Astro 350

Lecture 14

February 18, 2022

Announcements:

- **Homeowrk 4 due today**
- Good news: now homework or discussion next week
- Bad news: **Midterm exam in class next Friday**
  info on Canvas

Last time: cold gas? not dark matter!

so: *if dark matter is "ordinary"* (=made of atoms)
  not diffuse (not gas): *must be compact*

compact objects as dark matter: *failed or dead stars*

stars have life cycles *Q: how do we know?*

The Stability of the Sun

the Sun maintains the same size

at least over human timescales

$\rightarrow$ don't consult weather for daily Sun growth or shrinkage

but because Sun keeps same size

$\rightarrow$ surface at rest

$\rightarrow$ not accelerating

$\rightarrow$ no *net* force

but the Sun definitely has mass & gravity

so every part of the Sun attracts every other part of the Sun

result is inward force on itself

Q: but the Sun does not collapse—what's going on?

Preventing Death By Black Hole

if gravity were the only force on the Sun
entire Sun in *free fall*!
$\rightarrow$ all matter pulled to center
$\rightarrow$ collapse to a black hole!

but this obviously is false! the Sun and stars do exist!
and are stable – Sun doesn't shrink daily!

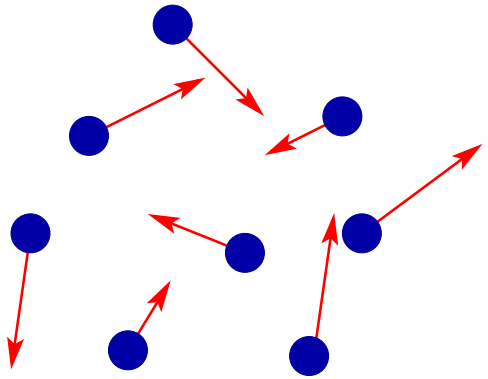
must be another force acting outward: **gas pressure**

Atoms, Gasses, Pressure, and Temperature

Take microscopic view of gas:

what are the atoms doing?

in any gas (stars, Universe, this room):

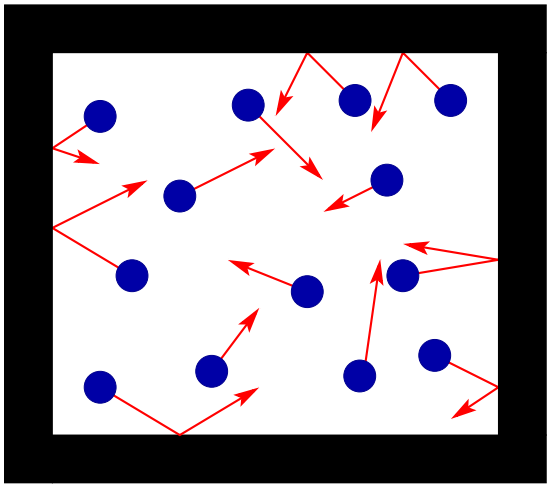


- atoms widely spread
  $\rightarrow$ empty space between particles
- *constantly in motion* as free bodies
  until collision with other gas particles
- collisions "scramble" /randomize motion direction
  and tend to equalize particle energies

Now zoom back to our macroscopic view:

- enclosed gas exerts force–pressure–on walls
  Q: how does atom picture explain this?
- *Q: how does gas change if turn up T? what are atoms doing?*

Gas Pressure



atom bombardment exerts force (transfers linear momentum)

e.g., atoms collide with piston, push it outward

this leads to outward pressure force

$\rightarrow$ have to overcome this to compress gas

`www: simulation: gas at atomic level`

Gas Temperature

temperature T is a measure of average atom speed

more precisely: $T \propto$ average atom energy for experts: ideal nonrelativistic gas has $kT = \frac{2}{3}\langle E \rangle = \frac{1}{3} m \langle v^2 \rangle$

so hotter gas $\rightarrow$ faster particles

and faster particles $\rightarrow$ higher pressure: $P \propto T$!

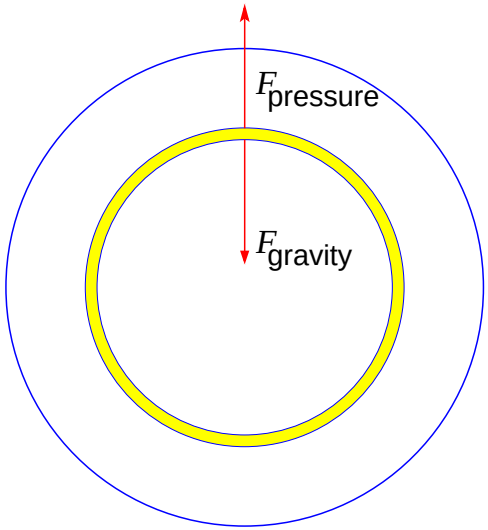
Q: so why doesn't the Sun collapse under its own weight?

Hydrostatic Equilibrium

consider a shell of gas in the Sun
the shell has mass, feels gravity
pulled to center: downward gravity force

but the Sun is stable: doesn't collapse
shell doesn't move: zero acceleration
so net force on shell is zero
$\rightarrow$ need upward force to counter gravity
gas pressure provides this force

balance of gravity and pressure in stars:
hydrostatic equilibrium



Poll: Cooling the Sun

Imagine a future industrial accident ("mistakes were made")
the Sun is robbed of its heat

What would happen if the Sun cooled off?

A the Sun would expand

B the Sun would shrink

C the Sun would remain the same size
but its atoms would have less random motion

Now now consider an interstellar gas cloud
Q: what conditions needed for it to form stars?

Star Birth: The Quest for Stability

cold gas clouds have small $T \rightarrow$ small pressure
$\rightarrow$ initially, pressure forces small
$\rightarrow$ gravitational collapse is (nearly) free fall

but *compression* $\rightarrow$ *heating*
as cloud collapses, pressure rises
until pressure forces as strong as gravity

eventually, star stabilized by becoming hot
inward gravity balanced by outward pressure
hydrostatic equilibrium achieved

newborn stars remain stable as long as equilibrium maintained
$\rightarrow$ have to keep *hot* to maintain pressure

Star Lifespans and Energy Sources

to fight gravity and be stable
the Sun must remain pressurized $\rightarrow$ must remain *hot*
and it does! Sun's T does not change (on human timescales)

but this is strange!

compare to a cup of coffee:
coffee starts out hot, but cools
  that is, loses heat energy to its environment
yet even though Sun emits energy too, at huge rate L
  still remains hot *Q: and so?*

Solar Power Source

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

To maintain luminosity (power output) L
  for a *lifespan* τ
  a star emits energy $E_{\text{emit}} = L\tau$
but energy conserved: fuel supply must be $E_{\text{fuel}} = E_{\text{emit}} = L\tau$
but since E_{fuel} finite, lifespan $\tau = E/L$ finite
$\rightarrow$ fuel will run out $\rightarrow$ all stars will die!

But what is fuel?
What form of energy in Sun is converted to light & heat?
Q: list all forms of energy in Sun?
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 $E_{\text{fuel},\odot} = L_\odot \tau_\odot$

Compare possible Solar energy sources:

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

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

- 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 $\rightarrow$ faster particles, collisions more frequent & energetic

Examples

- cooking food: heat $\rightarrow$ speed up chemical reactions $\rightarrow$ cooks!
- heat gas until particle energy $>$ electron binding to atoms
  e stripped away $\rightarrow$ 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 $\rightarrow$ 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

$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu$

$e^- + e^+ \rightarrow \gamma + \gamma$

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

Net effect:

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

each "p–p reaction" creates:

$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu$

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

"heavy hydrogen" nucleus

- e^+ **"positron"**

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

then $e^- + e^+ \rightarrow \gamma + \gamma$ energy! annihilation

- ν **"neutrino"**

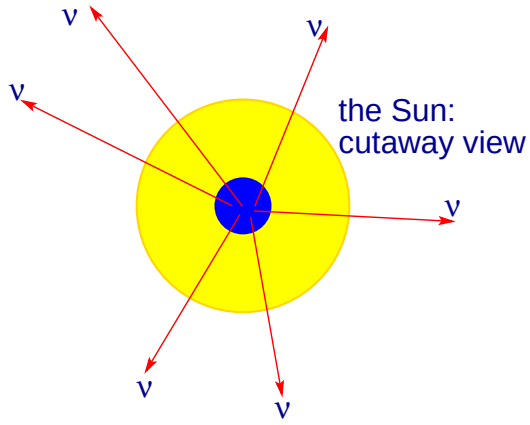
very low-mass ($m_\nu \ll m_e$) particle

only created in nuclear reactions ("weak" decays)

very weakly interacting particle

once born, go thru Sun, Earth, your body

but almost never interact



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 $4p \rightarrow {}^4\text{He} =$ 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`

Solar Neutrino Experiments: Results

- ⋆ All experiments detect solar νs!
- ⋆ Scattering experiments show neutrinos come from the Sun!
- ⋆ 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!

Using the Sun to probe neutrino properties:

(flavor transformation and mass)

Nobel Prize 2015!

Cosmic Gall

by John Updike

Telephone Poles and Other Poems

1963

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.

The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.

They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall.

And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.

At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed–you call
It wonderful; I call it crass.

Cosmic Gall

by John Updike

Telephone Poles and Other Poems

1963 + 2019 Update!

Neutrinos, they are very small.
They have no charge and ~~have no~~ tiny mass
And ~~do not~~ hardly interact at all.

The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.

They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall.

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The Nuclear Powered Sun: Lessons

Imagine: 100 years ago, you try to explain
that the Sun and all stars create tiny invisible particles
that pass through us all the time in huge numbers
and are essential byproducts of the working of stars

Q: a lesson for cosmology?