Astro 210

Lecture 28

April 2, 2018

Announcements:

- **HW8 due online in PDF, Friday 5:00 pm**

- **Solar Observing next week** April 2–5
  Mon, Tue, Wed, Thurs. 11:00 am to 3:00 pm
  Campus Observatory
  allow 20-30 minutes. take **selfie** with telescope

- Night Observing: no clear last night so
  substitute exercise posted on Moodle, due Friday 5:00 pm

Next semester (and beyond): Flex Your Astro Muscles

ASTR 210 prepares you for all upper level Astronomy courses!

ASTR 330: Extraterrestrial Life

ASTR 350: The Big Bang, Black Holes, and the End of the Universe

ASTR 404: Stellar Astrophysics

ASTR 406: Galaxies and the Universe

How the Sun Shines: The Story Thus Far

the Sun is a $L_\odot = 3.85 \times 10^{26}$ Watt lightbulb

Q: how do we know this?

Q: how is the Sun unlike a cup of coffee?

Q: how do we use this to learn about the source of solar energy? what other information is needed?

Q: what candidates are ruled out? what's left?

Nuclear Fusion in the Sun

The Sun is a nuclear reactor
i.e., nuclear reactions occur inside the Sun
change reactant nuclei into different product nuclei
$\longrightarrow$ elements transformed into other elements
$\longrightarrow$ cosmic alchemy!

Mechanism: high-energy/high-speed collisions between nuclei

$$\text{nucleus}_1 + \text{nucleus}_2 \rightarrow \text{nucleus}_3 + \text{energy} \qquad (1)$$

- nuke energy release $\longrightarrow$ stellar power source
- lighter nuclei combine $\longrightarrow$ heavier: **fusion**

Q: why are high energies, speeds needed?

Q: how do the nuclei get these energies & speeds?

In fact: many reactions can and do occur
but a small handful are the most important

Key reactions occur in "chains"

- first step involves pre-existing solar ingredients (*Q: namely?*)
- input for each new step is output from previous step

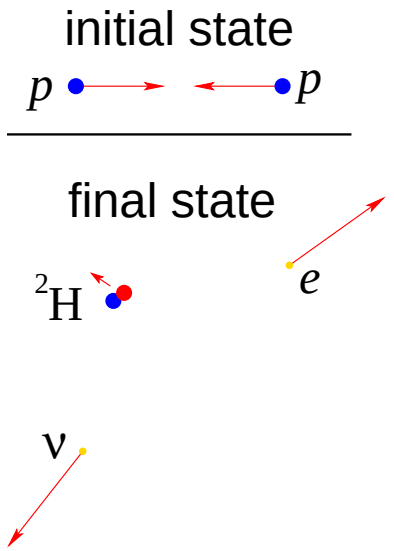
Dominant reactions: "pp" Chain

$$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu$$
$$e^- + e^+ \rightarrow \gamma + \gamma$$
$${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$$
$${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$$

Net effect:

$$4p + 2e^- \rightarrow \boxed{2n2p} = {}^4\mathrm{He} + \text{energy} + \ldots$$

each "p–p reaction" creates:



- ^{2}H=$\boxed{np}$ **"deuterium"**

"heavy hydrogen"

- e^+ **"positron"**

antimatter: anti-electron!

then $e^- + e^+ \rightarrow \gamma + \gamma$ energy!

annihilation

- ν **"neutrino"**

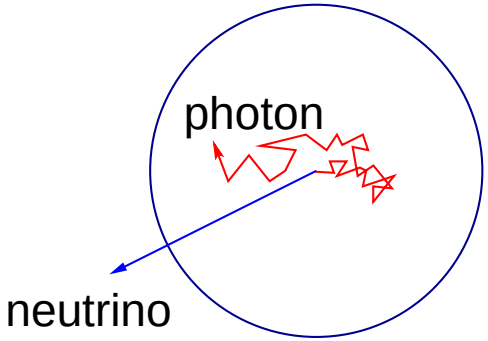
very low-mass ($m_\nu \ll m_e$) particle

only created in nuclear reactions ("weak" decays)

very weakly interacting particle

once born, go thru Sun, Earth, your body

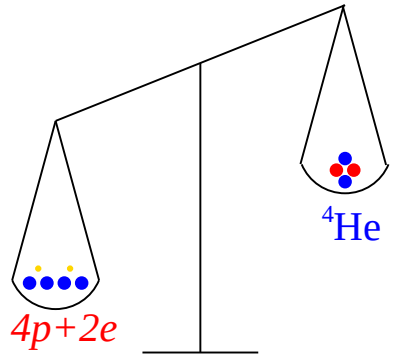
but almost never interact



Fusion Energy

Where does the energy come from? **mass!**
Einstein: mass m at rest contains energy $\varepsilon = mc^2$

Observed fact:
$m(^4\mathrm{He}_{\mathrm{atom}}) < m(4p + 2e)$!
whole $<$ parts!



Do the math:

$$\begin{array}{rrl} & m(4p+2e) & = 6.694 \times 10^{-27}\ \mathrm{kg} \\ - & m(^4\mathrm{He}) & = 6.644 \times 10^{-27}\ \mathrm{kg} \\ \hline = & \Delta m & = 5 \times 10^{-29}\ \mathrm{kg} \end{array}$$

fusion $\rightarrow$ mass reduction!
$\rightarrow$ rest mass decrease $\rightarrow$ energy release!

Where Does the Energy Go?

energy "reservoir" is from changes in mass
but where does it go?

recall pp chain:

$$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu \quad (2)$$

$$e^+ + e^- \rightarrow \gamma\gamma \quad (3)$$

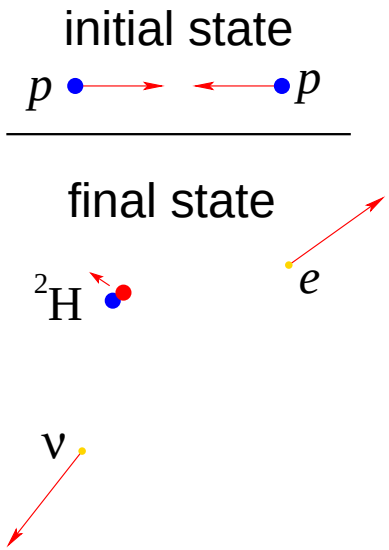
$${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma \quad (4)$$

$${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + p + p \quad (5)$$

in each reaction mass energy is released: $m_{\mathrm{final}} < m_{\mathrm{initial}}$
for each reaction: *Q: where does that energy go?*

∞ *Q: how does this ultimately lead to Sunlight?*

$$
\begin{aligned}
p + p &\rightarrow {}^2\mathrm{H} + e^+ + \nu \\
e^+ + e^- &\rightarrow \gamma\gamma \\
{}^2\mathrm{H} + p &\rightarrow {}^3\mathrm{He} + \gamma \\
{}^3\mathrm{He} + {}^3\mathrm{He} &\rightarrow {}^4\mathrm{He} + p + p
\end{aligned}
$$



★ for final state **nuclei**:
energy goes to *motion*: $v_{\text{nucleus}} \gg v_T$
$\Rightarrow$ large *kinetic energy*

then gradually slow, mostly via Coulomb scattering
$\rightarrow$ *heats* the plasma, also generates many photons

★ for final state **photons**:
carry momentum and very high energy: *gamma rays*!
then scatter violently, also *heat* the plasma

in each reaction mass $\rightarrow$ energy (kinetic, photons)
total for each $4p \rightarrow {}^4\text{He}$ fusion:
$Q = \Delta\varepsilon = \Delta mc^2 = 4.5 \times 10^{-12}$ Joules

Estimate Solar fusion energy supply:

$$E_{\text{fuse}} = \frac{\#\text{ nuclei in Sun}}{4\text{nuclei/fusion}} \times Q \sim 1.3 \times 10^{45} \text{ Joules} \qquad (6)$$

if *all* Sun's hydrogen is fuel, can burn for
$\tau_{\text{fuse}} = E_{\text{fuse}}/L = 3 \times 10^{18}$ sec $=$ 100 billion years!

iClicker Poll: Solar Nuclear Lifetime

if all Sun's hydrogen is fuel, nuclear fusion can burn for $\tau_{\text{fuse}} = E_{\text{fuse}}/L = 3 \times 10^{18}$ sec = 100 billion years!

Vote your conscience!

This is a crude estimate of the solar fusion lifespan–but how?

A this is an *over*estimate of the lifespan

B this is an *under*estimate of the lifespan

Solar Life Expectancy

We have overestimated fuel available for fusion:
assumed Sun can burn all if its hydrogen

$\rightarrow$ only fuse at high T, ρ
$\rightarrow$ core of Sun

true lifetime: $\tau \sim 1 \times 10^{10}$ yr $=$ 10 billion yrs
$\rightarrow$ Sun is middle aged
will last another $\sim$ 5 billion yrs

Q: how test that sun is nuke powered?

How Do We Know?

By the 1930's we knew that the Sun is nuclear powered

`www: Nobel Prize: Hans Bethe`

> The Sun is a mass of incandescent gas
> a gigantic nuclear furnace
> Where hydrogen is burned into helium,
> at temperatures of millions of degrees
> – Lou Singer and Hy Zaret, 1959; cover: They Might Be Giants 1993

Q: how could we be so sure?

Can we get even more direct confirmation?

Q: is another way to confirms the Sun is a nuclear reactor? A "smoking gun" signature?

The Evidence: Solar Neutrinos

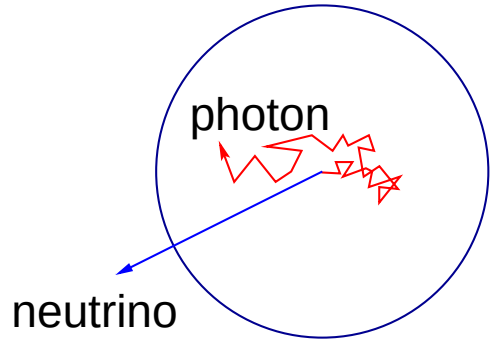
If the Sun takes $4p \rightarrow {}^4\text{He} =$ 2p2n
then it *must* convert $2p \rightarrow 2n$
$\rightarrow$ *must* produce neutrinos!
in fact: most made via $pp \rightarrow de^+\nu$

The Sun radiates neutrinos as well as photons!

...we are bathed in solar "neutrinoshine"

Moreover:

- since ν are weakly interacting
  they come directly from the solar core
  $\rightarrow$ messengers from the center of the Sun!
- but luckily, *weakly* interacting $\neq$ *non*-interacting
  $\Rightarrow$ solar neutrinos are potentially observable!
- clever experiments can try to "catch" them



In Search of Solar Neutrinos

experiments have been built to "see" solar neutrinos
by observing rare cases of ν interactions with atoms
all use huge underground detectors
Q: why huge? why underground?

Two types:
1. "radiochemical" – vats of fluid
see element change due to ν
ex: chlorine fluid $\nu + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$
collect Ar atoms (radioactive!)
`www: Davis chlorine experiment`

2. "scattering" – vats of ultra-pure water
see light pulses from
high-energy e^- scattered by νs
`www: SNO, Borexino`
`www: Super-K Sun image`

Solar Neutrino Experiments: Results

- ⋆ All experiments detect solar νs!
- ⋆ Scattering experiments show neutrinos come from the Sun!
- ⋆ Amount (flux) is just as predicted!

Q: what fundamental fact(s) is/are confirmed?

Solar Neutrino Results

I. proof that Sun powered by nuke fusion

II. νs give direct view into solar core

III. these underground vats are ν telescopes!

A new window on the Universe:

Nobel Prize 2002!

Using the Sun to probe neutrino transformation and mass:

Nobel Prize 2015!

Director's Cut Extras

Solar Neutrino Experiments: A Deeper View

1960s: original chlorine radiochemical experiment (Ray Davis):
- sensitive only to a small component of very high-energy νs
- signal detected, but flux $\Phi_\nu^{\rm obs} \approx \Phi_\nu^{\rm predicted}/3$

  birth of **"solar neutrino problem"** – where did they go?

1990's: solar neutrino deficit confirmed

possible explanations:
- theory of solar nuclear reactions is wrong/incomplete
- neutrino theory incomplete

it was already known that: *neutrinos have 3 varieties ("flavors")*
ν_e, ν_μ, ν_τ: named for partner they appear with
solar neutrinos produced as ν_e: should remain so
$\rightarrow$ unless neutrinos can transform into different flavors!

Q: how to test for the latter possibility?

The Sun Reveals New Neutrino Physics

if neutrino flavor transformations exist

- some particles born in Sun as ν_e
- can arrive at Earth as ν_μ or ν_τ
- but radiochemical experiments only "see" ν_e

To test:
build detectors sensitive to *all flavors*
this was done: Sudbury Neutrino Observatory (SNO)

early 2000s: SNO results weigh in

- ν_μ and ν_τ *detected* from Sun!
- *total flux* for *all* ν *agrees* with Solar model!
- **confirms new neutrino physics**
- also *transformations require neutrinos have mass!*
  non-obvious property of the quantum flavor transformations