Chapter 8:
The Sun

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AST 1002

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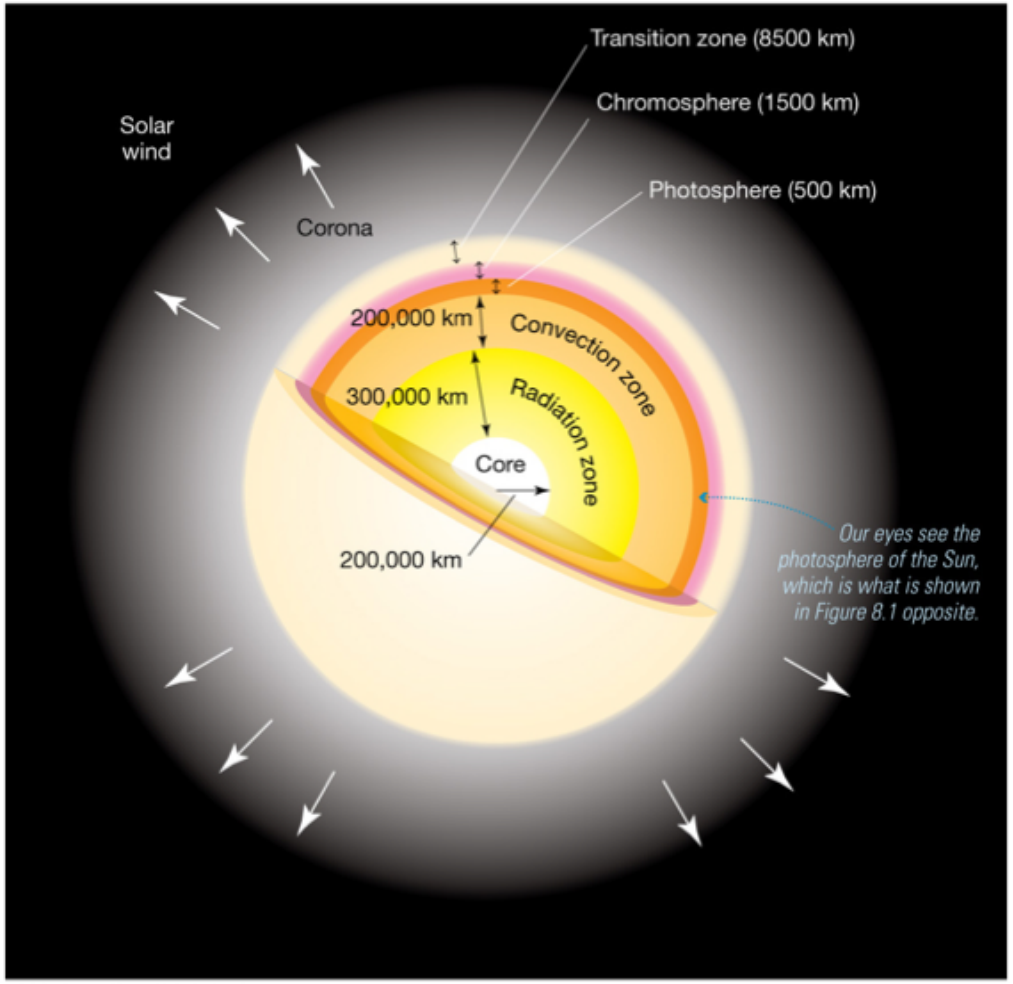
Properties of the Sun



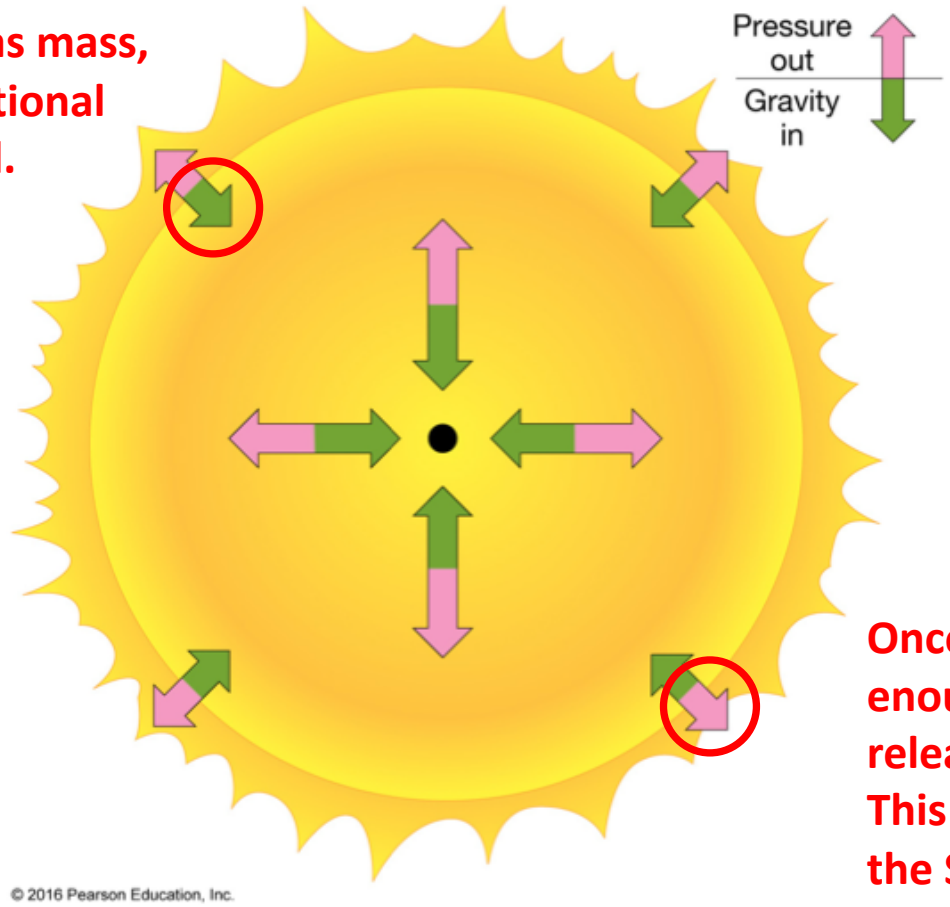
- The Sun is a **star**: a collection of hot gas, mostly hydrogen, which emits light like a blackbody. The Sun is a fairly typical star for our solar system.

- The Sun rotates, but unlike the Earth, it orbits differently between the equator and the poles.

- The Sun has several layers to it:
  - The innermost layer, the **core**, is where the Sun produces its power via nuclear fusion.
  - The **radiation zone**, in which the gas is a plasma (a gas of charged particles) and only light can escape.
  - The **convection zone**, through which energy escapes.
  - The **photosphere**, where the light we see is physically generated.
  - The 3 outer layers, the photosphere, chromosphere, and corona, form the **solar atmosphere**.

Equilibrium in the Sun

The hydrogen gas in the sun has mass, and all that mass has a gravitational attraction, pulling itself inward.



Once the hydrogen gets packed tightly enough, it can undergo fusion, releasing massive amounts of energy. This counteracts the gravity, keeping the Sun in equilibrium.

Nuclear Fusion

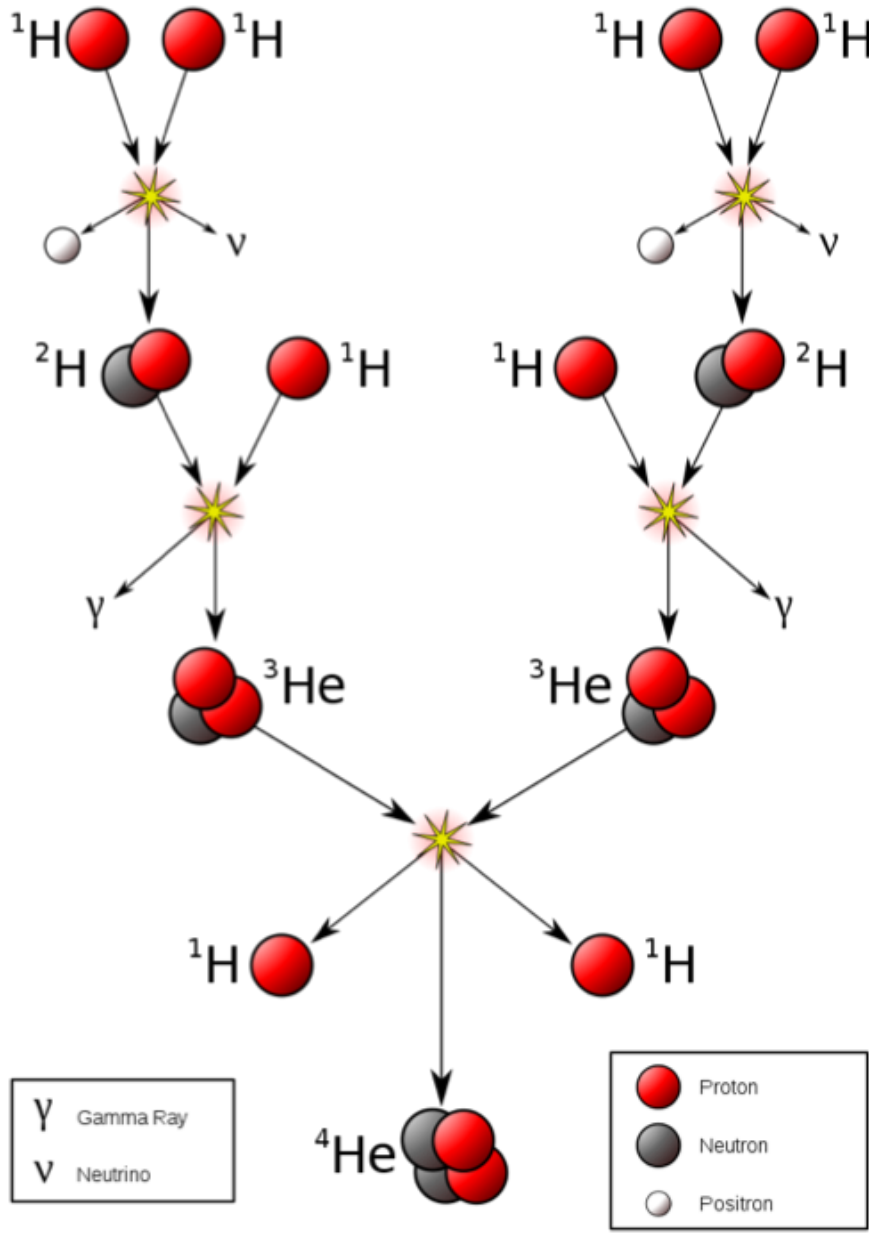
$$p^+ + p^+ \rightarrow {}^2\mathrm{H} + e^+ + \nu_e + \text{energy}$$

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

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

Overall:

$$4p^+ \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + \text{energy}$$



Nuclear Fusion Calculations

$m_p = 1.6726\times10^{-27}\text{kg}$
$m_{^4\text{He}} = 6.6442\times10^{-27}\text{kg}$
$m_e = 9.11\times10^{-31}\text{kg}$
$m_{\nu_e} = 0$ (approximately)

Step 1: Overall:

$$\underbrace{4p^+}_{\text{More mass}} \rightarrow \underbrace{{}^4\text{He} + 2e^+ + 2\nu_e}_{\text{Less mass}} + \underbrace{E}_{\text{Extra energy}}$$

Step 2:

$$\Delta m = \underbrace{4m_p - (m_{^4\text{He}} + 2m_e + 2m_\nu)}_{\text{Extra mass}} = 4.438\times10^{-29}\text{kg}$$

Δ = "Change in"

Step 3:

$$\underbrace{E}_{\text{Extra energy}} = \underbrace{(\Delta m)}_{\text{Extra mass}}c^2 = \boxed{3.994\times10^{-12}\text{J}}$$

Speed of light:
$c = 3\times10^8\ \text{m/s}$

Nuclear Fusion in the Sun

$$4p^+ \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + E$$

Occurs 9.58×10^{37} times every second

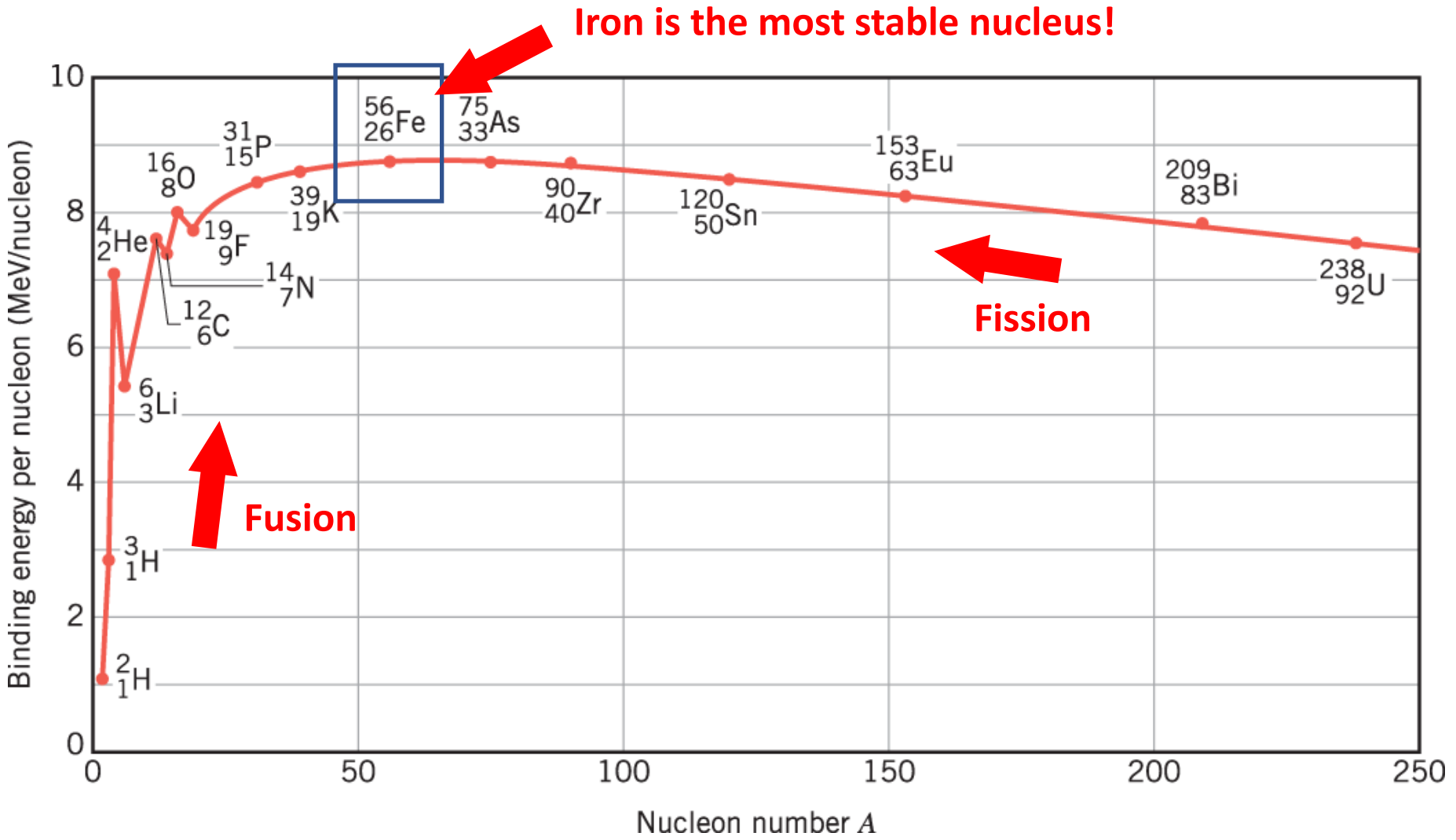
$E = 3.994\times10^{-12}\mathrm{J}$

$$\frac{\text{Energy}}{\text{second}} = N * E = 3.828\times10^{26}\ \mathrm{J/s}$$

Luminosity, L

Watts, W

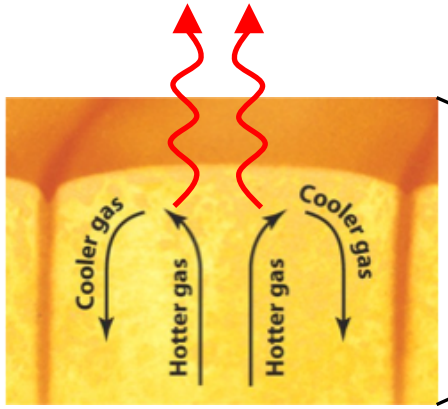
Fission vs. Fusion

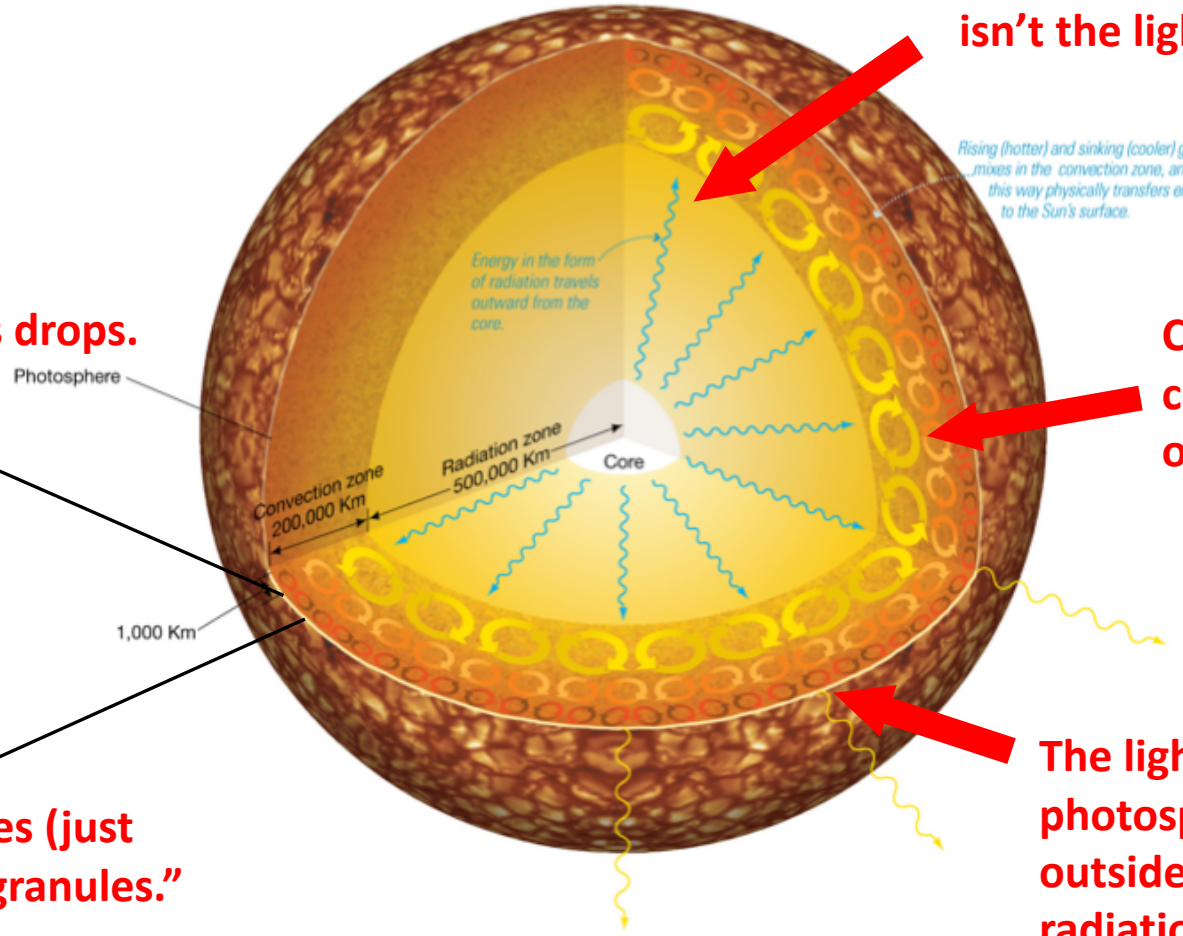


Radiation vs. Convection Zones

The radiation in the radiation zone isn't the light that escapes the Sun.

Heat leaves hot gas at top of convection cycle, then cool gas drops.





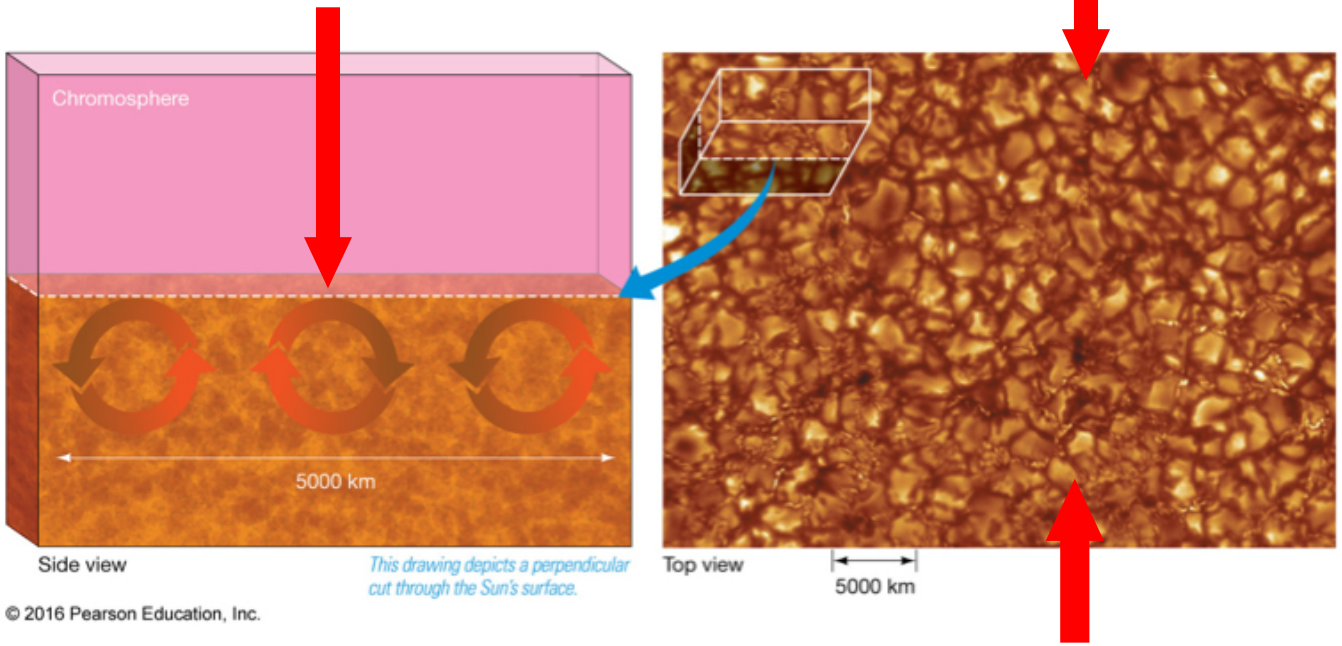
Convection cycles progressively carry energy up to the surface of the Sun.

Outer-most convection cycles (just under photosphere) form "granules."

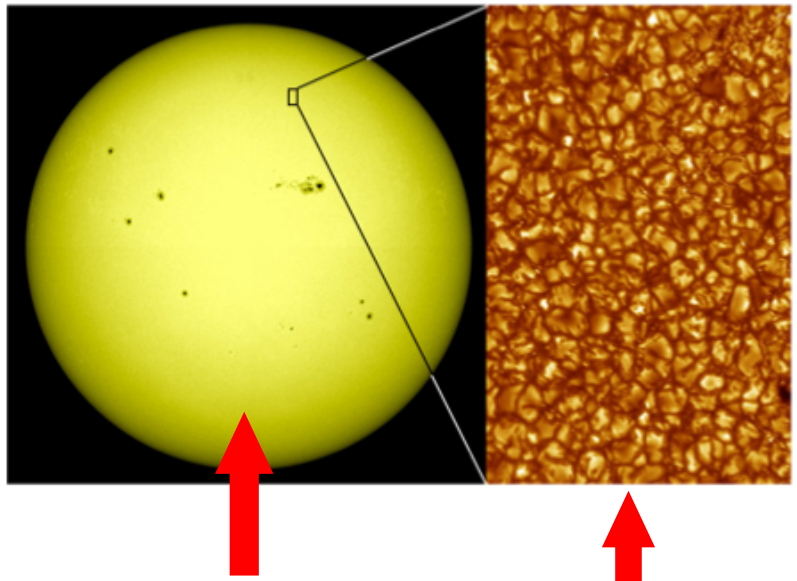
The light we see comes from the photosphere, which is a thin layer just outside the convection zone. This radiation is at a much lower energy.

Granules

The boundary is the photosphere.



Bright parts are slightly bluer than dark parts



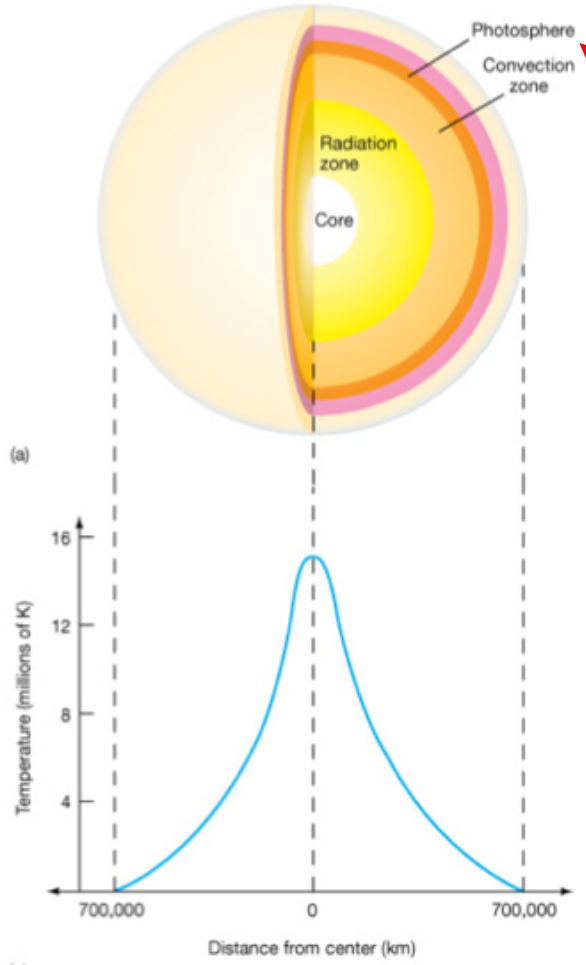
Diameter of the Sun is 1.4 million km

Granules are 1000km in size

Granules are produced by convection, the same as bubbles in boiling water.

https://www.youtube.com/watch?v=W_Scoj4HqCQ

Temperature of the Sun



The Sun is a blackbody, so the brightness and color of light we see is determined by temperature.

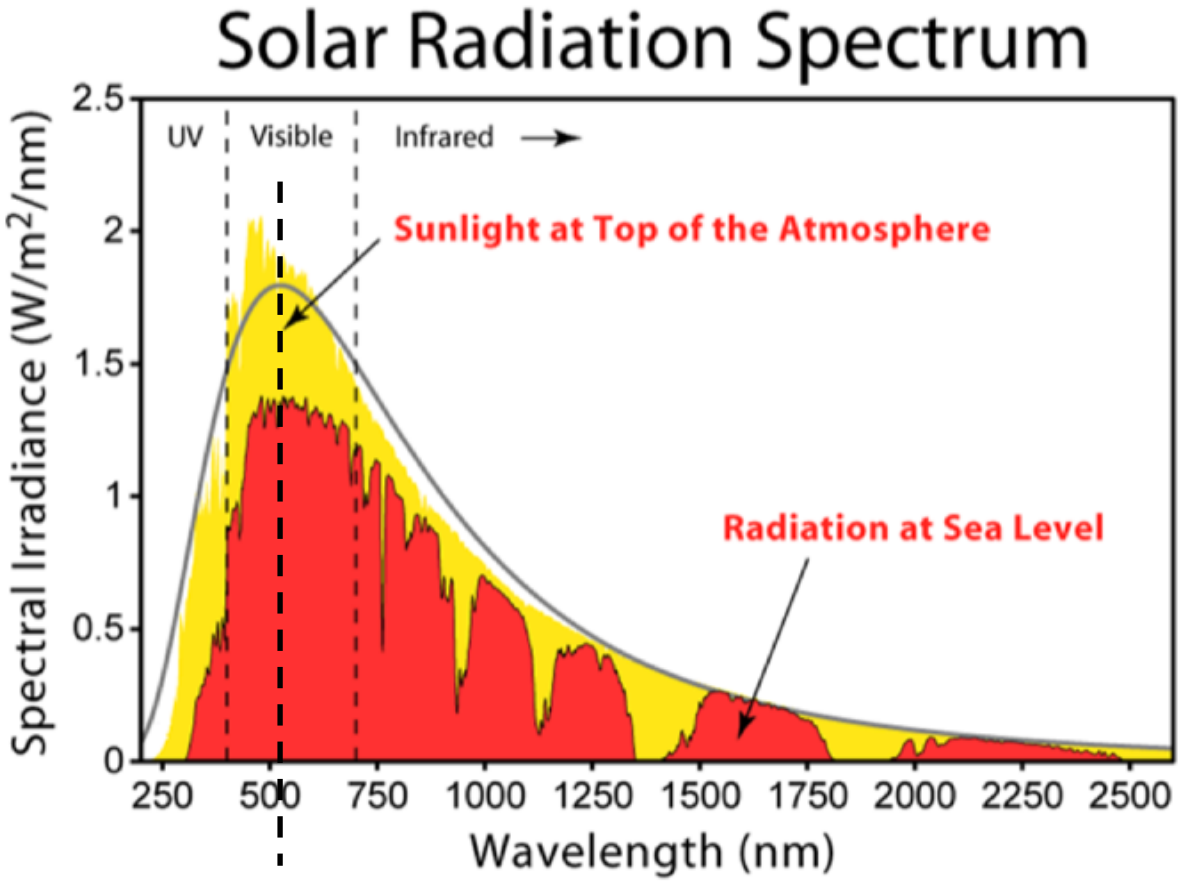
The photosphere is the visible part of the Sun, which is what acts as the blackbody.

The "temperature of the Sun" is the temperature of the photosphere! This is around 5800K.

Sun / Surface temperature

5,778 K

The Sun as a Blackbody



$\lambda_{max} \approx 500\text{nm}$

$b = 2.9\times10^{6}\ \text{nm}\cdot\text{K}$

Wein's Law:

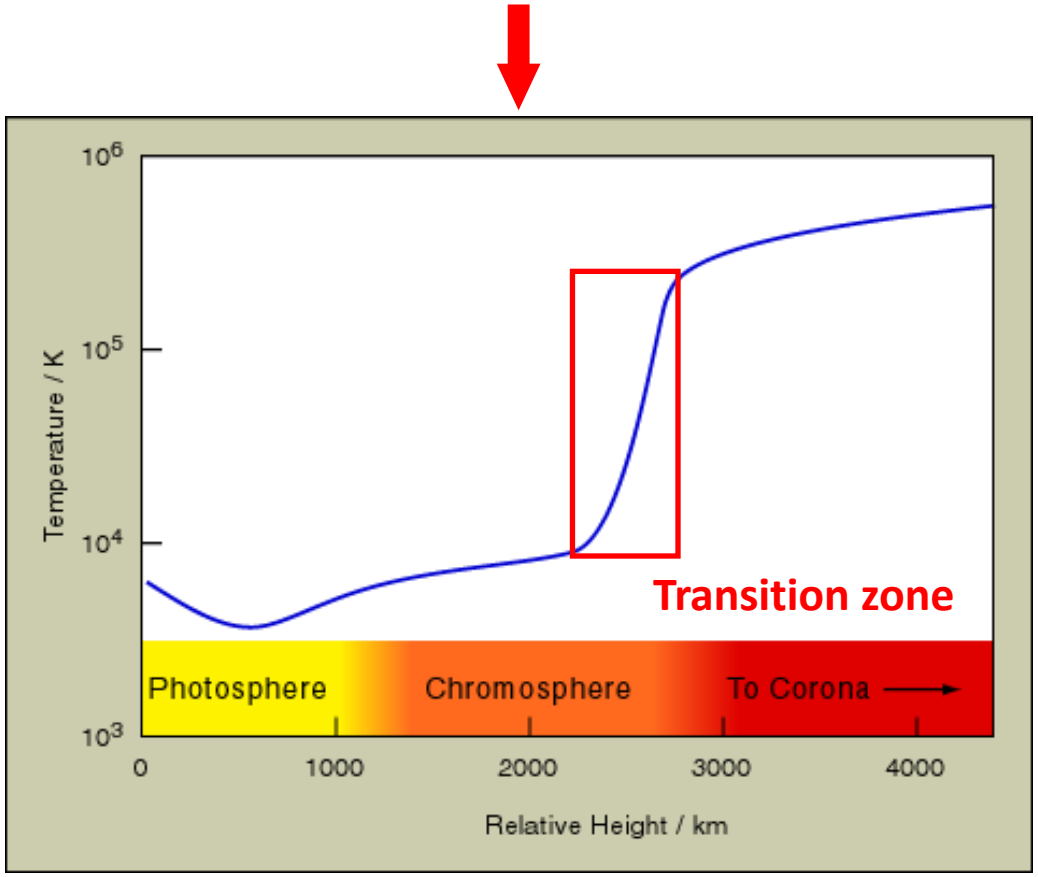
$$\lambda_{\max} = \frac{b}{T}$$

$$T = \frac{b}{\lambda_{\max}} = \boxed{5800\text{K}}$$

Temperature of the blackbody, and therefore temperature of the photosphere

Solar Atmosphere

Atmosphere contradicts temperature trend



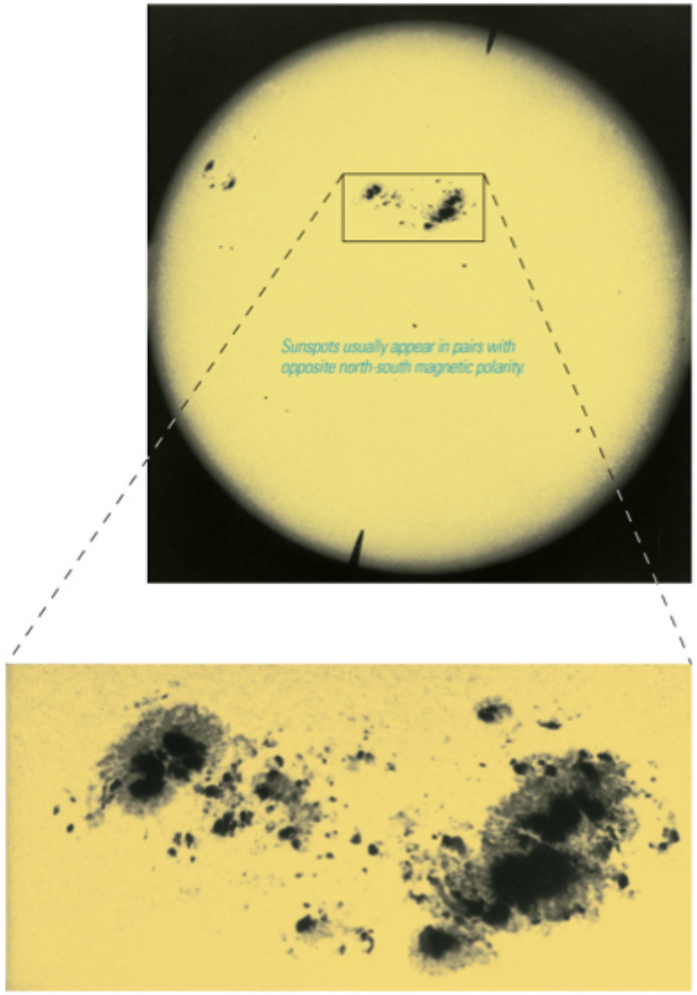
2nd Law of Thermodynamics:

Heat flows from hot to cold, never from cold to hot.

Coronal heating problem!

Possible solution: magnetic recombination

Sunspots



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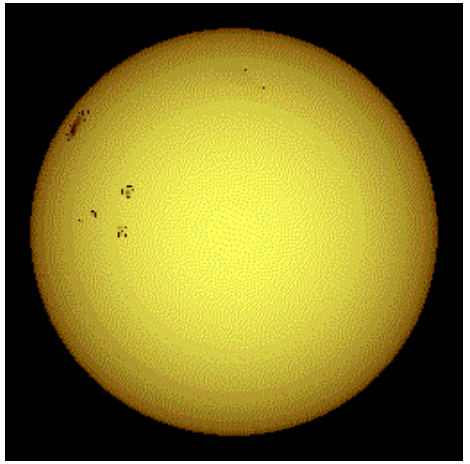
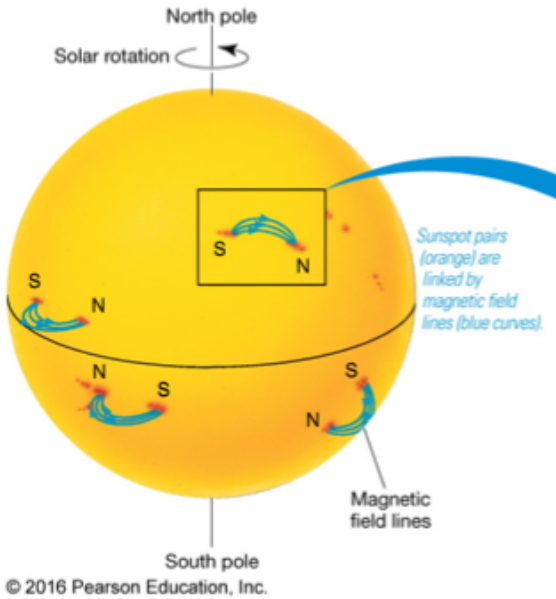


These looping magnetic fields are known as "prominences"



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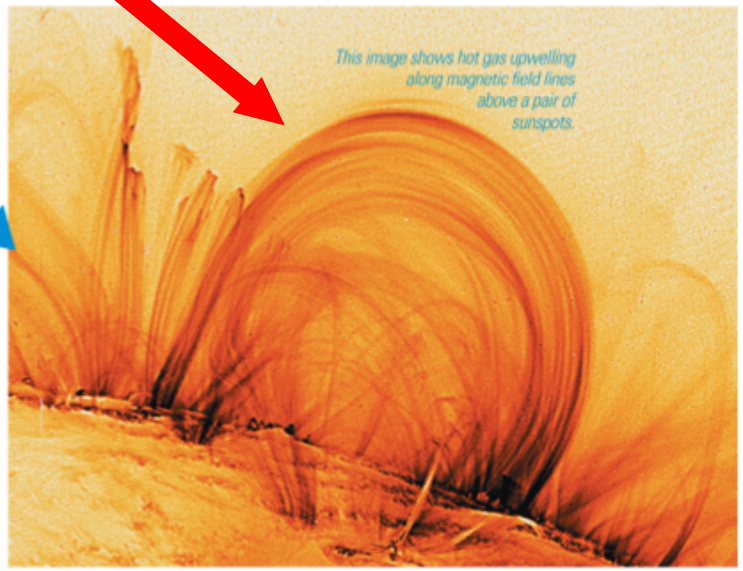
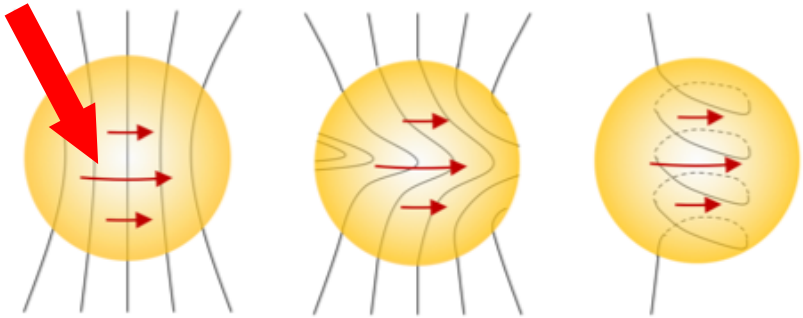
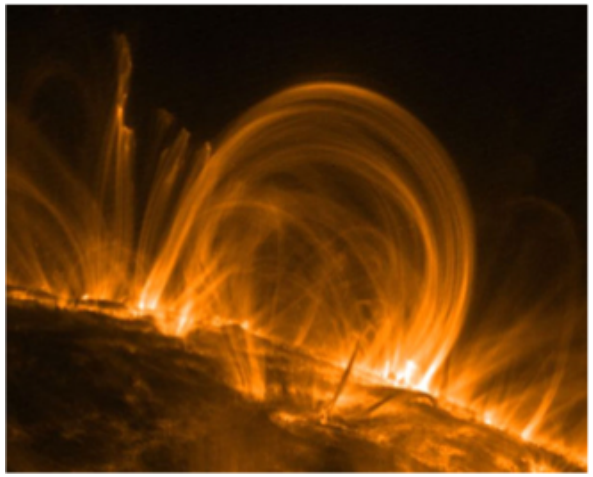
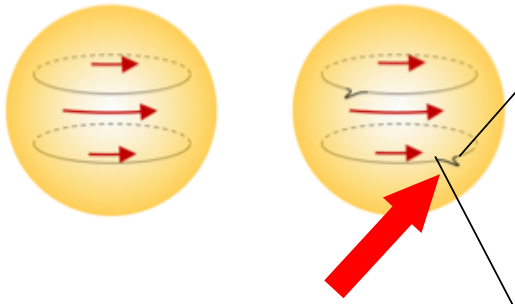


Magnetic Reconnection

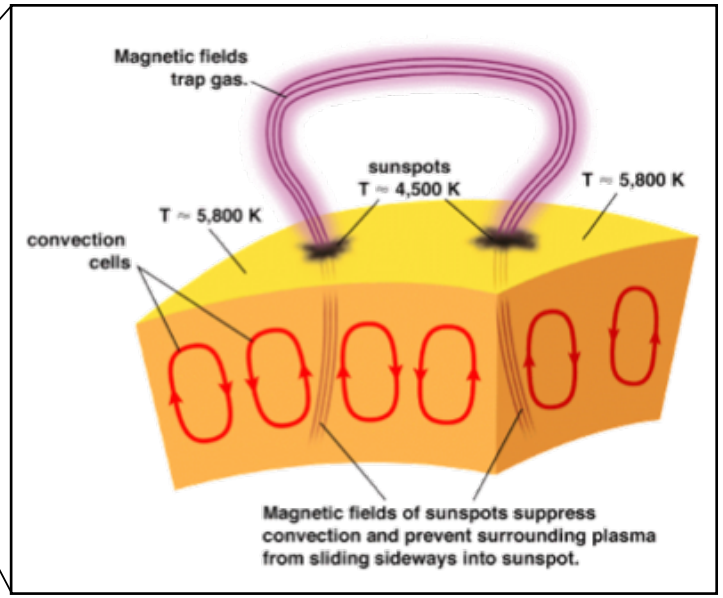
Equator rotates faster than poles



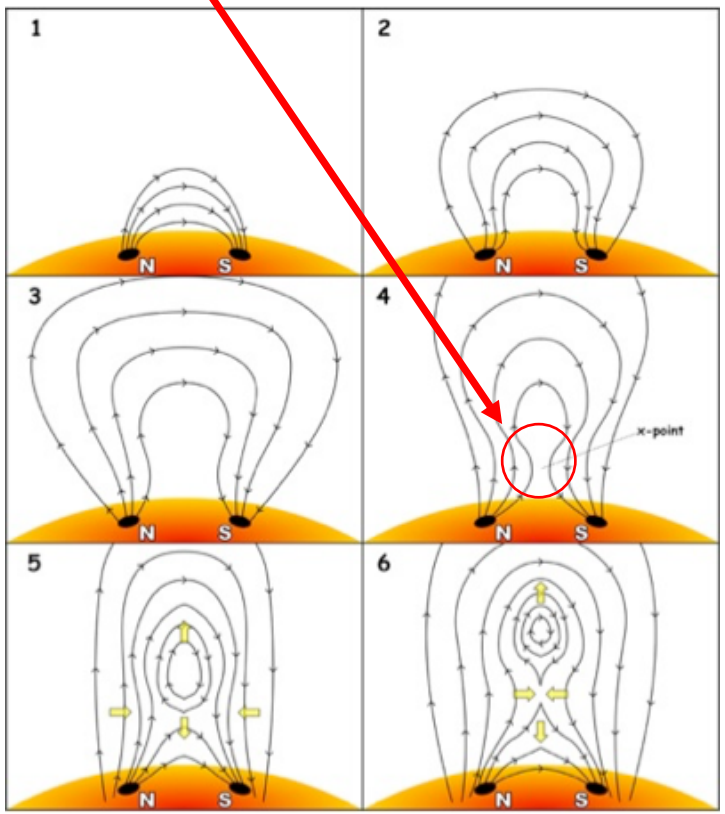




Magnetic loops develop kinks that poke out of Sun's surface

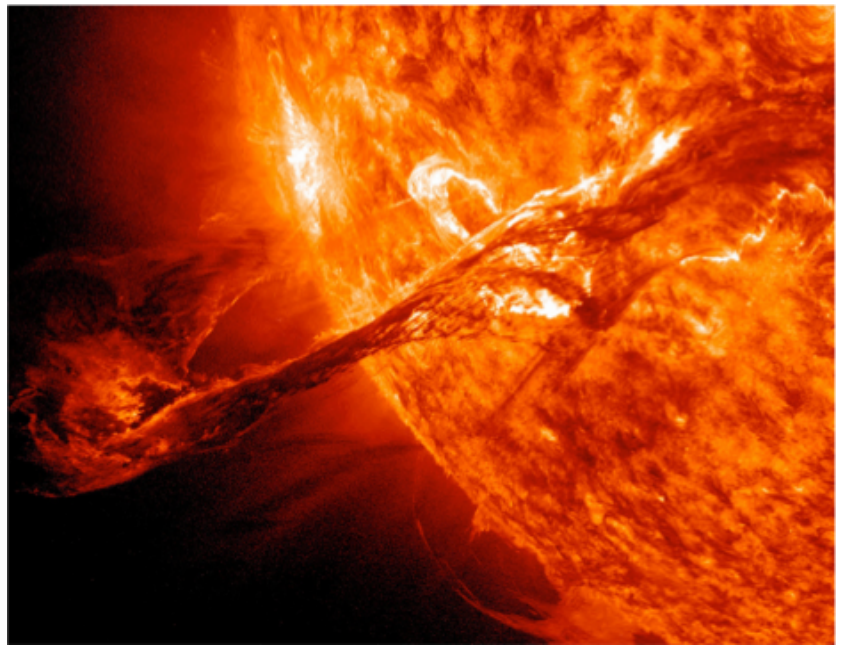


Reconnection point

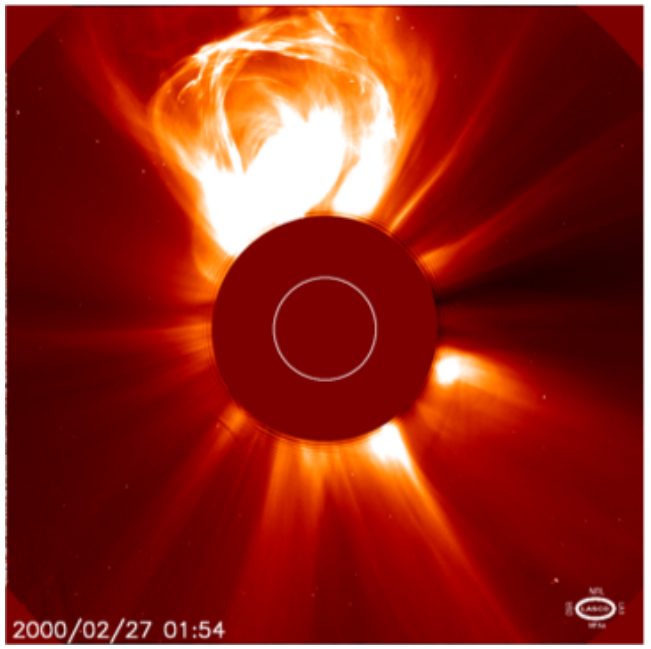


Massive energy released when magnetic fields reconnect, carried to corona to heat it.

Solar Flares vs. Coronal Mass Ejections



In a solar flare, prominence is still trapped by Sun's magnetic field



In a coronal mass ejection, prominence is energetic enough to escape Sun's magnetic field

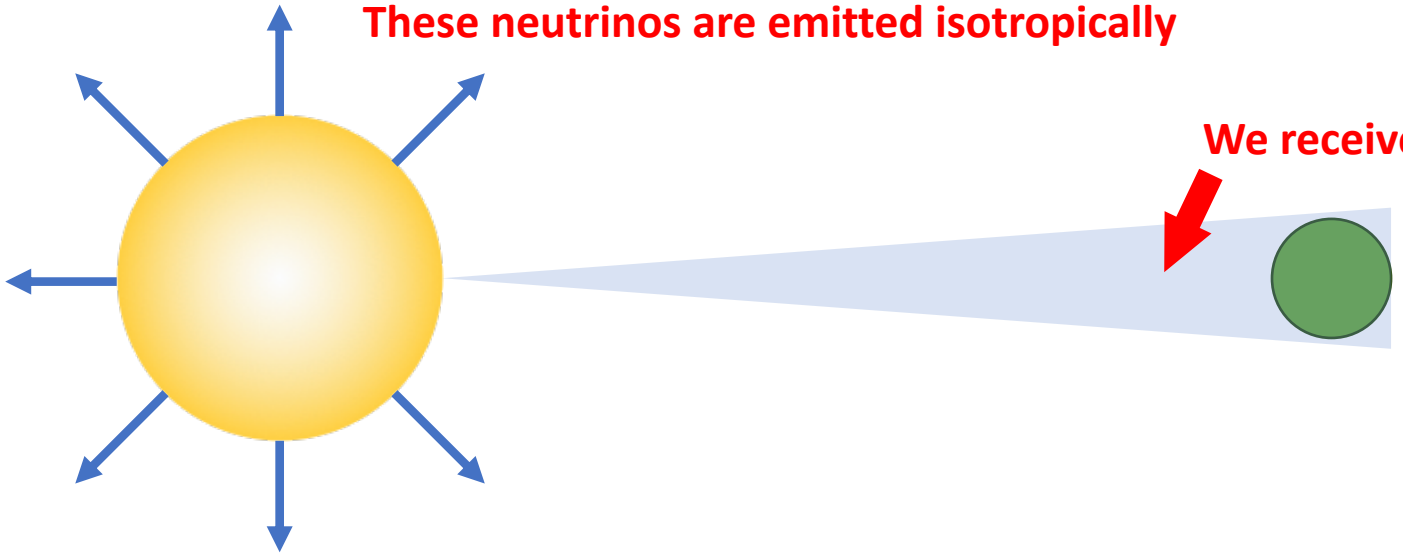
Difference between flares and CME's: https://www.youtube.com/watch?v=TWjtYSRlOUI

Solar Neutrinos

Specific type of neutrino, known as "electron neutrino."
Recall, 9.58×10^{37} are made every second.

Fusion:

$$4p^+ \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + \text{energy}$$



Solar neutrino problem: We can predict how many neutrinos per second we should receive. However, we only observe 1/3 of them.