Astro 350
Lecture 15
February 21, 2022

Announcements:

- Good news: now homework or discussion next week
- Bad news: **Midterm exam in class next Friday**
- Exam info on Canvas:
  Update–one page of handwritten notes allowed
  sample questions and homework solutions posted today
  Wed class will include time for your questions

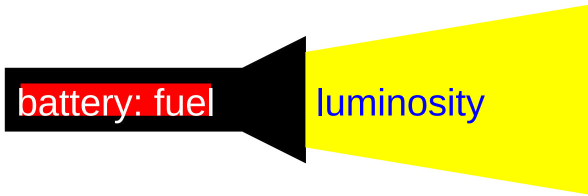
last time: the Sun is not a cup of coffee!
Of course, but here – difference is thermodynamic
i.e., regarding temperature, and heat flow
Q: what's the difference? what does this tell us?

Solar Power Source

To stay hot, Sun requires *heat source = energy source*

To maintain luminosity (power output) $L =$ (energy emitted)/time
for a *lifespan* τ
a star emits energy $E_{\rm emit} = L\tau$

but energy conserved: fuel supply must be $E_{\rm fuel} = E_{\rm emit} = L\tau$
but since $E_{\rm fuel}$ finite, lifespan $\tau = E/L$ finite
$\rightarrow$ fuel will run out $\rightarrow$ all stars will die!



flashlight analogy:

- luminosity = light output
- energy/fuel supply = battery capacity or “juice”

energy conservation: light stops after battery “dies”
more batteries → longer lifespan

But what is fuel for the Sun? what is the solar “battery”
What form of energy in Sun is converted to light & heat?
Q: list all forms of energy in Sun?

random kinetic energy of gas particles in Sun: *thermal energy*
we want to know what *other form of energy*
is *converted into thermal energy*

Q: how can you tell which is the fuel supply?

we know (from radioactive dating) that

Sun lifetime $\tau_\odot$ = Solar System age = 4.6 billion years

But: this requires enormous fuel supply $E_{\mathrm{fuel},\odot} = L_\odot \tau_\odot$

that is: a long flashlight lifetime requires big battery

Compare possible Solar energy sources:

- rotational energy (spin down, release KE):
  $\tau_{\mathrm{rot}} = 100$ yr
- chemical energy (make entire Sun from TNT!):
  $\tau_{\mathrm{chem}} = 20,000$ yr
- gravitational energy (contract $\rightarrow$release grav PE)
  $\tau_{\mathrm{grav}} = 20$ million years = 0.02 billion years

Q: implications?

Cosmic Nuclear Reactors

Sun needs huge energy supply–a mystery until 1920's
nuclear energy discovered, only source that comes close
→ the Sun is a nuclear reactor!
→ all stars are nuclear reactors!

Mechanism: *high-energy collisions*

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

- nuke energy release → stellar power source
- lighter nuclei combine → heavier: **fusion**
  changes elements → stellar alchemy

To work: need high-energy collisions

- in lab: particle accelerator
- *Q: what about in stars?*

Nuclear Reactions in Stars–and the Universe!

macroscopic temperature $\leftrightarrow$ microscopic atom/particle motion
hotter $\to$ faster particles, collisions more frequent & energetic

Examples

- cooking food: heat $\to$ speed up chemical reactions $\to$ cooks!
- heat gas until particle energy $>$ electron binding to atoms
  e stripped away $\to$ gas of free e and ionized nuclei
  $\Rightarrow$ "plasma" – occurs for $T \gtrsim 10,000$ K
  $\Rightarrow$ star interiors and early Universe are plasmas!
- heat a plasma until particle energy $>$ nuclear binding
  i.e., collision energy $>$ energy binding p and n together
  $\Rightarrow$ simulate particle accelerator conditions, get nuke reactions!
  need $T \gtrsim 10^7$ K = 10 million Kelvin

The Lives of Stars

The life of a star is a struggle against its own gravity

- if gravity force balanced by pressure, star is stable and to keep pressurized, must stay hot!
- if pressure weaker then gravity, star unstable collapses under its own weight

Birth

stars formed when cold gas clouds collapse due to gravity
compression $\rightarrow$ heating, until T at center $\rightarrow$ 10^7 K
"birth" when first nuke reactions begin

Youth and Midlife (Main Sequence) – All Stars

in core of star, nuclear reactions convert H $\rightarrow$ He

- energy release $\rightarrow$ heat $\rightarrow$ maintains outward pressure $\rightarrow$ balances inward gravity $\rightarrow$ stability! ("hydrostatic equilibrium")

Hydrogen Burning in Stars

interstellar gas is mostly (about 75%) hydrogen
stars formed from this gas $\to$ stars begin as mostly H

nuclear "burning" of hydrogen to helium:
- key reactions occur in "chains"
- first step involves pre-existing solar ingredients
- input for each new step is output from previous step

Dominant reactions: "pp" Chain

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

∞

Net effect:

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

each "p–p reaction" creates:

$p + p \to$ ^{2}H $+ e^{+} + \nu$

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

"heavy hydrogen" nucleus

- e^{+} **"positron"**

antimatter: positively charged anti-electron! more later about antimatter

then $e^{-} + e^{+} \to \gamma + \gamma$ energy! annihilation

- ν **"neutrino"**

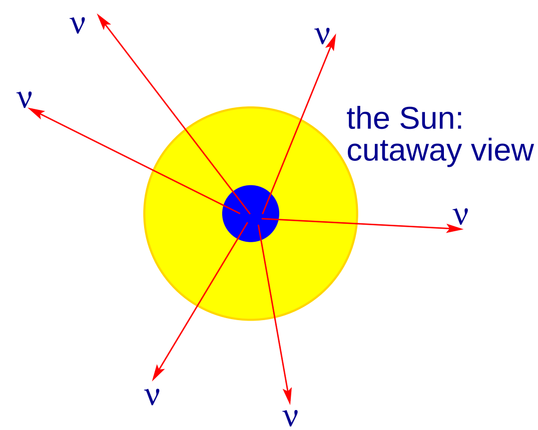
very low-mass ($m_{\nu} \ll m_{e}$) particle

only created in nuclear reactions ("weak" decays)

very weakly interacting particle

once born, go thru Sun, Earth, your body

but almost never interact



The Nuclear Powered Sky

Before 1930's:

- a mystery how the Sun could burn for billions of years
- no known energy source would work

In the 1930's:

nuclei, nuclear reactions, nuclear energy discovered

it was realized that this can power the Sun and all stars

`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

Inner Space and Outer Space

Lesson: a deeper understanding of “inner space”
i.e., the microscopic world
led to a deeper understanding of “outer space”
i.e., the astronomical/cosmological world

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 $4p \to {}^4\text{He} = \boxed{\text{2p2n}}$

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

$\to$ *must* produce neutrinos!

in fact: most made via $pp \to de^+\nu$

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
  $\to$ 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 $\nu + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^{-}$
collect Ar atoms (radioactive!)
`www: Davis chlorine experiment`

2. "scattering" – vats of ultrapure water
see light pulses from
high-energy e^{-} scattered by νs
`www: SNO ball`
`www: Super-K Sun image`