Astro 210

Lecture 27

March 27, 2018

Announcements

- good news: no new homework this week
- bad news: **Hour Exam 2** this Friday
  March 30, in class, info posted on Moodle

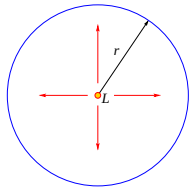
- **Night Observing one** *last chance after break*
  first clear night will be final opportunity
  due date extended to March 30

Solar Energy Output: Luminosity

solar power output = luminosity:
measured from apparent brightness = flux

$$F = \frac{L}{4\pi r^2} \quad (1)$$

$$= 1370 \text{ W/m}^2 \text{ at } r = 1 \text{ AU} \quad (2)$$



$\Rightarrow L_\odot = 4\pi r^2 F = 3.85 \times 10^{26}$ W

at sun surface
$F_{\text{surf}} = L_\odot / 4\pi R_\odot^2 = 6.3 \times 10^7$ W/m^2

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!

Q: therefore?

How Does the Sun Shine?

The Sun radiates: shines from thermal radiation

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

- total power output = rate of energy emission = luminosity

$$L_\odot = 4\pi R_{1\ \rm AU}^2 F_\odot(1\ \rm AU) = 3.85 \times 10^{26}\ \rm Watts \qquad (3)$$

$\rightarrow$ 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

themodynamic lesson:

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

Contrast with the Sun

- surface $T_\odot$ constant over human lifetimes
  but energy *is* radiated, at enormous rate
- ergo: something must replace the lost energy

▷ What is solar heat source?
  $\rightarrow$ a mystery in Astronomy until the 20th century

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 $L = dE/dt$

assume:

- Sun always emits energy at today's rate (L constant)
- radiation lasts for time $\tau_\odot$ = "lifetime" of Sun
  Q: what is a minimum value for $\tau_\odot$?

energy output over Sun's liftime:

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

Energy conservation:

solar energy supply = lifelong energy output

Sorting Solar Energy Sources

The game:

- guess energy sources in the Sun (and stars!)
- compute/estimate supply ("battery") for each candidate solar energy "reservoir"
- assume Sun has some way to "tap" each source
  $\rightarrow$ convert energy to heat (thermal atom motion)
  $\rightarrow$ keep $T_{\rm surf}$ hot, replenish radiated energy
- then see how long each source could light up the Sun

Q: Energy sources?

Q: how long do they need to last?

Solar Batteries: Required Lifetime

we found from radioactive dating of meteorites:
the solar system is very old: age $t_{\rm SS} = 4.55 \times 10^9\ yr$
Sun's present age essentially the same:
$t_{\odot,\rm now} = t_{\rm SS} = 4.55$ billion years

total energy output over this time is huuuge!
$\longrightarrow$ required huge energy reservoir

in other words: important solar energy source(s) $\equiv$ long-lived:
$\tau_{\rm source} = E_{\rm res}/L_\odot = \tau_\odot > t_{\odot,\rm now} \approx 5$ billion yr

∞ *Q: possible sources–not just right answer, but any energy reservoirs?*

iClicker Poll: Rank the Energy Sources

Vote your conscience!

Of the proposed solar energy reservoirs

Which one is the largest, i.e., can power the Sun longest?

Which one is the smallest?

Possible Solar Energy Sources

- Gravity

if Sun contracts $\rightarrow$ release grav. P.E.

estimate gravitational energy "reservoir"
approximate Sun as uniform sphere:
$PE_{\text{grav}} = -3/5\ GM_{\odot}^2/R_{\odot} = 2 \times 10^{41}$ Joules
$\rightarrow E_{\text{contract}} = -PE$

if grav energy fuels the Sun, lasts for
$\tau_{\text{grav}} = E_{\text{contract}}/L = 5 \times 10^{14}$ sec = 17 Myr
but: Sun, SS age is 4.6 billion yrs
$\rightarrow$ not enough!

• Chemical Energy: binding energy of atom/molecules

if entire Sun interior made of TNT (!)

burning $\rightarrow$ break bonds $\rightarrow$ release chemical energy $\rightarrow$ heat

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

• Rotational Energy

Sun spins, has rotational energy

(rotational equivalent of kinetic energy)

$$E_{\rm rot} = \frac{1}{2} I \omega^2 \approx \frac{1}{5} M_\odot (\omega_\odot R_\odot)^2 \qquad (4)$$

if made Sun spin down (somehow)

convert spin energy to heat

but: $\tau_{\rm rot} \approx 400$ 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?"
$\rightarrow$ 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
$\longrightarrow$ elements transformed into other elements
$\longrightarrow$ cosmic alchemy!

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

$$\text{nucleus}_1 + \text{nucleus}_2 \rightarrow \text{nucleus}_3 + \text{energy} \qquad (5)$$

- 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"**

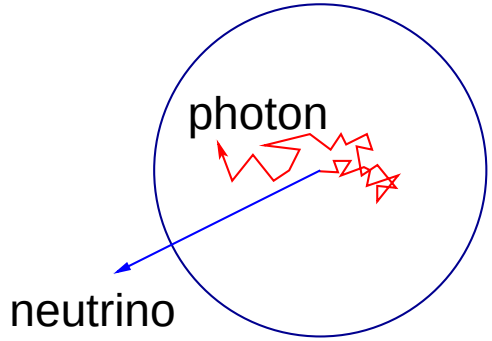
very low-mass ($m_\nu \ll m_e$) particle

only created in nuclear reactions ("weak" decays)

very weakly interacting particle

once born, go thru Sun, Earth, your body

but almost never interact



Hour Exam 2 Review