

Astro 210
Lecture 29
November 3, 2010

Announcements

- HW 8 available, due in class Friday
- **Solar Observing** today and tomorrow
 - ▷ schedule, report form online

Last time: The Sun—overview

Q: why doesn't the gas float away or collapse on itself?

Q: why does the Sun appear to have a sharp edge?

iClicker Poll: Solar Observing

Monday was a bust for solar observing
but yesterday was ideal; staff included your TA Rukmani

Vote your conscience!

So—did you go to solar observing yet?

A I did! And now I have that warm feeling of astro-goodness

B No...but I will go if it clears up today, I promise

C No...I will wait and count on good weather tomorrow
even though the forecast is “mostly cloudy”

The Facts of Life for the Sun

Fact: the Sun constantly radiates energy
and at a huge rate: $dE/dt = L_{\odot} = 4 \times 10^{26}$ Watts!

Fact: the Sun has a finite ($\neq \infty$) mass
and thus a finite fuel supply (whatever that fuel may be)

Fact: Energy is conserved
no free lunch!

ω *Q: therefore?*

How Does the Sun Shine?

The Sun radiates: shines from thermal radiation

- recall: surface flux $F_{\text{surf},\odot} = \sigma T_{\text{surf},\odot}^4 = 60 \text{ MWatt/m}^2$

- total power output = rate of energy emission = **luminosity**

$$L_{\odot} = 4\pi R_{1 \text{ AU}}^2 F_{\odot}(1 \text{ AU}) = 3.85 \times 10^{26} \text{ Watts} \quad (1)$$

→ the Sun is a 4×10^{26} -Watt lightbulb

- But also: the Sun has **constant** temperature, luminosity (over human timescales \gtrsim centuries)

‡

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

The Sun is Not a Cup of Coffee

Coffee Thermodynamics

Demo: cup of coffee: cools

thermodynamic lesson:

- left alone, hot coffee cools (surprise!)
 - energy radiated, not replaced
- to keep your double-shot soy latte from cooling need Mr. Coffee machine—energy (heat) source

Contrast with the Sun

- Sun doesn't cool
 - but energy *is* radiated, at enormous rate
- ergo: something must replace the lost energy
- ▷ What is solar heat source?
 - a mystery in Astronomy until the 20th century

⁵ Q: *possible energy/heat sources which Sun taps?*

Q: *how to test/compare which are important?*

Energy Conservation and the Sun

recall: power is energy flow rate $L = dE/dt$

if lose energy at constant rate,

$$E_{\text{lost}} = L\tau$$

with $\tau =$ “lifetime” of Sun

Energy conservation:

energy supply = lifelong energy loss

The game:

- compute/estimate supply (“battery”) for each candidate solar energy “reservoir”
- assume Sun has some way to “tap” each source
 - convert energy to heat (thermal atom motion)
 - keep T_{surf} hot, replenish radiated energy
- then see how long each source could light up the Sun
- important source(s) \equiv long-lived:

$$\tau_{\text{source}} = E_{\text{res}}/L_{\odot} > \tau_{\odot} = 5 \text{ billion yr}$$

Possible Solar Energy Sources

- Gravity

if Sun contracts → release grav. P.E.

estimate gravitational energy “reservoir”

approximate Sun as uniform sphere:

$$PE_{\text{grav}} = -3/5 GM_{\odot}^2/R_{\odot} = 2 \times 10^{41} \text{ Joules}$$

$$\rightarrow E_{\text{contract}} = -PE$$

if grav energy fuels the Sun, lasts for

$$\tau_{\text{grav}} = E_{\text{contract}}/L = 5 \times 10^{14} \text{ sec} = 17 \text{ Myr}$$

but: Sun, SS age is 4.6 billion yrs

↘ → not enough!

- **Chemical Energy**

if **entire** Sun interior made of **TNT** (!)

burning → release chemical energy → heat

but: $\tau_{\text{chem}} = 20,000$ years! yikes!

- **Rotational Energy**

Sun spins, has rotational energy

(rotational equivalent of kinetic energy)

$$E_{\text{rot}} = \frac{1}{2}I\omega^2 \approx \frac{1}{5}M_{\odot}(\omega_{\odot}R_{\odot})^2 \quad (2)$$

if made Sun spin down (somehow)

convert spin energy to heat

but: $\tau_{\text{rot}} \approx 400$ years!!

∞

Lesson: Sun requires **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?

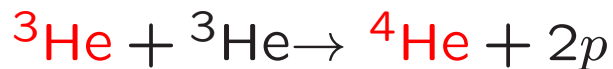
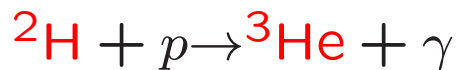
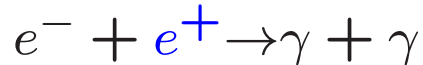
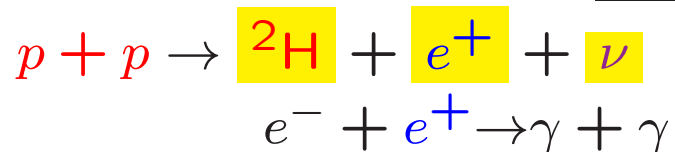
Q: how do the nuclei have these energies & speeds?

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

Key reactions occur in “chains”

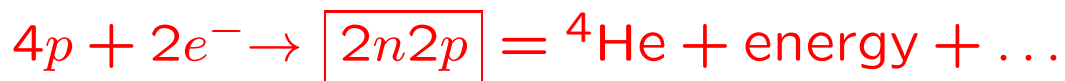
- first step involves pre-existing solar ingredients (*Q: namely?*)
- input for each new step is output from previous step

Dominant reactions: “pp” Chain



Net effect:

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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