Astro 596/496 NPA

Lecture 27

April 3, 2019

Announcements:

- **Preflight 5 due Friday**
- one last respite for the weary (apologies!)
  no class meeting Friday

Last Time: began the nuclear and particle astrophysics of stars

first stop: **the multimessenger Sun**

Q: hydrogen burning in the Sun: inputs and outputs?

Q: first stages of pp *chain?*

Solar Hydrogen Burning: Big Picture

Sun: main sequence, $4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e$

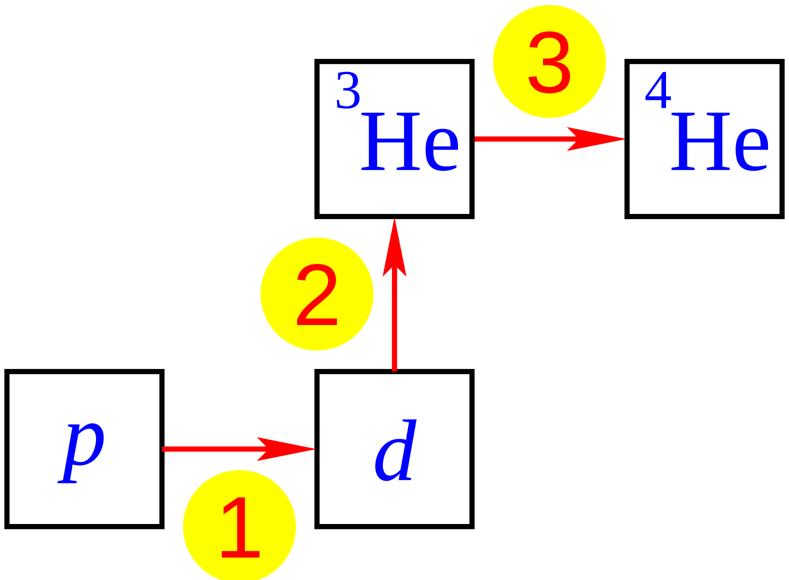
Reaction chains usually begin with

$$p + p \rightarrow d + e^+ + \nu_e \tag{1}$$

weak reaction: slowest step in chain. Next:

$$d + p \rightarrow {}^3\text{He} + \gamma \tag{2}$$

PP–I Chain



1. $pp \rightarrow de\nu$
2. $dp \rightarrow {}^{3}\mathrm{He}$
3. ${}^{3}\mathrm{He}\;{}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He}\;pp$

Deuterium in the Sun

deuterium evolution in Sun:

$$\dot{n}_d = -\lambda_{dp} n_d n_p + \lambda_{pp} n_p^2/2 \quad (3)$$

$$= -\Gamma_{\mathrm{per}\,d}(dp \to {}^3\mathrm{He}\gamma) \left(n_d - n_d^{\mathrm{eq}} \right) \quad (4)$$

self-regulating:
driven to equilibrium $\dot{n}_d = 0$
in timescale $\tau_d = 1/\Gamma_{\mathrm{per}\,d} \sim 1$ s (!)

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{eq}} = \left(\frac{n_{d,\mathrm{eq}}}{n_p}\right) = \left.\frac{\lambda_{pp}}{2\lambda_{dp}}\right|_{T_c} \sim 10^{-18} \quad (5)$$

why so small? ratio of Weak to EM reaction

note: $pp \to de^+\nu_e$ has proton consumption rate
$\dot{n}_p|_{pp \to de\nu} = -\lambda_{pp} n_p^2 = -2\Gamma_{\mathrm{per}\,p} n_p$ *Q: why?*

Q: what happens to ^{3}He*?*

Helium-3

source: $dp \to {}^3\text{He}\,\gamma$
dominant sink: ${}^3\text{He} + {}^3\text{He} \to {}^4\text{He} + p + p$

$$\dot{n}_3 = -2\lambda_{33} n_3^2/2 + \lambda_{dp} n_d n_p \quad (6)$$

approximate $n_d \approx n_d^{\text{eq}}$
again a *self-regulating equilibrium*, with

$$n_3^{\text{eq}} = \sqrt{\frac{\lambda_{dp}}{\lambda_{33}} n_d^{\text{eq}} n_p} = \sqrt{\frac{\lambda_{dp}}{\lambda_p}} n_p \quad (7)$$

so in solar core

$$\left(\frac{{}^3\text{He}}{\text{H}}\right)_{\text{eq}} \sim 10^{-5} \quad (8)$$

reached in timescale $\tau_3 \sim 10^6$ yr
...and longer at lower temp
$\Rightarrow$ large ^{3}He gradient outward in Solar core

Q: what about ^{4}He*?*

Helium-4

in **PP-I**, source is ^{3}He ^{3}He$\rightarrow$^{4}He p p

no sink!

Q: so what is equilibrium abundance?

time change of ^{4}He:

$$\dot{n}_4 = \lambda_{33} n_3^2/2 \approx \frac{1}{2}\lambda_{33}(n_3^{\rm eq})^2 = \frac{\lambda_{pp}}{4} n_p^2 = -\frac{1}{4}\,\dot{n}_p|_{pp\rightarrow de\nu} \qquad (9)$$

Q: physical significance of last equality?

^{4}He "ash" accumulates over time in solar core

at expense of protons (H "fuel")

Alternatives to pp-I

hydrogen burning via pp chain:

$$p + p \rightarrow d + e^{+} + \nu_e \quad (10)$$

then overwhelmingly, the next step is

$$d + p \rightarrow {}^{3}\text{He} + \gamma \quad (11)$$

then pp-I

$$^{3}\text{He} + {}^{3}\text{He} \rightarrow {}^{4}\text{He} + p + p \quad (12)$$

Q: other possible fates of ^{3}He*? neutrino production in each?*

The pp-II, pp-III Chains

PP-I

$^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + p + p$

$^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$

PP-II

$^7\text{Be} + e \rightarrow {}^7\text{Li} + \nu_e$

$^7\text{Li} + p \rightarrow {}^4\text{He} + {}^4\text{He}$

PP-III

$^7\text{Be} + p \rightarrow {}^8\text{B} + \gamma$

$^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_e$

$^8\text{Be} \rightarrow {}^4\text{He} + {}^4\text{He}$

minor additions to energy and neutrino generation:

pep 3-body reaction: $ppe^- \rightarrow d\nu_e$

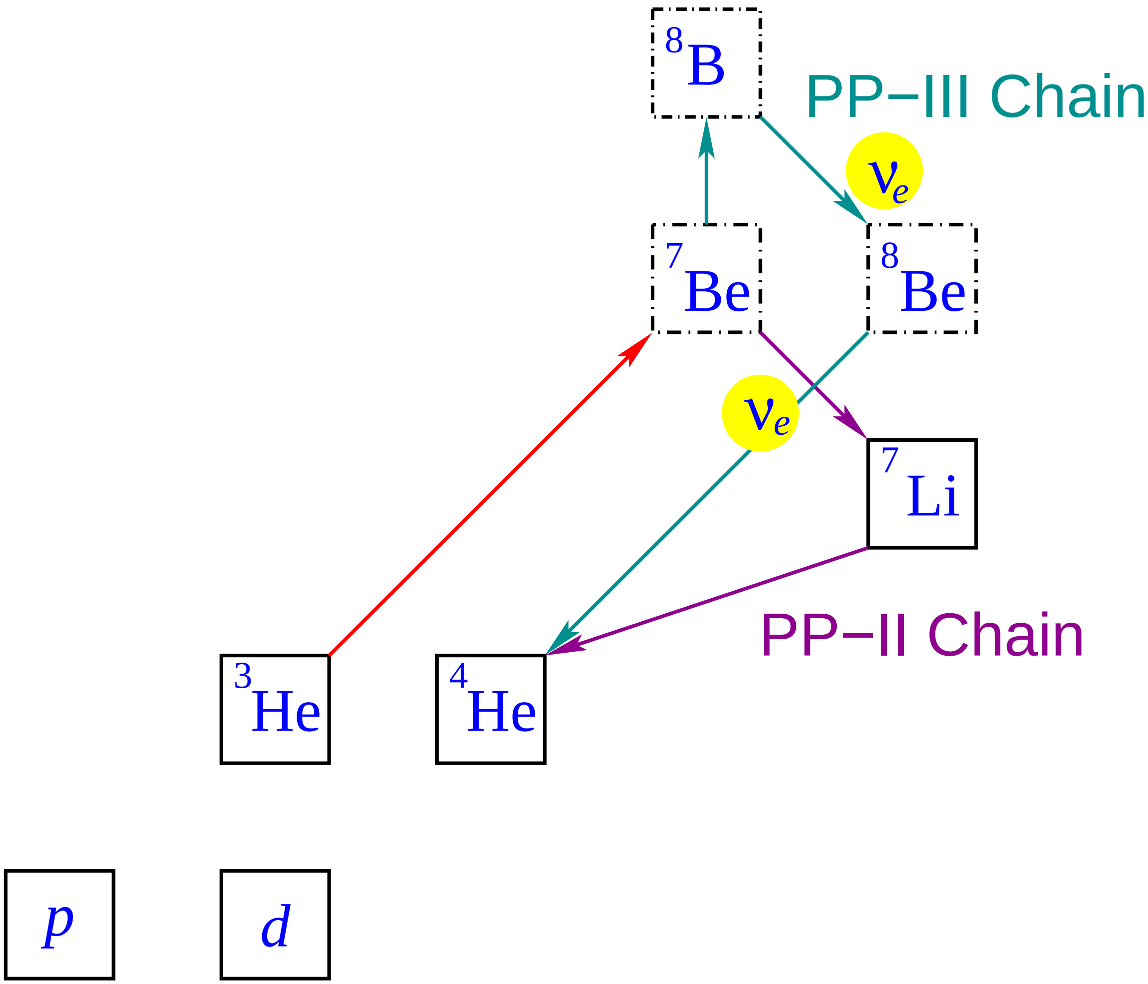
hep weak reaction: $^3\text{He}\, p \rightarrow {}^4\text{He}\ e^+\ \nu_e$

PP-II and PP-III chains: different ^{3}He *fate*

^{7}Be branching is key:

e capture rate $\sim 1000\times$ p capture rate

- ^{7}Be: 15% of ν production
- ^{8}B: $\sim 0.02\%$ of ν production



8B
PP–III Chain
νe
7Be
8Be
νe
7Li
PP–II Chain
3He
4He
p
d

The CNO Cycle

consider reactions on *pre-existing* C, N, O

$$\begin{array}{ccccc} ^{12}\mathrm{C} & \xrightarrow{(p,\gamma)} & ^{13}\mathrm{N} & \xrightarrow{e^+\nu_e} & ^{13}\mathrm{C} \\ (p,\alpha)\uparrow & & & & \downarrow(p,\gamma) \\ ^{15}\mathrm{N} & \xleftarrow{e^+\nu_e} & ^{15}\mathrm{O} & \xleftarrow{(p,\gamma)} & ^{14}\mathrm{N} \end{array}$$

follow one trip around cycle:

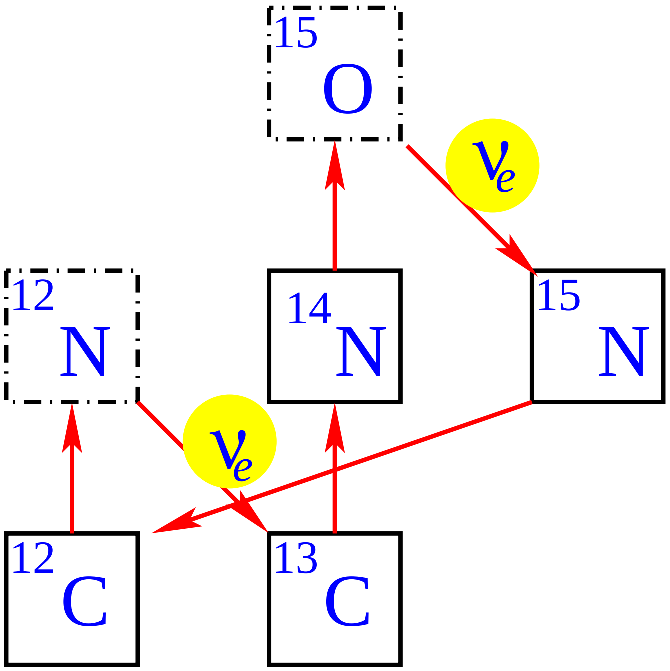
Q: net input of particles? net output? net change of CNO?

CNO act as $4p \rightarrow {}^4$He *catalyst*!

Coulomb barriers high ($Z = 6, 7, 8$): *need high* T_c to go

$\Rightarrow$ CNO cycle minor in Sun (CNO $\rightarrow$1.6% $L_\odot$)

but main H-burner for $M \gtrsim 1.5 M_\odot$



CNO Cycle

Standard Solar Neutrino Production

Rxn	$E_{\nu,\mathrm{max}} = Q$	$\langle E_\nu \rangle$	Total SSM Flux Φ_ν (10^{10} ν cm^{-2} s^{-1})
$pp \to de\nu$	0.420 MeV	0.265 MeV	6.0
^{7}Be $e \to {}^7$Li ν	lines: ^{7}Li$^{\mathrm{gs}}$ = 0.861 MeV; ^{7}Li* = 0.383 MeV		0.47
^{8}B$\to {}^8$Be e ν	17.98 MeV	9.63 MeV	5.8×10^{-4}

Q: Why are the ^{7}Be *neutrinos monoenergetic?*

`www: Bahcall neutrino spectrum`

pp neutrinos — largest flux, but low energies

^{7}Be neutrinos — monoenergetic, strong $\sim T_c^8$ dependence

^{8}B neutrinos — continuum, ultrastrong $\sim T_c^{20}$ dep

What should this mean for production vs radius?

`www: Bahcall fig of production vs` R

Standard Solar Model Predictions

What are key SSM ν ingredients, predictions?

- which (anti)neutrinos produced?

- time variations: at source? in detectors?

- $L_\odot$ fixes what?

- what connection between $\Phi_\nu(^7\text{Be})$ and$\Phi_\nu(^8\text{B})$?

- ν spectra: determined by what?

SSM Predictions

SSM Key Predictions:

- at source: steady ν_e flux from Sun
- elliptical Earth orbit $\longrightarrow$ annual flux variation
  $\Delta\Phi_\nu/\Phi_\nu \simeq 2\delta r_\oplus/r_\oplus \sim 4e_\oplus \sim 7\%$
- pp flux $\sim$ fixed by $L_\odot$
- ^{7}Be, ^{8}B flux T-dep, but $\Phi_\nu(^7\text{Be}) > \Phi_\nu(^8\text{B})$
- neutrino spectra fixed by β decay
  indep of solar model (since $T_{c,\odot} \sim 1\text{keV} \ll Q_{\text{nuke}}$)

Q: how to test these predictions?

Solar Neutrino Experiments

Original motivation (Davis, Bahcall):

- confirm nuke energy generation
- measure $T_{\odot,c}$

Facts of life:

1. ν →small σ: mean free path $\ell_\nu \gg R_\odot$ so detector size $\ll \ell_\nu$: detector is optically thin
2. $E_\nu \lesssim few$ MeV → large natural background
   e.g., radioactivity, cosmic ray muons

Q: what is needed for neutrino observatory?

Neutrino Observatories: Design Requirements

1. **Large** detector. optically thin $\rightarrow$ volume matters, not area
ν-nucleus absorption $\sigma_{\nu A} \sim 10^{-44}$ cm^2
$\Rightarrow$ event rate per target $\Gamma_\nu(A) = \Phi_\nu \sigma_{\nu A} \sim 10^{-36}$ s^{-1}
Solar Neutrino Unit: 1 SNU $= 10^{-36}$ event s^{-1} target^{-1}
Want net rate $R = N_{\rm targ}\Gamma \gtrsim 1$ day^{-1} $\sim 10^{-5}$ s^{-1}
$\Rightarrow$ Need $N_{\rm targ} = R/\Gamma \sim 10^{31}$

$$M_{\rm targ} = A m_u N_{\rm targ} \sim 10^9 \left(\frac{A}{50}\right) \text{ g } \sim \left(\frac{A}{50}\right) \text{ kiloton}$$

big!

2. Go **underground**.
"Clean" lab, low-background material

Radiochemical Experiments: Chlorine

Homestake Mine Ray Davis Jr. et al 1967-1995
site: gold mine(!) in Lead, SD, USA `www: Homestake+Davis`
target: chlorine (cleaning fluid!, 0.61 kton)
process: $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e$ (endothermic)
threshold: ν must supply $|Q| = 0.814$ MeV
$\Rightarrow$ only measure ^{7}Be, ^{8}B νs
procedure: cycle fluid $\rightarrow$ filter, collect ^{37}Ar atoms: $\sim few/$week!

Measure:

$$\Gamma_{\text{obs}} = 2.56 \pm 0.16 \pm 0.16 \text{ SNU} \quad (13)$$

Compare to SSM prediction:

$$\frac{\Gamma_{\text{obs}}}{\Gamma_{\text{SSM}}} = 0.33 \pm 0.03 \pm 0.05 \ll 1! \quad (14)$$

Only see $\sim 1/3$ of predicted flux!
$\Rightarrow$original *Solar neutrino problem*

Radiochemical Experiments: Gallium

- GALLEX: Gran Sasso, Italy (1990's)
- SAGE: Baksan, Russia (1990's)

target: (liquid) gallium metal
process: ${}^{71}\text{Ga} + \nu \rightarrow {}^{71}\text{Ge} + e$
threshold $|Q| = 0.233$ MeV $\rightarrow$ some pp νs contribute!
calibrated with mega-Curie source!

Measure:

$$\Gamma_{\text{SAGE}} = 75 \pm 7 \pm 3 \text{ SNU} \quad (15)$$
$$\Gamma_{\text{GALLEX}} = 78 \pm 6 \pm 5 \text{ SNU} \quad (16)$$

Compare:

$$\frac{\Gamma_{\text{obs}}}{\Gamma_{\text{SSM}}} = 0.59 \pm 0.06 \pm 0.04 \quad (17)$$

Significant deficit! *Solar neutrino problem #2*
Note: no info on neutrino energy spectrum

Water Čerenkov Experiments

target: water

process: electron scattering $\nu e \to \nu e$

for $E_\nu \gtrsim 0.5$ MeV, recoil electron $v_e \sim c$

but in water, refractive index $n = 1.34 \Rightarrow v_e > c/n$

emit "sonic boom" photons: Čerenkov radiation

"optical shock wave," cone of light

cone opening angle depends on $v_e \to E_e$

`www: Super-K events`

Q: advantages of water Čerenkov vs radiochemical?

In praise of Water Čerenkov

- detect neutrinos in "real time"
- $E_e \rightarrow \nu$ energy $\rightarrow$ spectrum
- cone orientation $\rightarrow \nu$ direction info!

Super-Kamiokande. Kamioka Mine, Japan: 1996-

`www: Super-K image`

direction: νs point back to Sun (check)

`www: Neutrino image of the Sun`

$e\nu$ elastic scattering in pure water

Energy threshold: 5 MeV $\Rightarrow$ see only ^{8}B νs

spectrum: shape matches SSM

...but $\Phi(^8\mathrm{B})_{\mathrm{SK}}/\Phi(^8\mathrm{B})_{\mathrm{SSM}} \sim 50\%$!

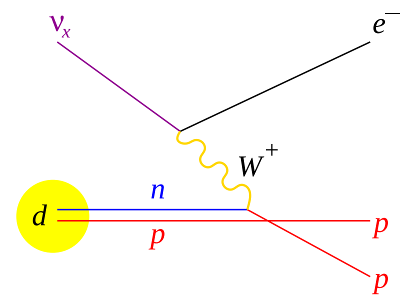
Solar neutrino problem #3

Sudbury Neutrino Observatory (SNO)

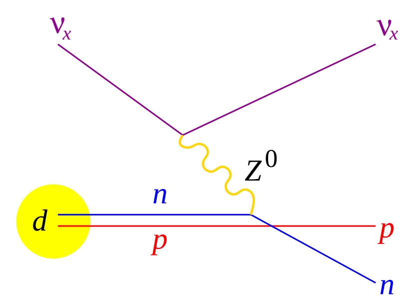
SNO **Art McDonald et al**: 1999-present
site: mine in Sudbury, Ontario, Canada
ultrapure heavy water: D_2O

Reactions:

$\nu_e + d \rightarrow e^- + p + p$ **Charged current**: ν_e *only*
Threshold: 1.4 MeV $\rightarrow$ ^{8}B only



$\nu_x + d \rightarrow \nu'_x + p + n$ ν' flavor $= \nu$ flavor
Neutral current: *all flavors*
Threshold: 2.2 MeV $\rightarrow$ ^{8}B only



also: Salt phase – dissolve NaCl in SNO tank
big σ for $^{35}\mathrm{Cl}(n,\gamma)^{36}\mathrm{Cl}$ $\rightarrow$ improved NC

SNO Results

Charged-current flux: ν_e only

$$\Phi_{\text{CC}}^{\text{SNO}} = \left[1.59^{+0.08}_{-0.07}(\text{stat})^{+0.06}_{-0.08}(\text{sys})\right] \times 10^6\ \nu\ \text{cm}^{-2}\ \text{s}^{-1} \quad (18)$$

Neutral-current flux: all ν species

$$\Phi_{\text{NC}}^{\text{SNO}} = [5.21 \pm 0.27(\text{stat}) \pm 0.38(\text{sys})] \times 10^6\ \nu\ \text{cm}^{-2}\ \text{s}^{-1} \quad (19)$$

Thus we have

$$\frac{\Phi_{\text{CC}}^{\text{SNO}}}{\Phi_{\text{NC}}^{\text{SNO}}} = \frac{\nu_e \text{ flux}}{\text{all } \nu \text{ flux}} = 0.306 \pm 0.026(\text{stat}) \pm 0.024(\text{sys}) \quad (20)$$

Which means...

Implications: New Neutrino Physics!

The Sun makes only ν_e

Q: why? e.g., why not ν_μ*?*

$\longrightarrow$ if no new ν physics, only ν_e at Earth

$\longrightarrow$ predict $\Phi_{\text{CC}}(\nu_e) = \Phi_{\text{NC}}(\nu_x)$

SNO measures $\Phi_{\text{CC}}(\nu_e) > \Phi_{\text{NC}}(\nu_x)$!

with *very* high confidence!

non-ν_e flux arriving in detector!

A big deal:

- demands new neutrino physics
- indep. of detailed solar model