# The Structure and Composition of the Sun

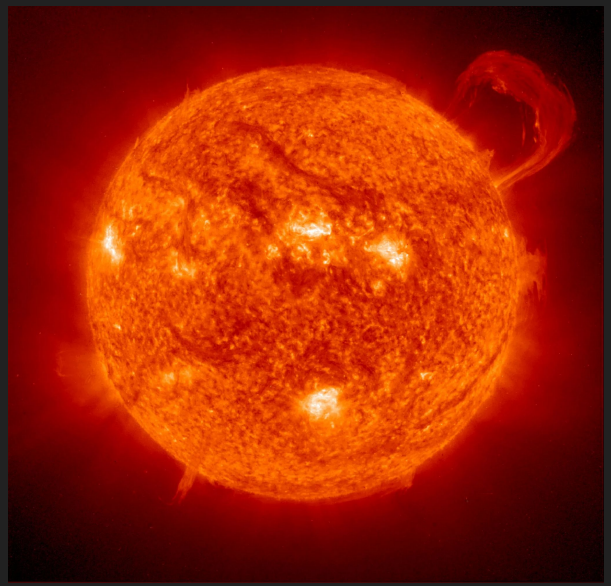
# Outline

- Solar Luminosity-
- Energy mechanisms-
  - Combustion
  - Contraction
  - Nuclear fusion
- Proton-proton chain-
- Hydrostatic equilibrium-
- Composition of the Sun
  - Poll everywhere
- Zeeman effect
- Structure of the Sun
  - Radiative core
  - Convective envelope
  - Photosphere
  - Chromosphere
  - Corona

# Solar luminosity



- Luminosity- Intrinsic brightness, independent of distance. Energy per second
- Solar Luminosity- brightness of the Sun
- 1 $L_\odot$ = $3.828 \times 10^{26}$ Joules released in one second, Watts



# Solar luminosity



- $4 \times 10^{24}$ (4 septillion) 100-Watt light bulbs

# Solar luminosity



- US energy consumption in 2023: 93.59 quadrillion ($10^{15}$) BTU
- Sun emits 4 million times this energy every second.

# Solar luminosity



- World nuclear arsenal: ~12,000 weapons, 30,000 megatons TNT
- Sun emits 3 million times this energy every second.

# Energy mechanisms

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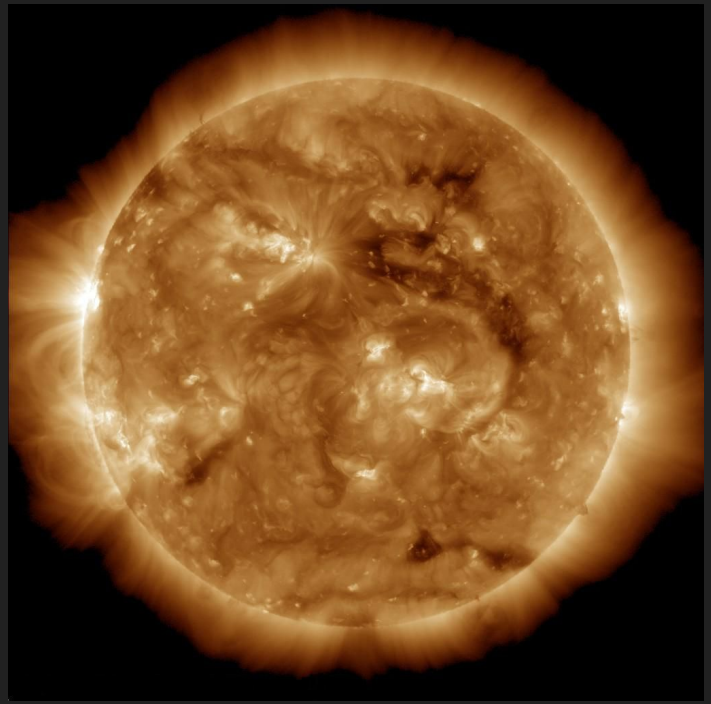
- 3 main ideas for what could power the Sun:
  1. Combustion
  2. Contraction
  3. Nuclear fusion
- We know the Sun's energy output is L = 3.828E26 Watts, and mass M = 2E30 kg.
- Test these hypotheses



# Energy mechanisms- Combustion

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- If the Sun is powered by combustion, we can estimate its expected lifetime.
- The Sun's total available energy is:
  - The Sun's total mass (kg) x The energy that can be released per kg (J /kg)
- The Sun's lifetime is then total energy / energy output per year

$$\tau\ (\text{years}) = \text{Mass} \times \frac{1}{\text{Energy output per second}} \times \frac{\text{years}}{\text{second}} \times \frac{\text{Energy}}{\text{Mass}}$$

$$\tau\ (\text{years}) = 2 \times 10^{30}\ \text{kg} \times \frac{1}{3.828 \times 10^{26}\ \text{J s}^{-1}} \times \frac{1\ \text{year}}{\pi \times 10^{7}\ \text{s}} \times \frac{\text{Energy (J)}}{\text{Mass (kg)}}$$

$$\tau\ (\text{years}) \approx 10^{-4} \times \frac{\text{Energy (J)}}{\text{Mass (kg)}}$$

# Energy mechanisms- Combustion



Lifetime (years) = $10^{-4}$ x Energy released (J) per mass consumed (kg)

1. Standard gasoline is a highly efficient combustible. Burning 1 kg of it released 40 Megajoules (40E6 J) of energy. What is the oldest the Sun could be if combustion was the source of the Sun's energy?
   a. 4 million years
   b. 400,000 years
   c. 40,000 years
   d. 4,000 years

# Energy mechanisms- Combustion



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   c. 40,000 years
   **d. 4,000 years**

# Energy mechanisms- Combustion



- The Sun could only live for a few thousand years if powered by combustion.
- Some rocks on Earth are ~4 billion years old.
- Not supported

# Energy mechanisms- Contraction

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- Astronomers realized a contracting body releases energy.

$$\langle U \rangle = \frac{3GM_\odot^2}{10R_\odot}$$

$$\tau \approx \frac{\langle U \rangle}{L_\odot}$$

$$\tau \approx \frac{3GM_\odot^2}{10R_\odot L_\odot}$$

$$L_\odot = 3.828 \times 10^{26}\ \mathrm{W}$$

$$M_\odot = 2 \times 10^{30}\ \mathrm{kg}$$

$$R_\odot = 6.957 \times 10^{8}\ \mathrm{m}$$

$$\tau \approx 9.57\ \text{million years}$$

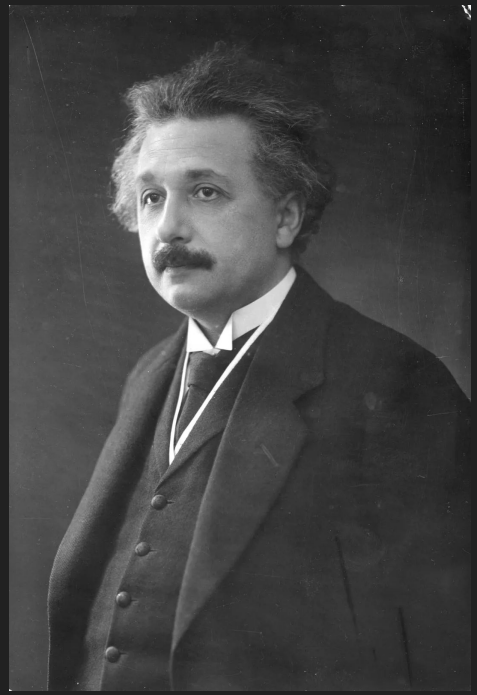
# Energy mechanisms- Nuclear fusion



- Contraction could not be the source of the Sun's energy
- Einstein's Theory of Special Relativity was key to explain the Sun.
- Mass-energy equivalence

$$E = mc^2$$

- Tiny amounts of matter can be converted to tremendous amount of energy.
- A single gram of matter can power your house for ~2,000 years if converted entirely to energy.
- To power the Sun, about 4 billion kilograms of matter is converted to energy every second.



# Energy mechanisms- Nuclear fusion

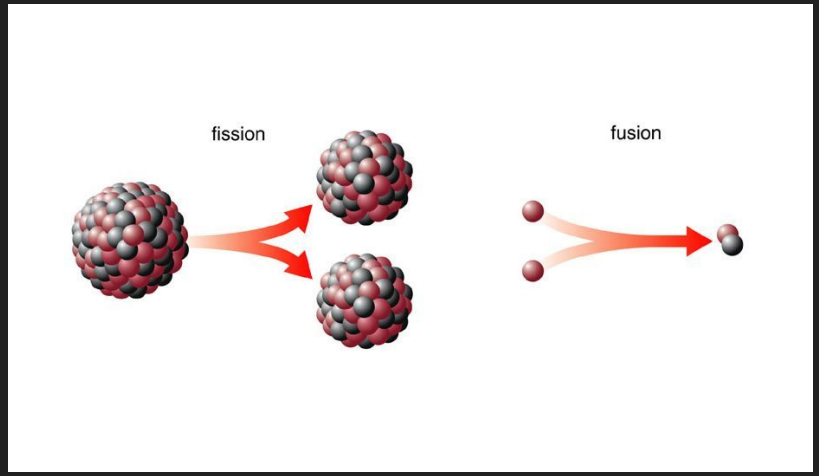


- A helium atom has two protons and two neutrons.
- Hydrogen has only one proton.
- Helium is 0.7% less massive than four hydrogen atoms.
- Leftover mass is released as energy.
- Based on this ratio, 600 billion kg of hydrogen are burned every second.
- 6E29 kg of hydrogen in the core, lifetime of ~10 billion years.
    - The Sun is about halfway through its life.

# Fusion, not Fission

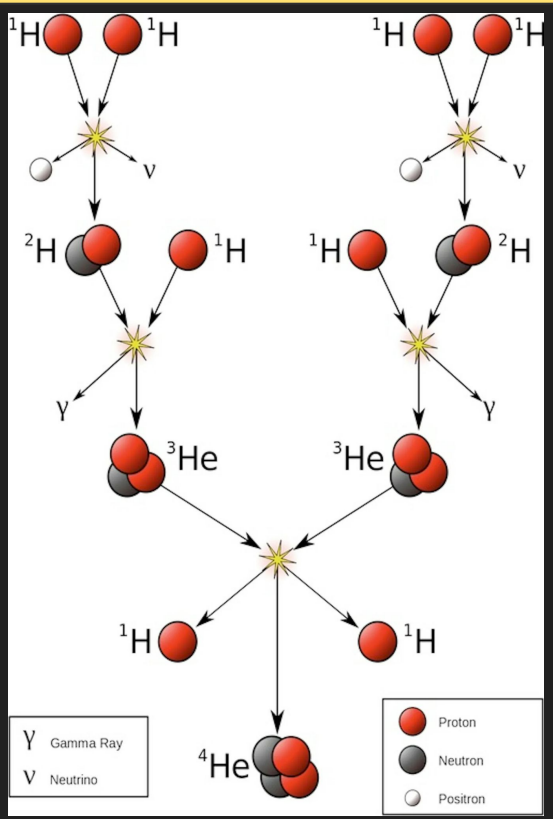


- Merging light nuclei, fusion.
  - The Sun
  - Hydrogen bomb
- Breaking up heavy nuclei, fission.
  - Nuclear power plants
  - “Atom” bombs



# Proton-proton chain

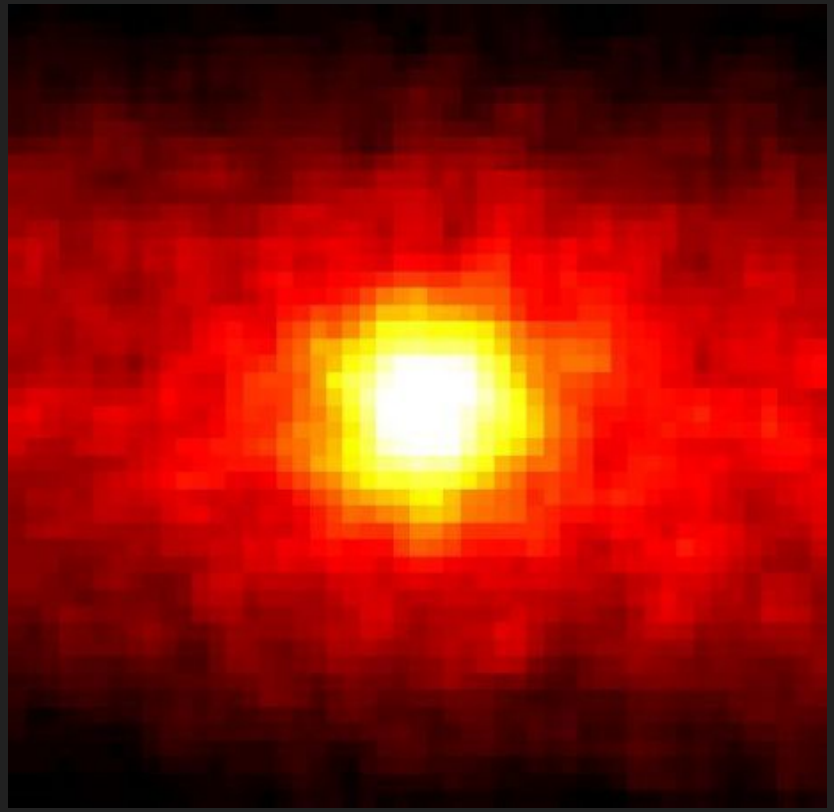
- Fusion in the Sun called proton-proton chain.
- 4 hydrogen atoms net 1 helium atom
- Requires high temperatures (7 million K)
- Produces energy (photons), helium, and the neutrino



# Proton-proton chain



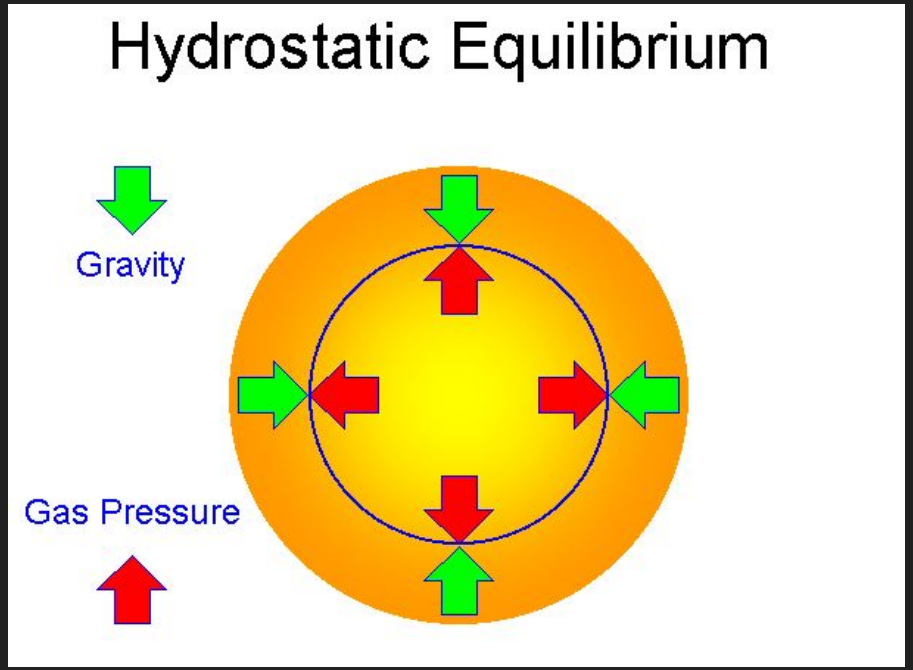
- The Sun should release neutrinos from the reactions in its core.
- Hard to detect
- They pass through Earth undeflected, without interacting
- Neutrino detects over hundred of days produce this image of the Sun.



# Hydrostatic equilibrium

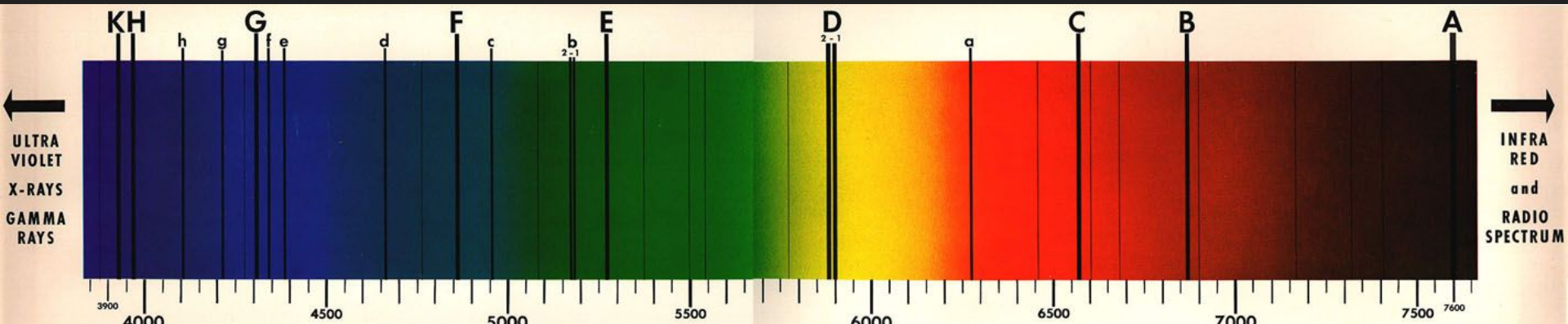


- The Sun contracted due to gravity in the Solar System.
- Why doesn't the Sun contract more?
- The outward pressure from fusion in the core balances the inward force of gravity.
- *Hydrostatic equilibrium*.



# Composition of the Sun

- The Sun's spectrum reveals absorption from oxygen, hydrogen, sodium, iron, calcium. Is the Sun made of the same material as Earth?
- These are only transitions in the visible bandpass.
- The Sun is mostly hydrogen and helium, from Cecilia Payne.



# Composition of the Sun



**The Abundance of Elements in the Sun**

| Element | Percentage by Number of Atoms | Percentage By Mass |
|---|---|---|
| Hydrogen | 92.0 | 73.4 |
| Helium | 7.8 | 25.0 |
| Carbon | 0.02 | 0.20 |
| Nitrogen | 0.008 | 0.09 |
| Oxygen | 0.06 | 0.80 |
| Neon | 0.01 | 0.16 |
| Magnesium | 0.003 | 0.06 |
| Silicon | 0.004 | 0.09 |
| Sulfur | 0.002 | 0.05 |
| Iron | 0.003 | 0.14 |

**Table 15.2**

# Poll everywhere



When poll is active respond at **PollEv.com/nikhilpatten355**

Send **nikhilpatten355** to **22333**

# Poll everywhere



results

# Zeeman effect

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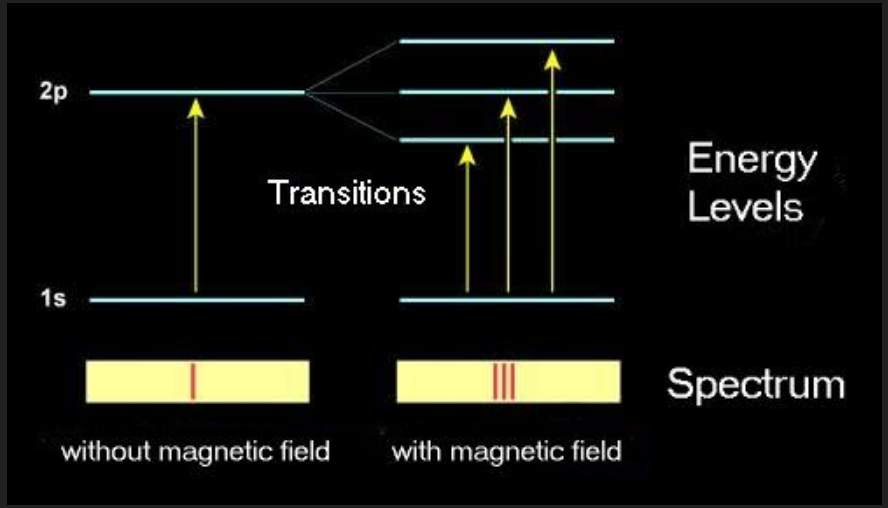
- Atomic transitions cause absorption lines in spectra.
- External magnetic field causes these absorption lines to split.
- Splitting is proportional to the strength of the magnetic field
- Known as the Zeeman effect.



# Zeeman effect

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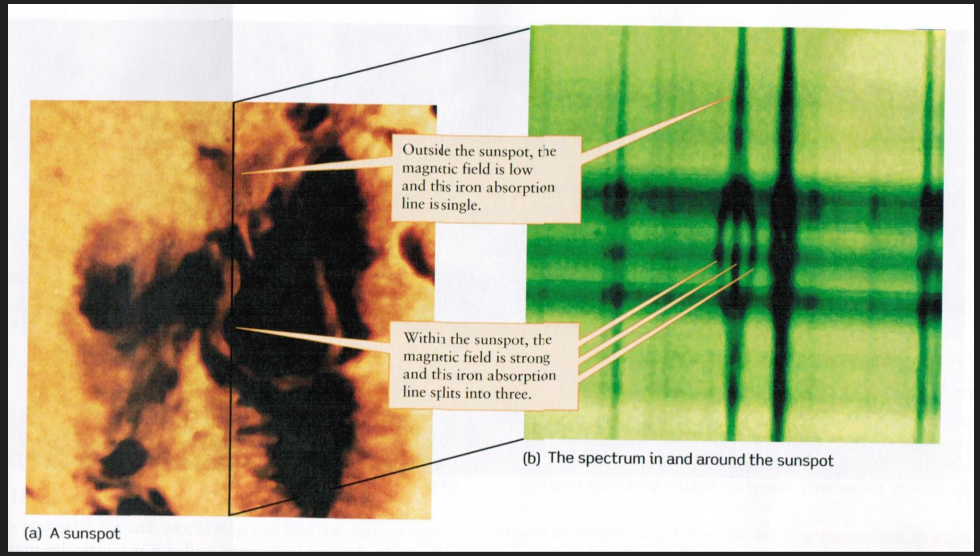
- We find spectral features from the Sun vary with time.
- The Sun has a changing magnetic field!



# Structure of the Sun

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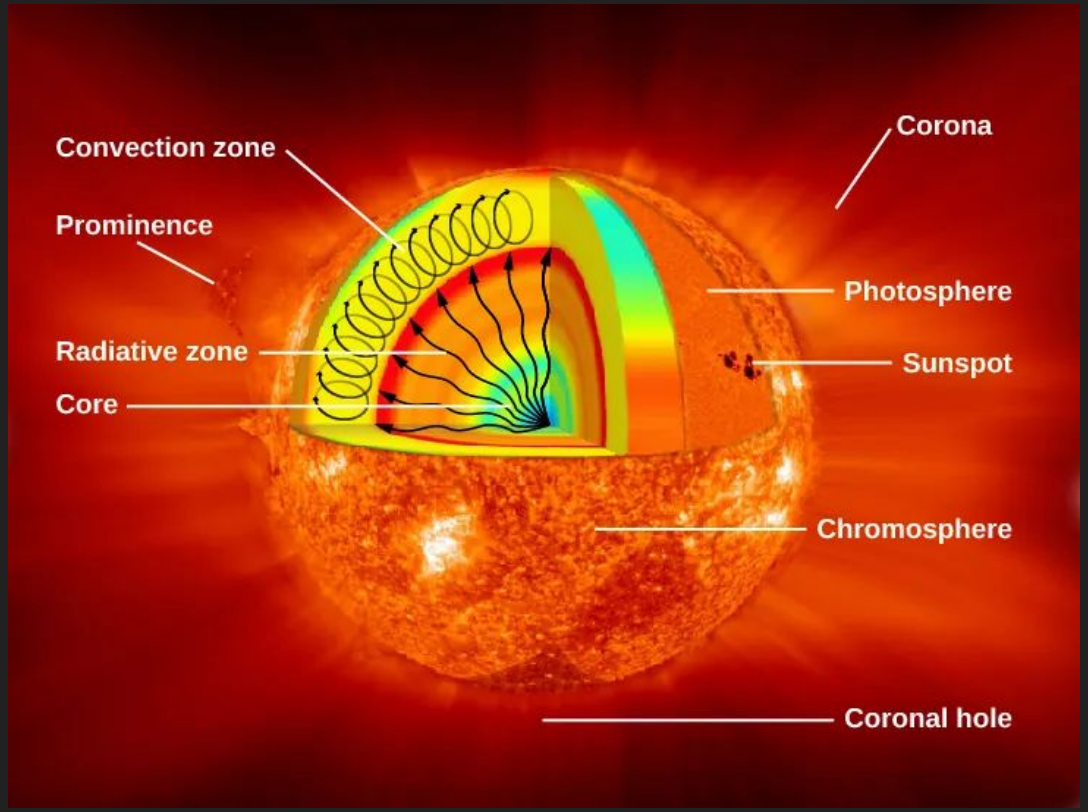

# Structure of the Sun- Radiative Zone



- Regions of the Sun split into method of radiative transport
- Energy travels through radiation
- Temperatures too low for fusion
- Photons leave core, scatter throughout the radiative zone
    - Takes a photon ~100,000 years to travel from the core to the convective zone.

# Structure of the Sun- Convective Zone

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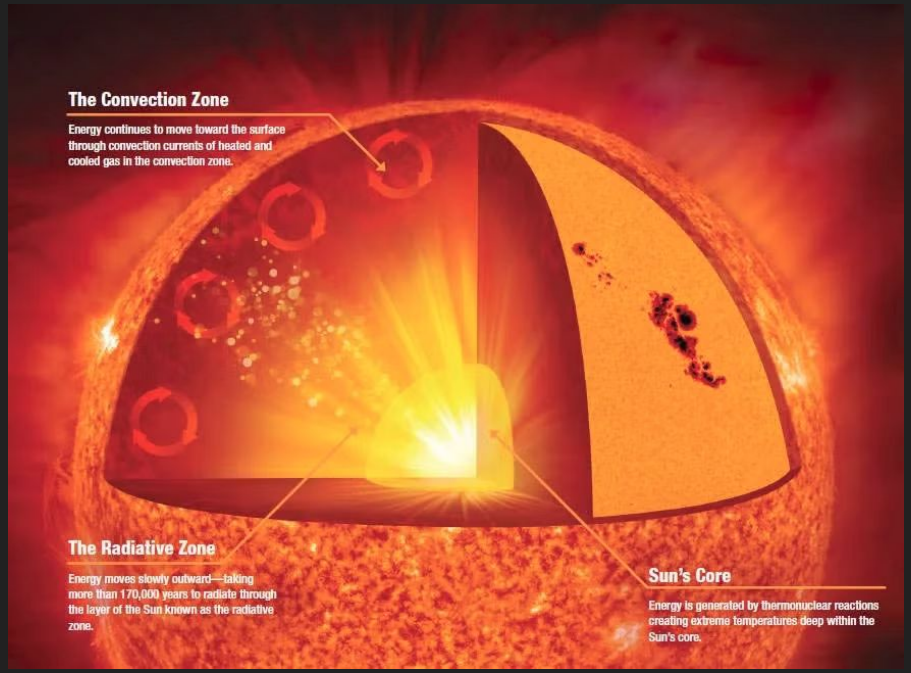
- Outside radiative zone
- Transport by convection
  - Hot gas rises, cool gas sinks
- Gives us the the mechanism to form a magnetic field
- Photosphere at the top of convective zone
- Surface of the Sun is covered in granules of convective gas reaching the top layer.
  - Like boiling water



# Structure of the Sun- Photosphere

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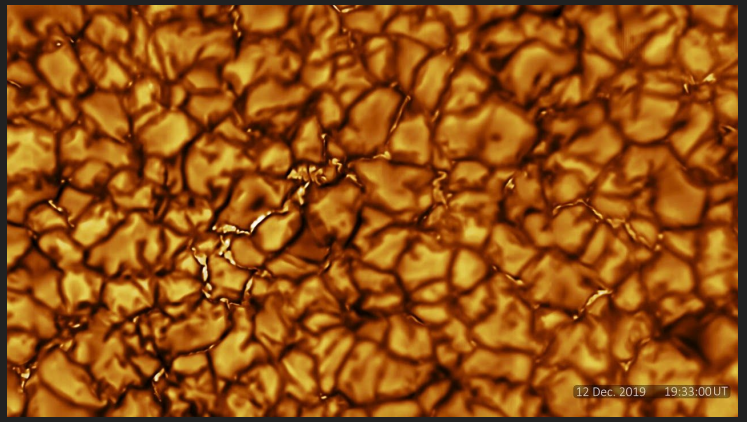
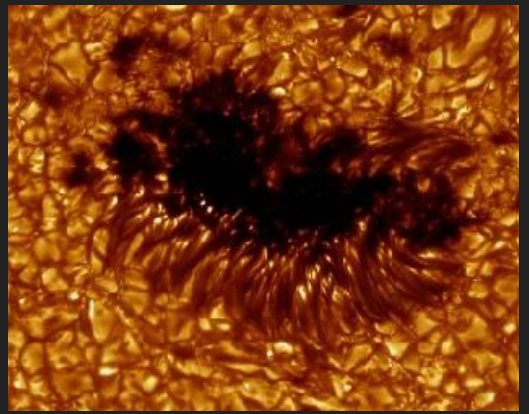
- Thin, opaque outer layer of the Sun
- Covered in granules, about 1000 km in size
- Hotter rising gas, cools and sinks down
- Irregular, cool “sunspots” form from irregularities in the magnetic field

solar granulation



# Structure of the Sun- Chromosphere

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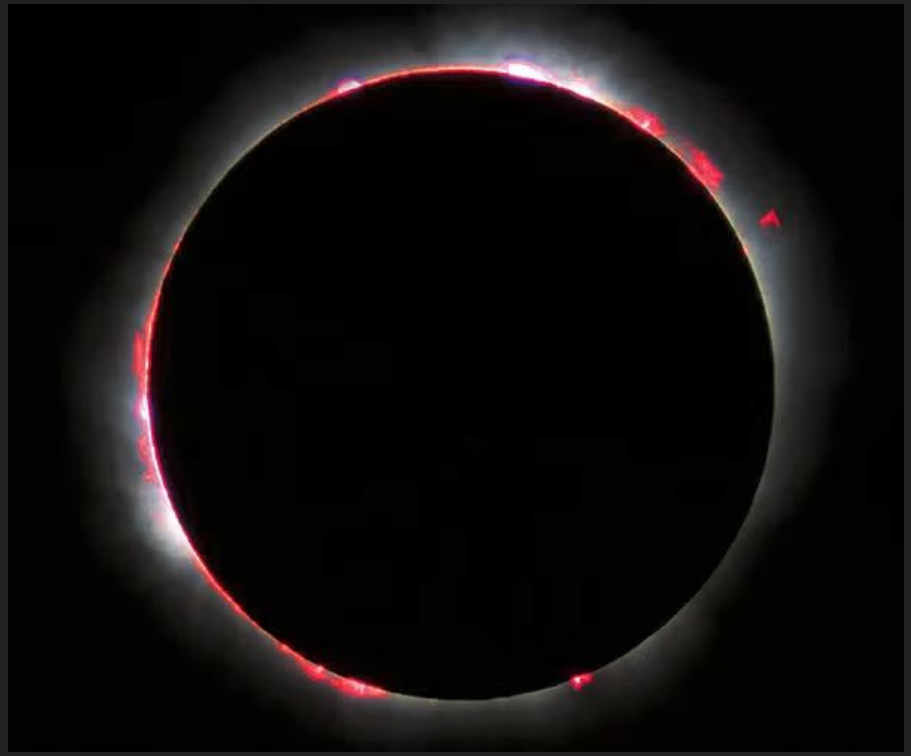
- Transparent outer layer of gases above the photosphere
- Hot gases that are cooling
- Hotter than the photosphere (10,000 K versus 5780 K).
- Discovery of helium



# Structure of the Sun- Corona

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- Extends millions of km above the photosphere
- Very low density gas heated to millions of Kelvin
- Charged particles moving along the Sun’s magnetic field lines
- Heating mechanism still active area of research

# Announcements



- No class/lab next Monday
- Homework 5 due Wednesday

# Next time



- The brightness and colors of stars