Astro 596/496 NPA
Lecture 30
April 12, 2019

Announcements:

- **Problem Set 5 due**
  Typo alert! Q3(f) should refer to KamLAND paper Fig 3
- **Preflight 6 due next Friday**

Last Time: neutrino oscillations

- neutrinos born in Sun, created via Weak interaction
  definite flavor: ν_e eigenstate
- propagate as mass eigenstate
- measured in Weak interactions: flavor eigenstates
- mixing controlled by mass square difference $\Delta m^2 = m_2^2 - m_1^2$
  and by (vacuum) mixing angle $\theta_{\rm V}$

Solar Neutrino Solutions

Using all solar ν data, most favored solution:

⋆ $\theta_{\mathrm{V}} = 32.5^\circ$

⋆ $\Delta m^2 = 7.1 \times 10^{-5}\ \mathrm{eV}^2$

Implications

- "large mixing angle" (LMA)

  Q: what angle gives maximal vacuum mixing? ...hint:

$$\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta_{\mathrm{V}} & \sin\theta_{\mathrm{V}} \\ -\sin\theta_{\mathrm{V}} & \cos\theta_{\mathrm{V}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- $\Delta m^2 = |m_2^2 - m_1^2|$ does *not* give either m_1 or m_2

  but does set *minimum* mass for either:

  $m_{\nu,\mathrm{min}} = \sqrt{\Delta m^2} = 8 \times 10^{-3}\ \mathrm{eV}$

Q: how to test this solution in the lab?

Laboratory test: KamLAND

(Kamiokande Liquid Scintillator Anti-Neutrino Detector)

sources: anti-neutrinos from Japanese nuke reactors

- $E_\nu = 2.6 - 8$ MeV
- avg distance $R \sim 180$ km

$\rightarrow$ if LMA, disappearance probability is

$$P_{\text{dis}} = \sin^2 2\theta_{\text{V}} \ \sin^2\left(2\pi \frac{R}{350\text{km}}\right) \tag{1}$$

Kamland observes flux *reduction*: $P_{\text{dis}} = 0.66$

E_ν spectrum $\rightarrow$ $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}$ eV^2

$\rightarrow$ confirms oscillations in general, and LMA in particular!

`www: KamLAND plots`

Q: remaining questions? experiments?

Next Step: Precision Neutrino Astronomy

- measure monoenergetic ^{7}Be neutrinos
  now detected in real-time!
  flux consistent with MSW LMA
  `www: Borexino`
- measure pp flux to $\sim 1\%$ $\Rightarrow$ better $\theta_{\rm V}$
  `www: Stanford Lab` New questions:

What are ν masses?

oscillations only measure splittings Δm^2
$\rightarrow$ know masses are *different* and *nonzero*
but don't even know hierarchy: is $m_1 < m_2$ or the reverse?

Is ν_i identical to $\bar{\nu}_i$?

yes: “Majorana” neutrinos
no: “Dirac” neutrinos, right-hand ν exist
can test with “neutrinoless double beta decay”
(rare nuclear decays, only go if Majorana)

Do neutrinos violate CP?

if so: maybe important in baryogenesis...
“leptogenesis” scenario: generate net *lepton* number, then translate this to net baryon number

Massive Stars

Neutrinos and Nucleosynthesis

Evolution of Massive Stars

in our context, massive: $M \gtrsim 8 - 10 M_\odot$

that is: destined to become core-collapse supernovae

Massive Star Demographics

based on initial mass function–distribution of star birth masses

- massive stars are $\sim 0.5\%$ by *number* of all stars born
- but comprise $\sim 10\%$ of *mass* going into stars

  Q: how can these both be true?

Massive star evolution: Main sequence:

- O and B types: $T_{\rm eff} \sim 10^4$–10^5 K, luminosity $L \sim (10^3$–$10^5)L_\odot$

  Q: implications?
- MS central conditions $(\rho_c, T_c) \sim (100 \ {\rm g/cm^3}, 3 \times 10^7 {\rm K})$

  Q: compare to center of Sun? implications?

Massive Stars: Main Sequence Implications

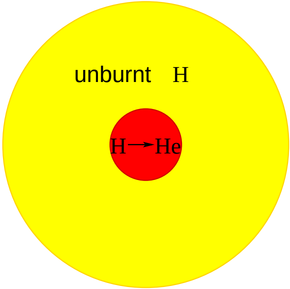
hot photosphere: $T_{\text{eff}} \sim 10^4 - 10^5$ K

- OB main sequence stars are blue/UV
- important sources of ionizing photons (H ii regions)

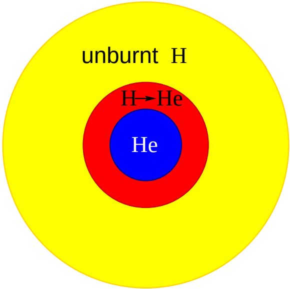
huge luminosity $L \sim (10^3 - 10^5) L_{\odot}$

- overrepresented in observed (flux-limited) star counts
- huge nuclear burning rates...
- ...and so *short main sequence lifetime* ($\lesssim$ 30 Myr)
- short life: don't travel far from birth sites
  massive stars trace ongoing star formation
- *rapidly die, eject new nucleosynthesis products to cosmos*

Massive Stars: Burning Phases

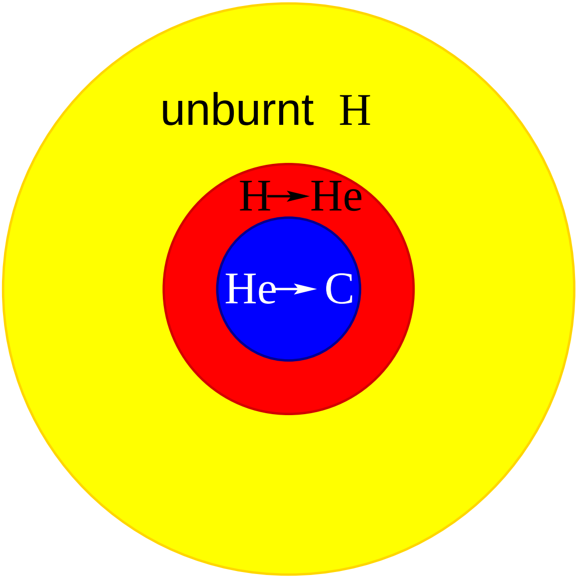


Main sequence: hydrogen burning
- $T_c \gtrsim 2\times$ hotter than Sun
- burn $p \rightarrow {}^4$He via CNO cycle
  avoid Weak $pp \rightarrow de\nu$: goes much faster



when core hydrogen exhausted:
- central fuel source gone → center cools
  hydrostatic equilibrium lost → *star contracts*
- unburned H in shell around core ignited
  shell H burning begins
- outer layers expand → **red supergiant**
- core contracts and heats → ignite...

Q: what is main nuclear reaction in core?



He burning via $3\alpha \longrightarrow {}^{12}\mathrm{C}$

a *3-body reaction*

Q: how might this work?

The Triple-Alpha Reaction

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

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

$$2\mu_\alpha = \mu_8$$
$$\Rightarrow n_8^{\mathrm{eq}} \sim n_\alpha^2/(mT)^{3/2} e^{-Q/T}$$
$Q = 0.092$ MeV $\sim 10^9$ K $\Rightarrow$ small abundance!

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

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

but: He→C burning too slow if cross section small

not enough carbon made if astrophysical $S(E)$ constant

Q: and so?

He→C burning too slow if $S(E)$ is constant
Fred 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`
→ early example of cosmos as poor woman's accelerator

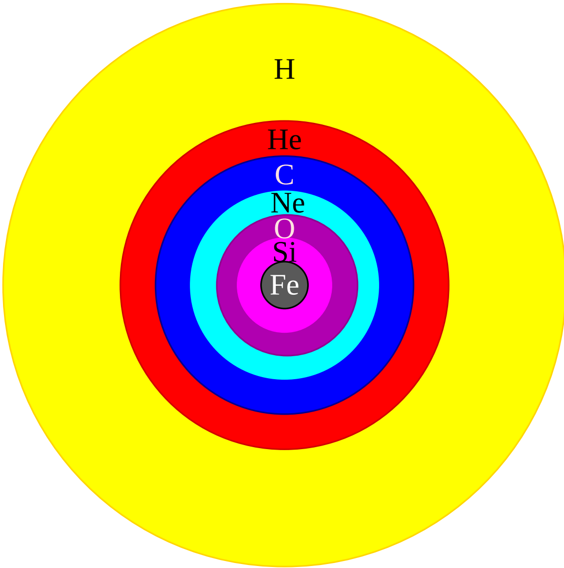
Along with ^{12}C production, also
^{16}O production via ^{12}C$(\alpha,\gamma)^{16}$O
Initially: $3\alpha \to {}^{12}$C dominates
Then: ^{12}C source $\propto n_\alpha^3$ low → ^{16}O made

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 → fuel in core
- burn core to exhaustion

repeat...



develop "onion skin" structure: `www: pre-SN`

favors "α-elements" : tightly bound

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

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:

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

ν escape → 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 $\rightarrow n_\gamma \sim T^3$ large

photodisintegration $^{28}\mathrm{Si} + \gamma \rightarrow p, n, \alpha$

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 → more tightly bound

Net effect: redistribute nucleons to most tightly bound

Nuclear Statistical Equilibrium

core driven to **nuclear statistical equilibrium (NSE)**
for $\boxed{N_i n + Z_i p \leftrightarrow A_i}$
chemical equilibrium $N_i \mu_n + Z_i \mu_p = \mu_i$

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

with B_i/A_i=binding energy per nucleon
max abundance → max Y_i should be $\sim$ largest B_i/A_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 $Y_e = n_e / n_{\text{baryon}} \in (0, 1)$ is the "electron fraction"

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 $N_i = Z_i = 28$: $\boxed{^{56}\text{Ni}}$
...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?

can't burn Fe → degenerate core

support: thermal, e degeneracy pressure–core is iron white dwarf!

but do burn Si in overlying shell

→ increase Fe core mass

when $M_{\text{core}} > M_{\text{Chandra}}$ → collapse

upon collapse: 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"

removes e and so reduces degeneracy pressure

- accelerates collapse (positive feedback)
- also: releases ν_e

Collapse Dynamics

Freefall timescale for material with density ρ (PS6):

$$\tau_{\text{ff}} \sim \frac{1}{\sqrt{G\rho}} \sim 446\ \text{s}\sqrt{\frac{1\ \text{g/cm}^3}{\rho_{\text{cgs}}}} \lesssim 1\ \text{sec}$$

but pre-supernova star very non-uniform density

Q: what does this mean for collapse?

inner core: homologous collapse $v \propto r$

outer core: quicly becomes supersonic $v > c_{\text{s}}$

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* → 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

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

- 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:
$E_{\rm ejecta} \sim M_{\rm ej} v^2 \sim (10 M_\odot)(c/20)^2 \sim 10^{51}$ erg $\equiv 1$ foe
but must relase grav binding

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

Q: Where does the rest go?
⇒ SN calculations must be good to $\sim 1\%$
to see the minor optical fireworks