

Astro 210
Lecture 31
April 11, 2011

Announcements

- HW 9 available, due at start of class Friday
- **Solar Observing**: this week
today(?!) and tomorrow 10:30am to 3:30 pm
allow about 30min
info, report form online

Last time: energy generation in the Sun and stars

- the Sun is not a cup of coffee
Q: how so? what does this teach us?
- ↳ ● choosing among possible solar energy sources
Q: how to do this without looking inside the Sun?

Last time: to maintain huge solar luminosity L_{\odot}
over long solar lifetime $\tau_{\odot} > 5$ billion years
requires an *enormous* energy source

The **only** viable candidate:

Nuclear Energy

The Sun is a vast nuclear reactor
in hot core, hydrogen converted to helium
by nuclear reactions

Note: needed *quantitative* estimates of burn times
to answer *qualitative* question “What powers the Sun?”

↷ → the power of (and necessity of) number crunching!

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

→ elements transformed into other elements

→ cosmic alchemy!

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



- nuclear energy release → stellar power source
- lighter nuclei combine → heavier: **fusion**

Q: why are high energies, speeds needed?

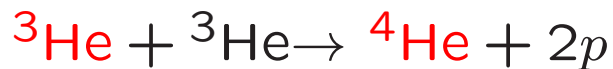
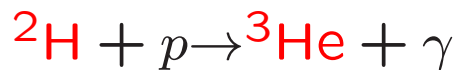
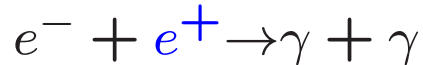
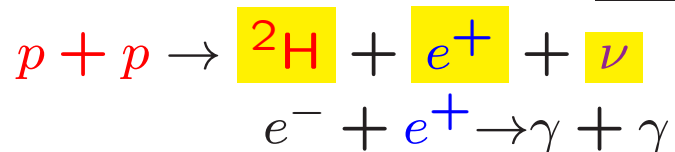
^ω *Q: how do the nuclei get these energies & speeds?*

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

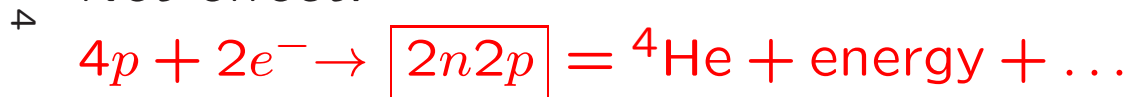
Key reactions occur in “chains”

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

Dominant reactions: “pp” Chain



Net effect:



each “p–p reaction” creates:

- ${}^2\text{H} = \boxed{np}$ “**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

ν escape diagram

Fusion Energy

Where does the energy come from? **mass!**

www: Big Al

www: scale cartoon

Einstein: $\boxed{\varepsilon = mc^2}$

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

Do the math:

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

fusion \rightarrow mass reduction!

\circ \rightarrow rest mass decrease \rightarrow energy release!

in each reaction mass \rightarrow energy (kinetic, photons)

$$Q = \Delta\varepsilon = \Delta mc^2 = 4.5 \times 10^{-12} \text{ Joules}$$

for each $4p \rightarrow {}^4\text{He}$ fusion

Estimate fusion energy supply:

$$E_{\text{fuse}} = \frac{\# \text{ nuclei in Sun}}{4 \text{ nuclei/fusion}} \times Q \sim 1.3 \times 10^{45} \text{ Joules} \quad (2)$$

if all Sun's hydrogen is fuel, can burn for

$$\tau_{\text{fuse}} = E_{\text{fuse}}/L = 3 \times 10^{18} \text{ sec} = 100 \text{ billion years!}$$

Vote your conscience!

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

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- A** this is an *over*estimate of the lifespan
 - B** this is an *under*estimate of the lifespan

Solar Life Expectancy

Overestimated fuel available for fusion:

→ only fuse at high T , ρ

→ core of Sun

true lifetime: $\tau \sim 1 \times 10^{10}$ yr = 10 billion yrs

→ Sun is middle aged

will last another ~ 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?

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*Q: is another way to confirm the Sun is a nuclear reactor? A
“smoking gun” signature?*

The Evidence: Solar Neutrinos

If the Sun takes $4p \rightarrow {}^4\text{He} = \boxed{2p2n}$

then it *must* convert $2p \rightarrow 2n$

→ *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
→ messengers from the center of the Sun!
- but luckily, *weakly* interacting \neq *non*-interacting
⇒ 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 $\nu + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$

collect Ar atoms (radioactive!)

www: Davis chlorine experiment

2. “scattering” – vats of ultrapure water

see light pulses from

high-energy e^- scattered by ν s

www: SNO ball

www: Super-K Sun image

Upshot:

- ★ All experiments detect solar ν s!
- ★ 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. ν s give view into solar core
- III. these are ν telescopes!

A new window on the Universe:

Nobel Prize 2002!

Poetry reading: John Updike, "Cosmic Gall"

The Stars as Suns

We've proved that that Sun is nuclear reactor
but (we'll see that) the Sun is a typical star
⇒ **all** stars run by thermonuclear fusion

The Night sky, the Universe lit up ultimately by nuclear power