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?"
$\rightarrow$ 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
$\rightarrow$ elements transformed into other elements
$\rightarrow$ 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 $\rightarrow$ stellar power source
- lighter nuclei combine $\rightarrow$ 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

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

Do the math:

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

fusion $\rightarrow$ mass reduction!

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

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

Estimate fusion energy supply:

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

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!

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

Overestimated fuel available for fusion:

$\rightarrow$ 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 ultrapure water
see light pulses from
high-energy e^- scattered by νs
`www: SNO ball`
`www: Super-K Sun image`

Upshot:

⋆ All experiments detect solar νs!

⋆ 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 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
$\Rightarrow$ **all** stars run by thermonuclear fusion

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