound
`www: Brad Meyer movie`

Driven to **nuclear statistical equilibrium (NSE)**
for $\boxed{N_i n + Z_i p \leftrightarrow A_i}$
chem eq: $N_i \mu_n + Z_i \mu_p = \mu_i$

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

with B_i=binding energy max $\sim$ 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 → ^{4}He: $\eta \simeq 0$

If no β decays later, η unchanged

At $\eta = 0$, NSE max not at ^{56}Fe but at

double magic $N_i = Z_i = 28$: ^{56}Ni

...but ^{56}Ni unstable outside SN core!

then decays → crucial for light curve!

end with "*iron core*"

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

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
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 ν_es

Collapse Dynamics

Freefall timescale for material with density ρ:
$\tau_{\rm ff} \sim 1/\sqrt{G\rho} \sim 446 \text{ s}/\sqrt{\rho_{\rm cgs}} \lesssim 1$ 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: quicly becomes supersonic $v > c_{\rm s}$
outer envelope: unaware of collapse

Bounce and Explosion

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

repulsive sort-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$^{\text{TM}}$
5. successful *explosion* observed

   $\rightarrow v_{\text{ej}} \sim 15,000$ km/s $\sim c/20$!

Why step 3? What's the miracle?

"prompt shock" fails:

do launch shock, but

- overlying layers infalling

$\longrightarrow$ ram pressure $P = \rho v_{\rm in}^2$

- dissociate Fe $\rightarrow$ lose energy

shock motion stalls $\rightarrow$ "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:
$E_{\text{ejecta}} \sim M_{\text{ej}} v^2 \sim (10 M_\odot)(c/20)^2 \sim 10^{51}$ erg $\equiv 1$ foe
but must relase 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?
$\Rightarrow$ SN calculations must be good to $\sim 1\%$
to see the minor optical fireworks