

Reading: Chapter 16 (next week: Chapter 17)

Astro 150 Fall 2020: Lecture 9 page 1

Exam 1: Tomorrow, in Recitation (and online) - please be on time/early - see Canvas for details

Last time: **Our Sun - a star, up close and personal**

- our local star, the Sun, is the touchstone for all of stellar astronomy
- what we see at and above the surface of the Sun tells us about how its energy eventually gets out into space
- The Sun is a dynamic powerhouse of light, magnetism, and turbulence.

Today: **How does the Sun shine?**

- We understand the inner workings of the Sun through our knowledge of physics.
- The Sun's interior produces huge amounts of energy that spreads from the center through to the surface in a variety of ways.
- The source of energy for the Sun is nuclear fusion.

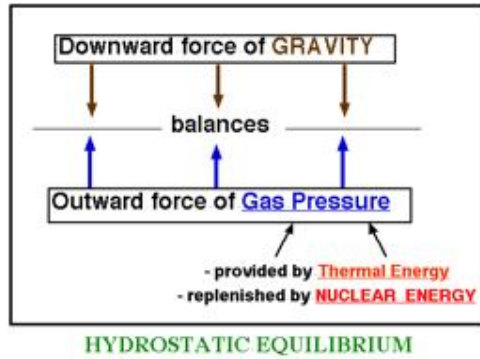
The Inside of the Sun:

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- What keeps the Sun shining?
- **What keeps the Sun from collapsing?**
 - Mechanical Structure
 - balance between gravity and gas pressure
 - Thermal Structure
 - production, flow, and escape of radiant energy
 - Energy Source

Mechanical Structure

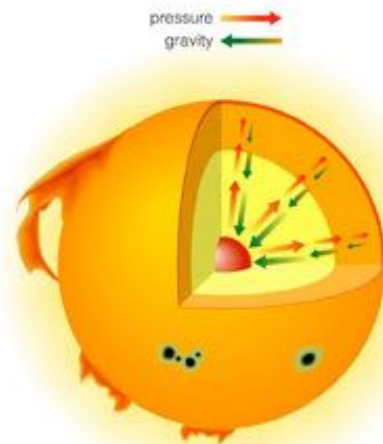
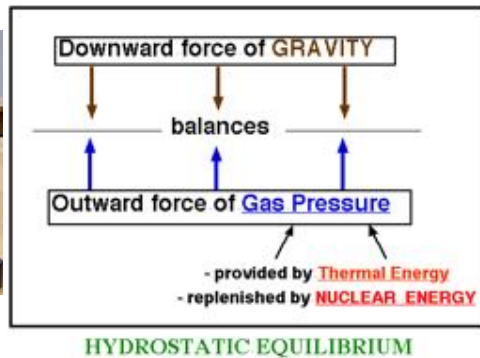
- Gravity versus Pressure



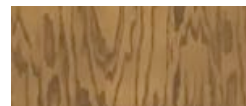
- punishment is swift for violation
- Pressure increases with depth

Mechanical Structure

- Gravity versus Pressure



- punishment is swift for violation
- Pressure increases with depth



Thermal Equilibrium

- Energy in = energy out
 - globally: energy produced = energy lost
 - locally: flow in bottom = flow out top

- Heat Transport Processes

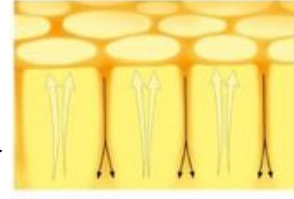
1. **conduction** - direct contact

2. **convection**

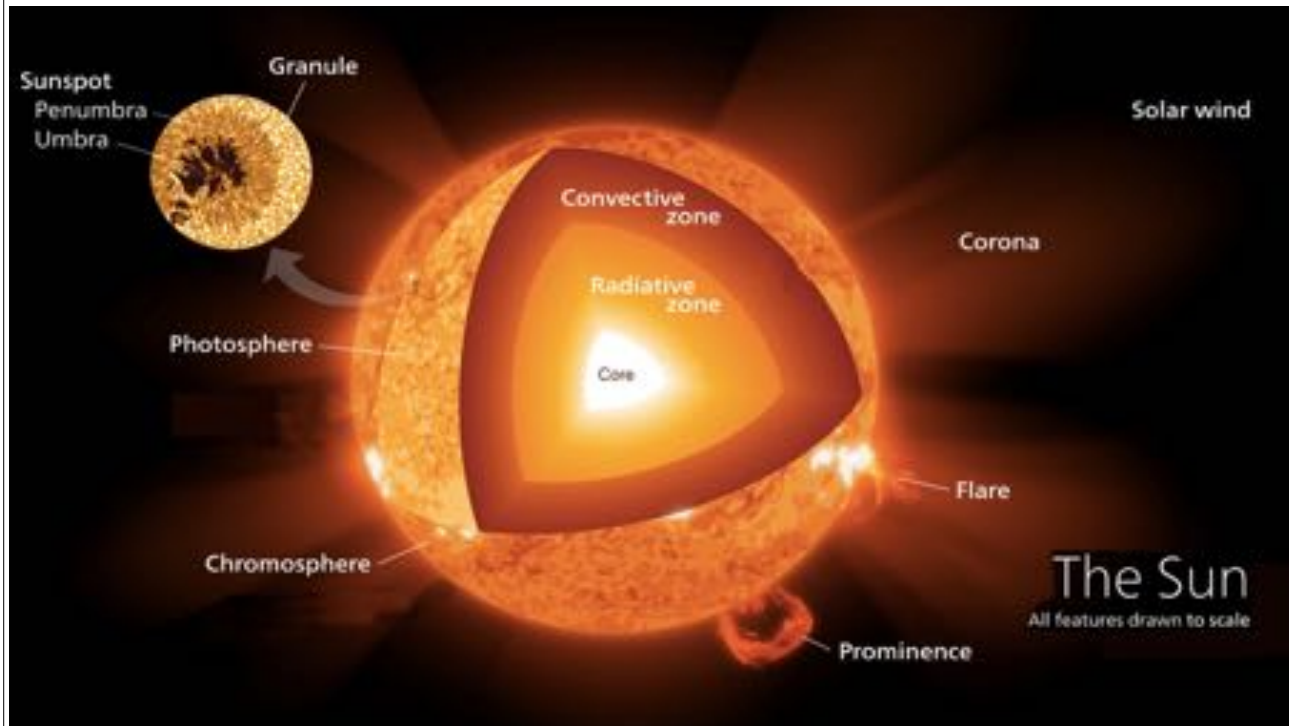
1. bulk motion of matter
2. occurs when temperature changes rapidly with depth

3. **radiation**

- transport by photons
- transparent stuff -- rapid transport
- opaque stuff -- slow transport
- 1 million years for energy to flow out from center!



“I’ve been waiting an hour
for roast duck.”



Energy Source for the Sun

- **Combustion?**

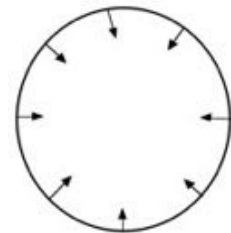
- 1 kg of coal per square meter per second!
- whole Sun consumed in 10,000 years! . . .nope

- **Gravitational Contraction?**

Kelvin and Helmholtz, 1871

- falling objects acquire energy that can be converted to heat
- slow contraction can provide heat energy to keep the Sun shining
- contraction by 20 meters each year can keep the Sun shining
- K-H contraction can provide energy for

100 million years!



BUT

various evidence shows that the Sun has
been shining for at least

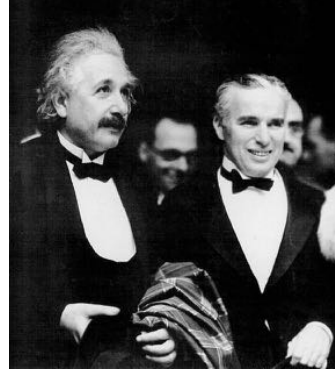
4.6 billion years!

Where does this energy come from?

(a hint: $E = m c^2$)

Answer: NUCLEAR FUSION

"They cheer for me because they all understand me and they cheer for you because nobody understands you."



Atomic Structure

- Atom = nucleus and electrons
(+ charge) (- charge)

nucleus = protons and neutrons

- Chemical element
- all atoms w/ same number of protons

| Element | # protons | # | symbol |
|----------|-----------|----|--------|
| Hydrogen | 1 | 0 | H • |
| Helium | 2 | 2 | He •• |
| Carbon | 6 | 6 | C |
| Oxygen | 8 | 8 | O |
| Iron | 26 | 30 | Fe |

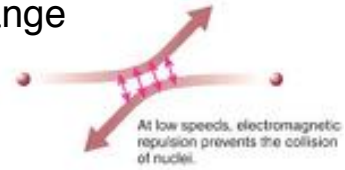
Relevant Forces

- Electromagnetism: repulsive *and* long-range



- Strong Nuclear Force: attractive but short range

- binds protons together in nucleus
- **stronger than EM at very small distances**

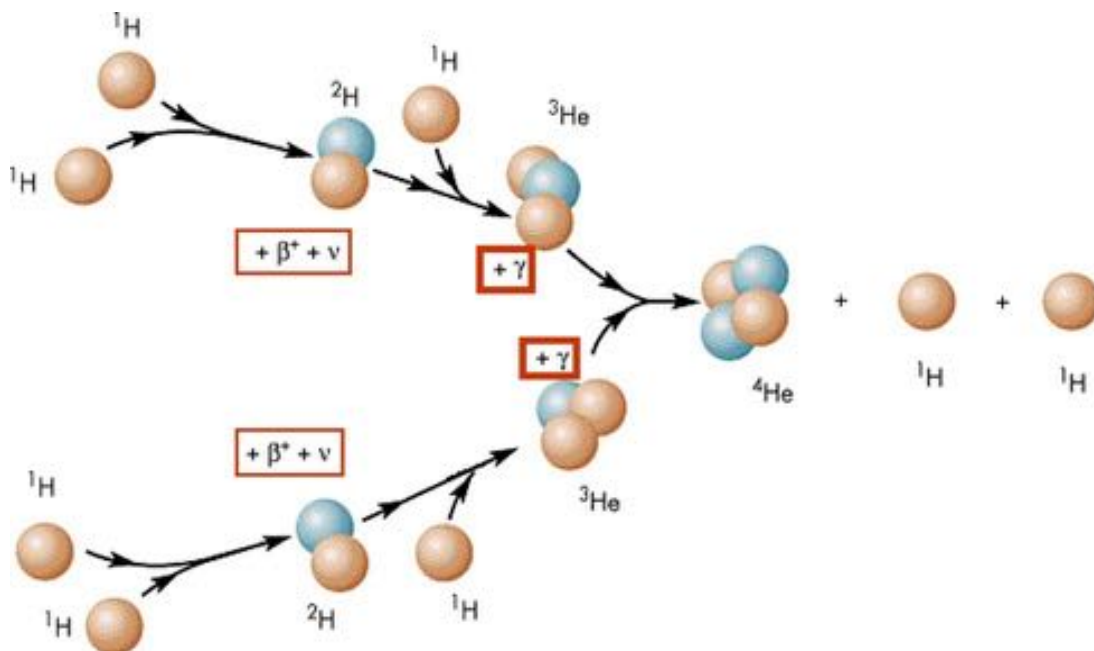


- At 10,000,000 K

- nuclei move quickly
- (+) nuclei get very close in collision
- strong nuclear force can take over



- **Nuclei stick together --- FUSION!**





- mass of $\text{H}^1 = 1.0078 \text{ AMU}$
- mass of $4 \times \text{H}^1 = 4.0312 \text{ AMU}$
- BUT: mass of $\text{He}^4 = 4.0026 \text{ AMU} \dots$
 0.0286 AMU
 disappears in p-p chain!
- converted into energy via $E=mc^2$
- 0.7% of H is converted into energy
- $E = 0.007 \times c^2$ ergs per gram of H \rightarrow He
- $E = 6 \times 10^{18}$ ergs per gram of H \rightarrow He

Hans Bethe - Nobel Prize in Physics
for work published in 1939

To supply the solar luminosity (4×10^{33} ergs/second)
the Sun must consume
 6.4×10^{14} grams of hydrogen every second!

How long can this go on?

$$M_{\text{sun}} = 2 \times 10^{33} \text{ grams}$$

$$\text{rate of consumption} = 6.4 \times 10^{14} \text{ grams/second}$$

$$\text{lifetime} = \frac{2 \times 10^{33} \text{ grams}}{6.4 \times 10^{14} \text{ grams/second}} \times 0.1$$

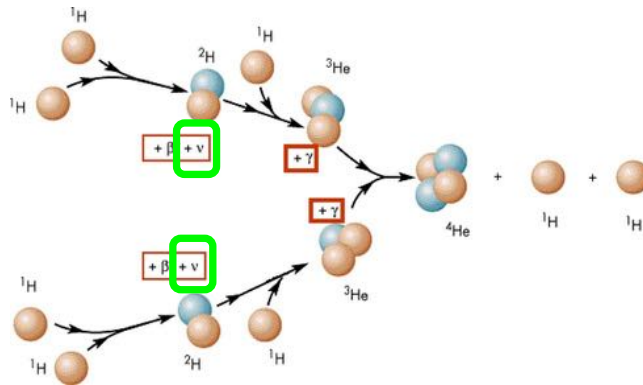
$$= 3.1 \times 10^{17} \text{ seconds}$$

$$= 10 \text{ billion years!}$$

...but the “solar neutrino ‘problem’” lurks

- Neutrinos

- massless particles
- travel at the speed of light
- rarely interact with matter
- produced in center of Sun during fusion



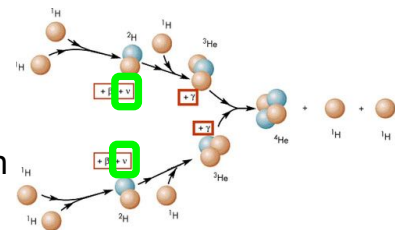
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- Experiments to detect solar neutrinos

- **Chemical method**: find *rare* changed atom in big sample
 - **Ray Davis** - 100,000 gallons of C_2Cl_4 in Homestake Mine
 - SAGE/GALLEX - gallium neutrino detector
- **Photodetectors**: detect *rare* recoil of affected particles
 - **Kamiokande II** - neutrino flashes in huge water tank
 - Sudbury Neutrino Observatory (SNO) - heavy water





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 - **Super Kamikande**
- 2002 Nobel Prize →
- 2015 Nobel Prize →
- **ALL show ~50% of expected neutrino rate! uh oh . . .**
 - **Solution: New physics needed** - neutrino oscillations