Chapter 16:
The Sun

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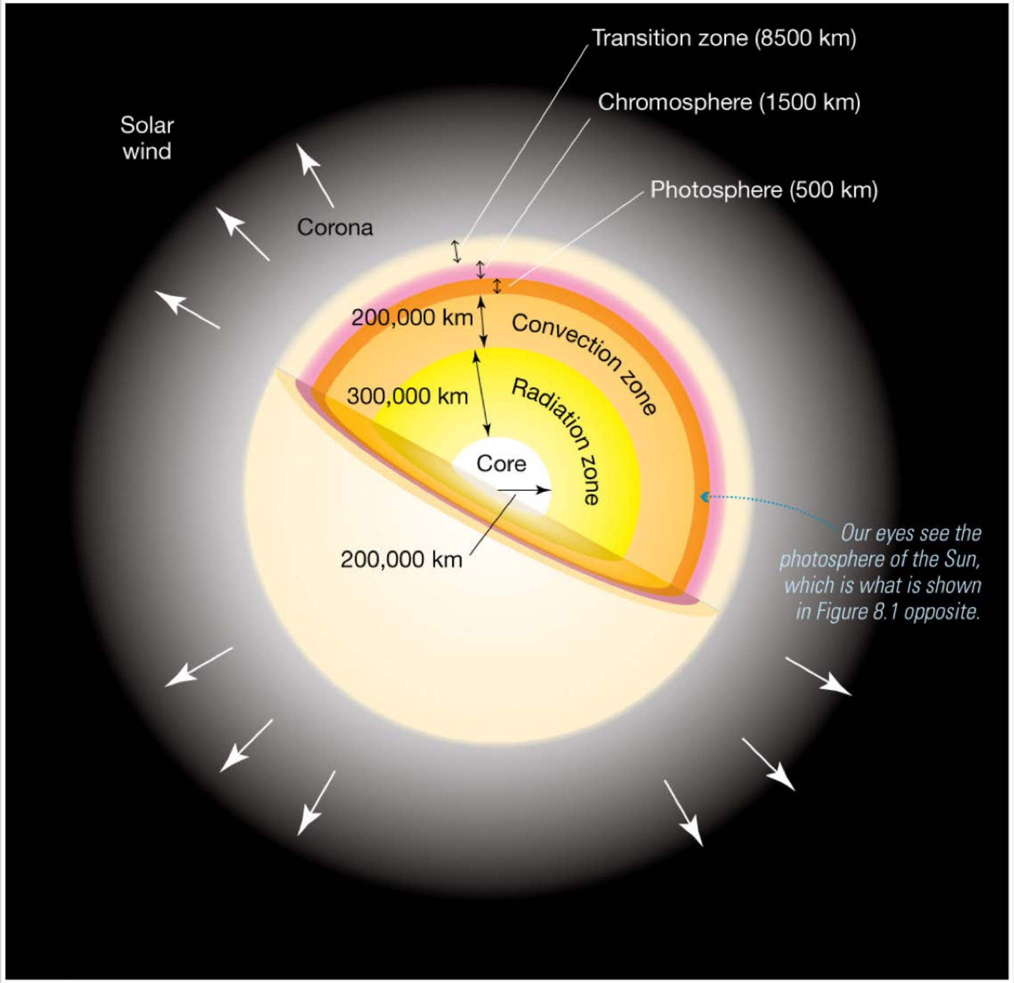
AST 1004

Properties of the Sun



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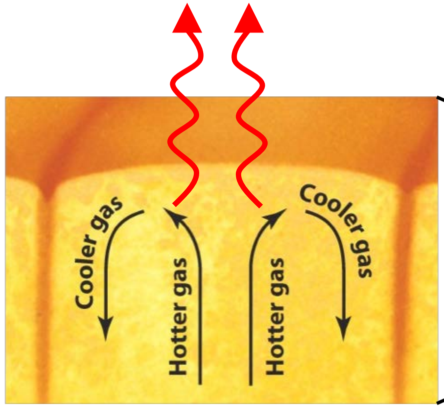
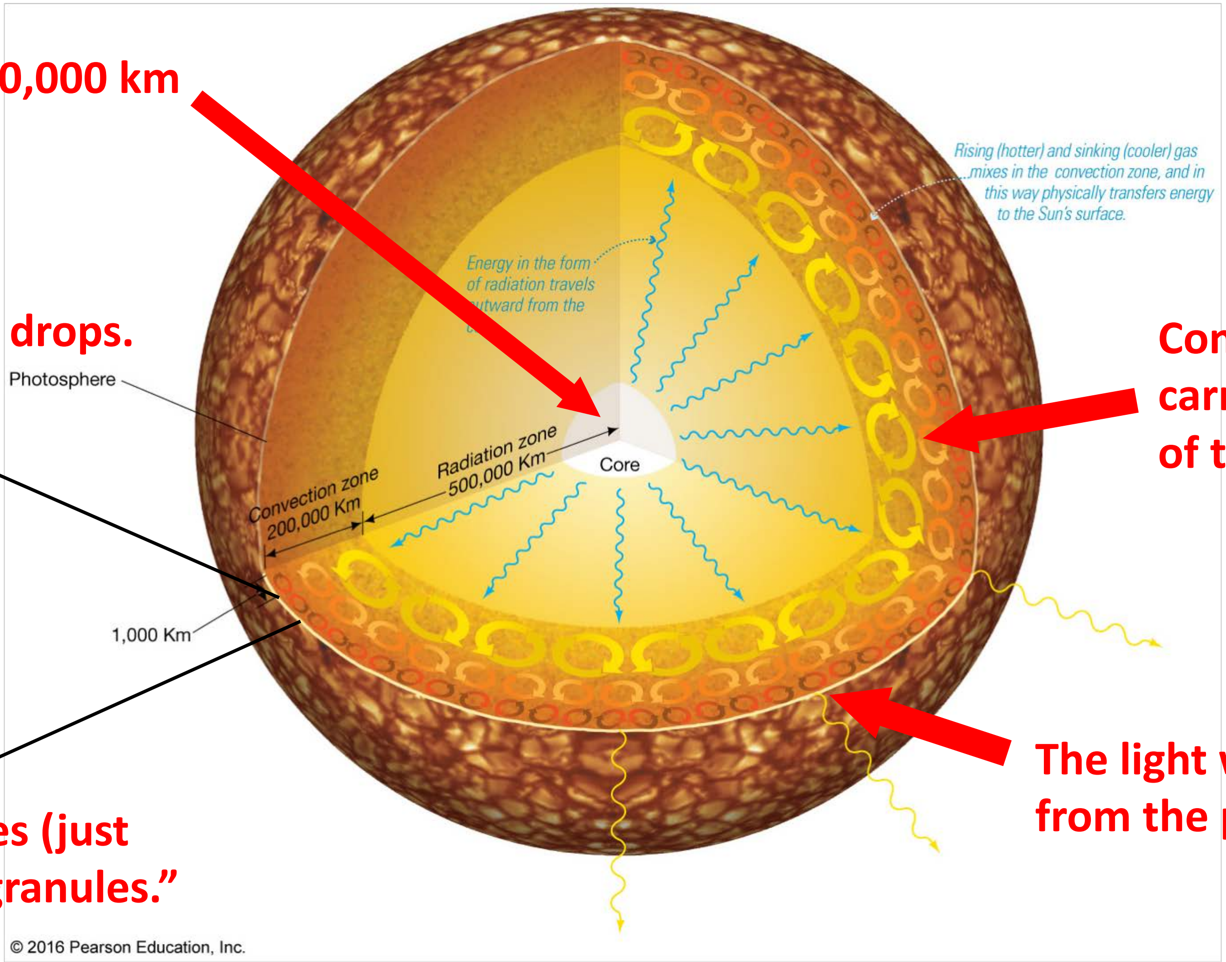
- The Sun is a **star**: a collection of hot gas, mostly hydrogen, which emits light like a blackbody. The Sun is a fairly typical star for our solar system.
- The Sun rotates, but unlike the Earth, it orbits differently between the equator and the poles.
- The Sun has several layers to it:
  - The innermost layer, the **core**, is where the Sun produces its power via nuclear fusion.
  - The **radiation zone**, a transparent gas (one that light can pass through) that allows light to move towards the surface.
  - The **convection zone**, an opaque gas (which light cannot pas through), which moves energy towards the surface via convection currents.
  - The **photosphere**, where the light we see is physically generated.
  - The 3 outer layers – the photosphere, chromosphere, and corona – form the **solar atmosphere**.

Radiation vs. Convection Zones

Core has radius of 200,000 km

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.

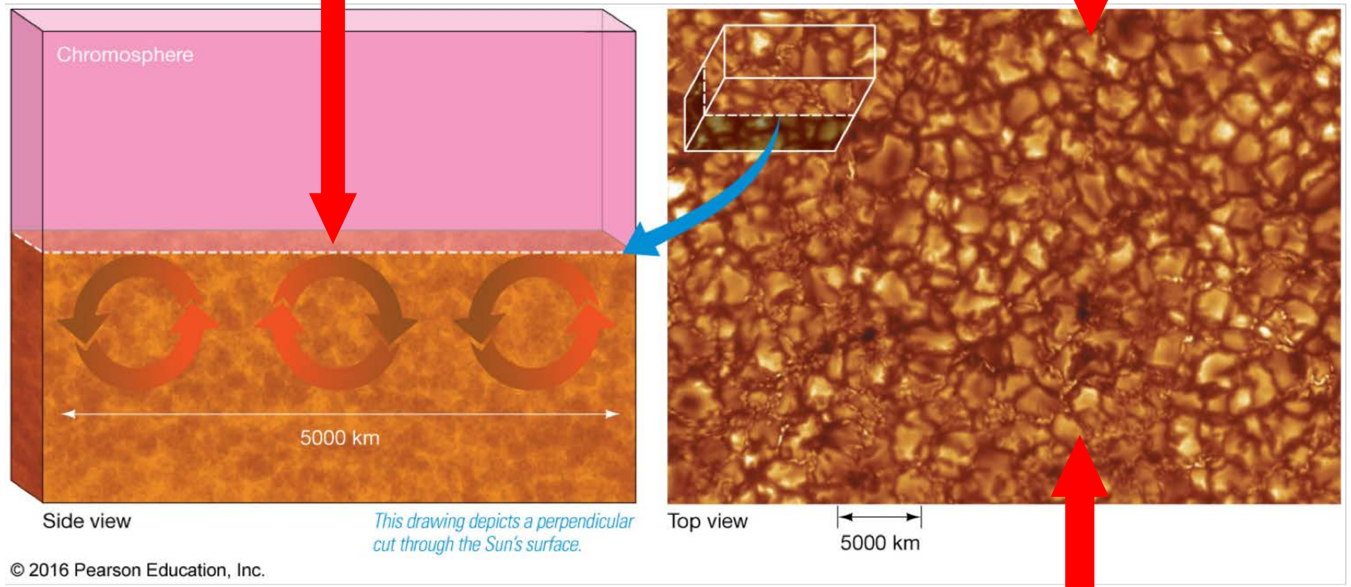
The light we see comes from the photosphere.

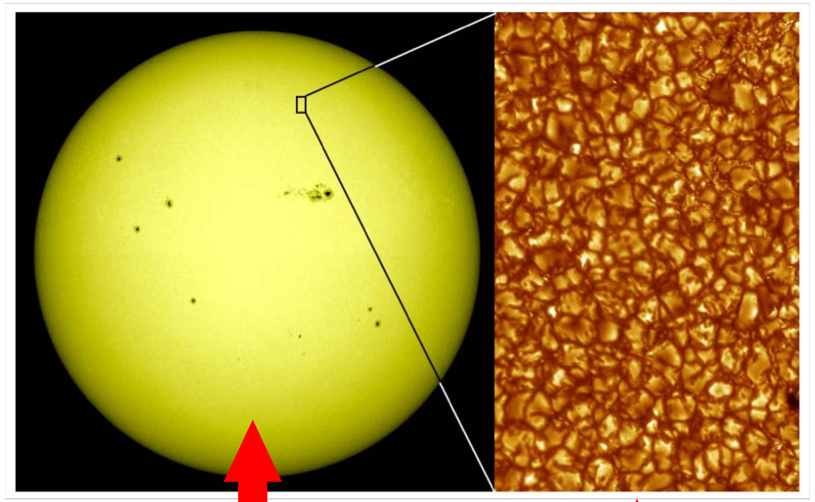
Outer-most convection cycles (just under photosphere) form "granules."

Granules

Bright parts are slightly bluer than dark parts

The boundary is the photosphere.





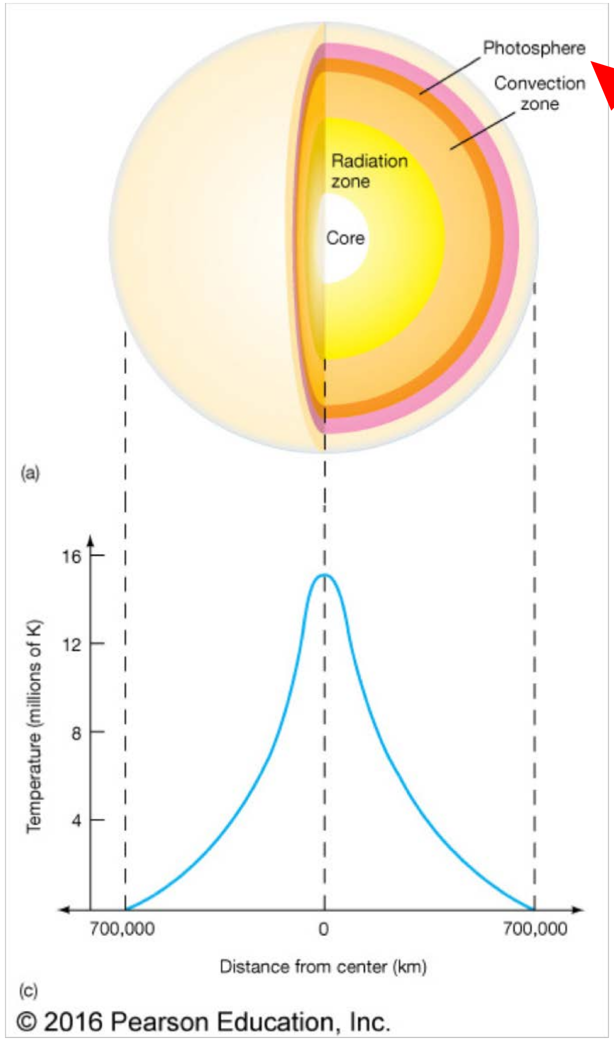
Diameter of the Sun is 1.4 million km

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

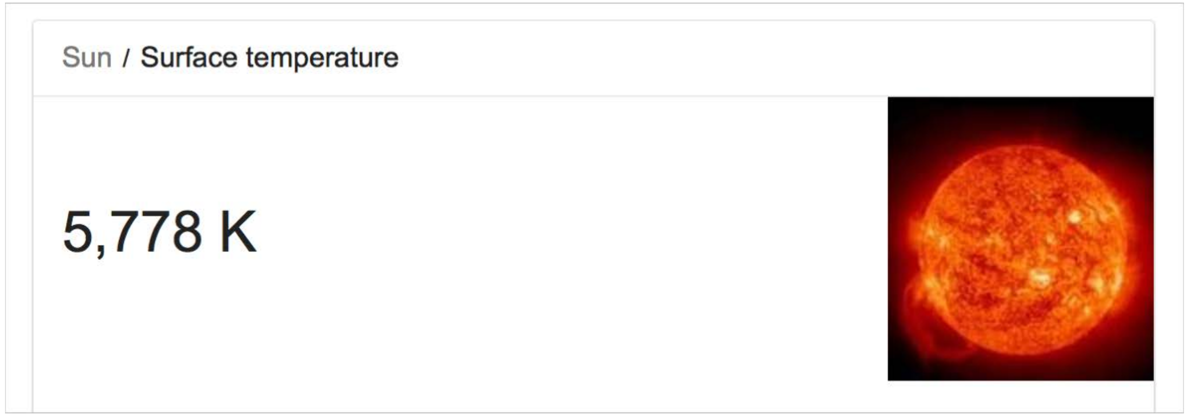
Temperature of the Sun



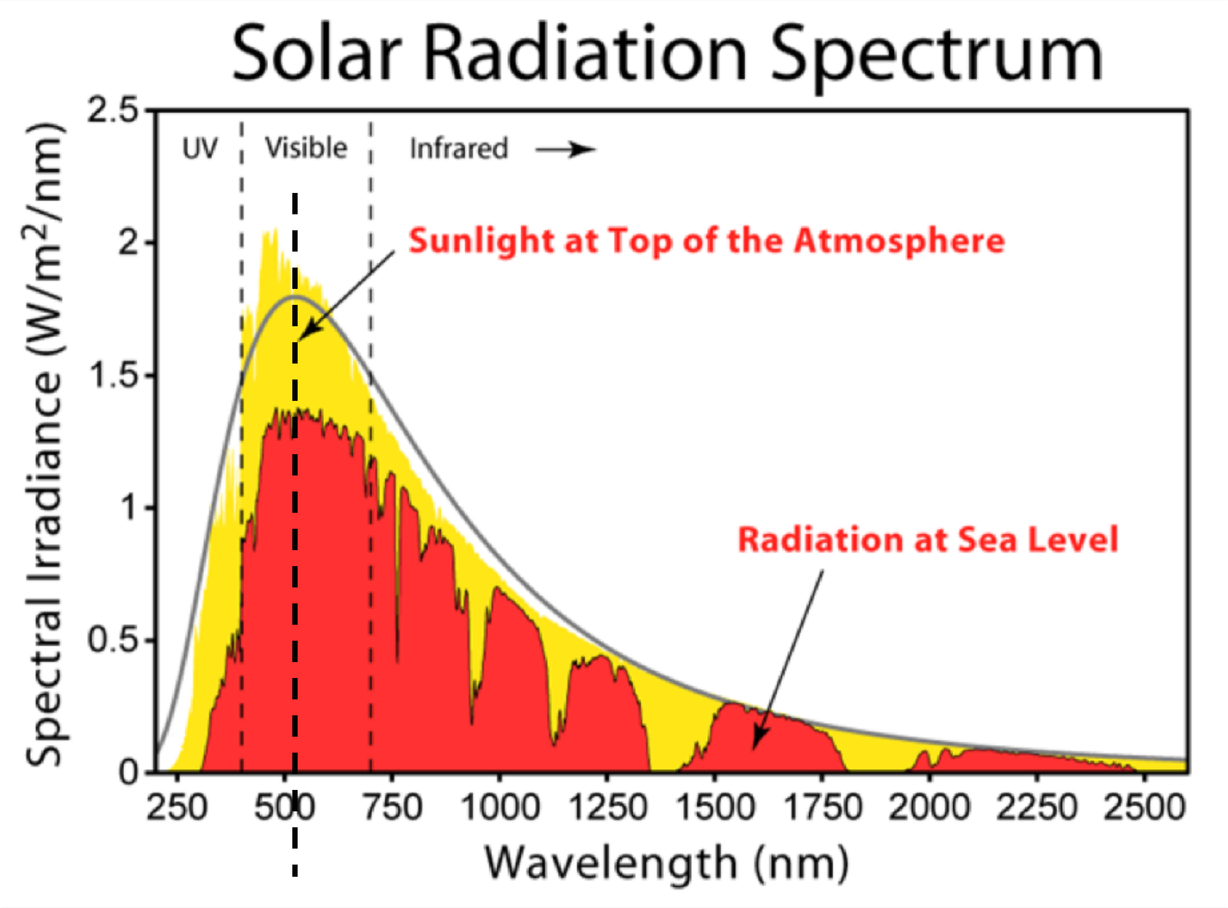
The Sun is a blackbody, so the brightness and color of light we see is determined by temperature.

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.



The Sun as a Blackbody



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

$\boldsymbol{b = 2.9 \times 10^6\ \mathrm{nm \cdot K}}$

Wein's Law:

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

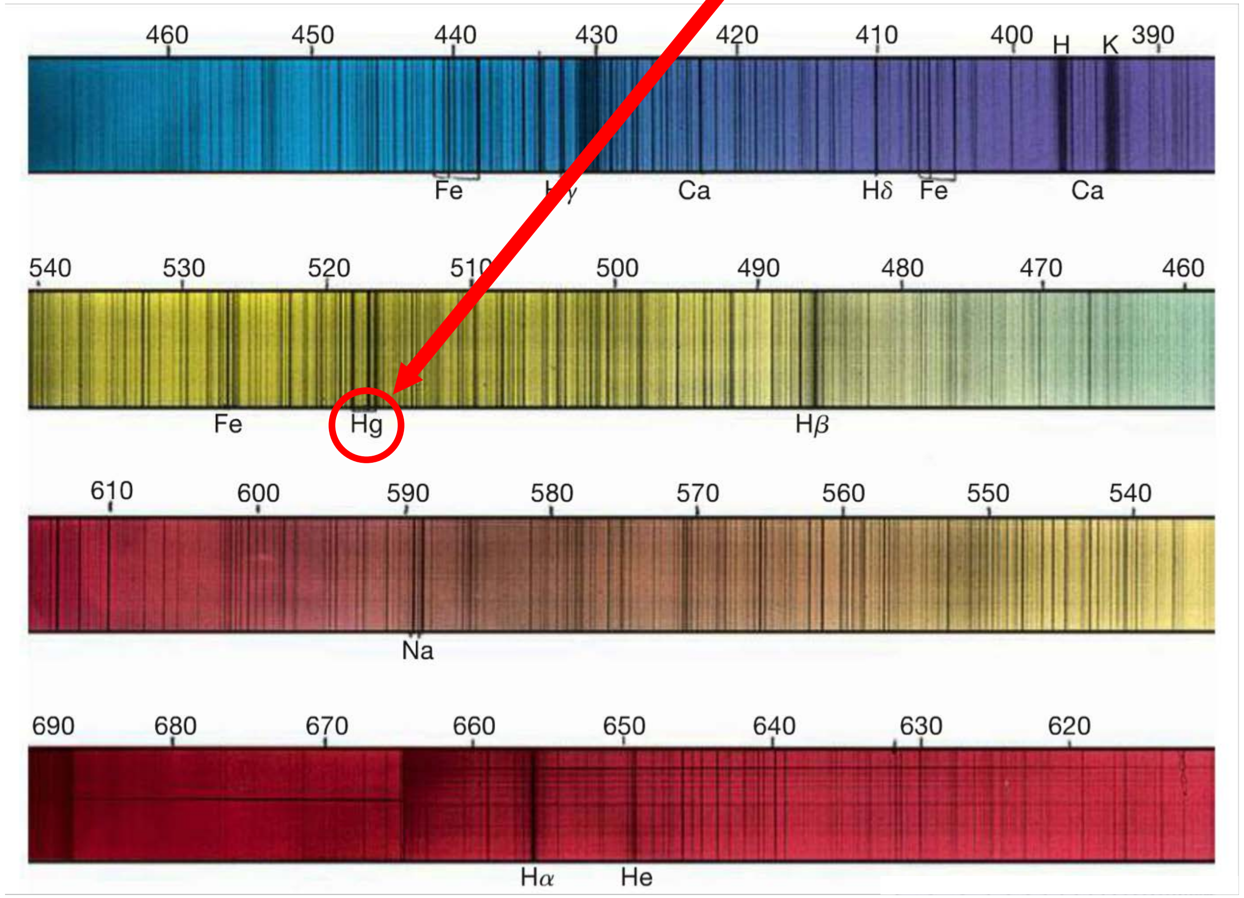
$$T = \frac{b}{\lambda_{\max}} = \boxed{5800\mathrm{K}}$$

Temperature of the blackbody, and therefore temperature of the photosphere, which we call the **surface temperature**.

Chemical Composition of the Sun

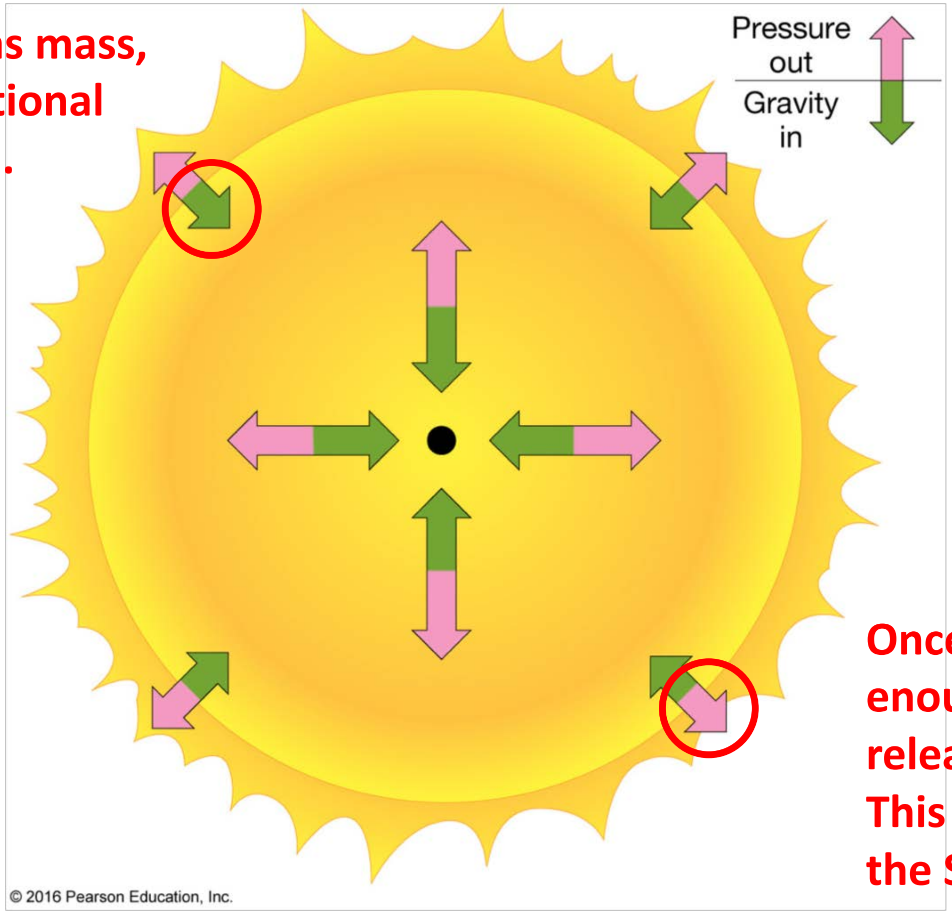
- In the emission spectrum, we can see the signatures of over 60 elements.
- By weight, the Sun is made of:
  - Hydrogen, 71.0%
  - Helium, 27.1%
  - Oxygen, 0.97%
  - Carbon, 0.4%
  - Nitrogen, 0.01%
  - Other elements

Hg is element 60, while Fe is element 26



Equilibrium in the Sun

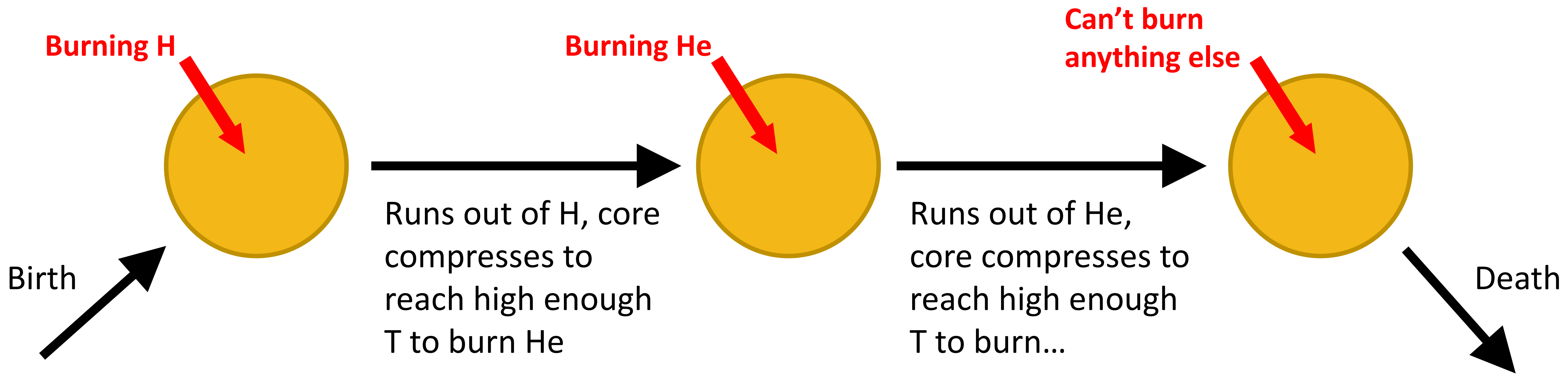
The hydrogen gas in the sun has mass, and all that mass has a gravitational attraction, pulling itself inward.



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.

(Very Basics of) Stellar Evolution

- Evolution is a fight to maintain equilibrium. Whenever the environment within the star changes, it's no longer in equilibrium and has to change to return to equilibrium.
- An important rule to remember: As gas gets pulled closer together – as it gets more dense – the temperature rises.



Mass Controls **all** characteristics

Remnant, as in what's left when the star dies.

Lifetime on the main sequence (i.e. while it's burning hydrogen).

Core temperature.

Stellar Remnant	Evolution Process	Mass	Typical Lifetime	Typical Temperature
Brown Dwarf	It doesn't evolve; it's too cold to ever undergo fusion.	$M < 0.08M_\odot$	100 trillion years	100,000 K
Red/Black Dwarf	Slowly burns all its hydrogen, becoming less and less bright.	$M < 0.5M_\odot$	16 trillion years	600,000 K
White Dwarf	Planetary nebula (gentle) or nova (somewhat violent).	$M < 8M_\odot$	10 billion years	15 million K
Neutron Star	Supernova (violent)	$M < 25M_\odot$	10 million years	85 million K
Black Hole	Supernova (violent) or "hypernova" (extremely violent).	$M > 25M_\odot$	500,000 years	200 million K

Nuclear Fusion (pp Process)

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

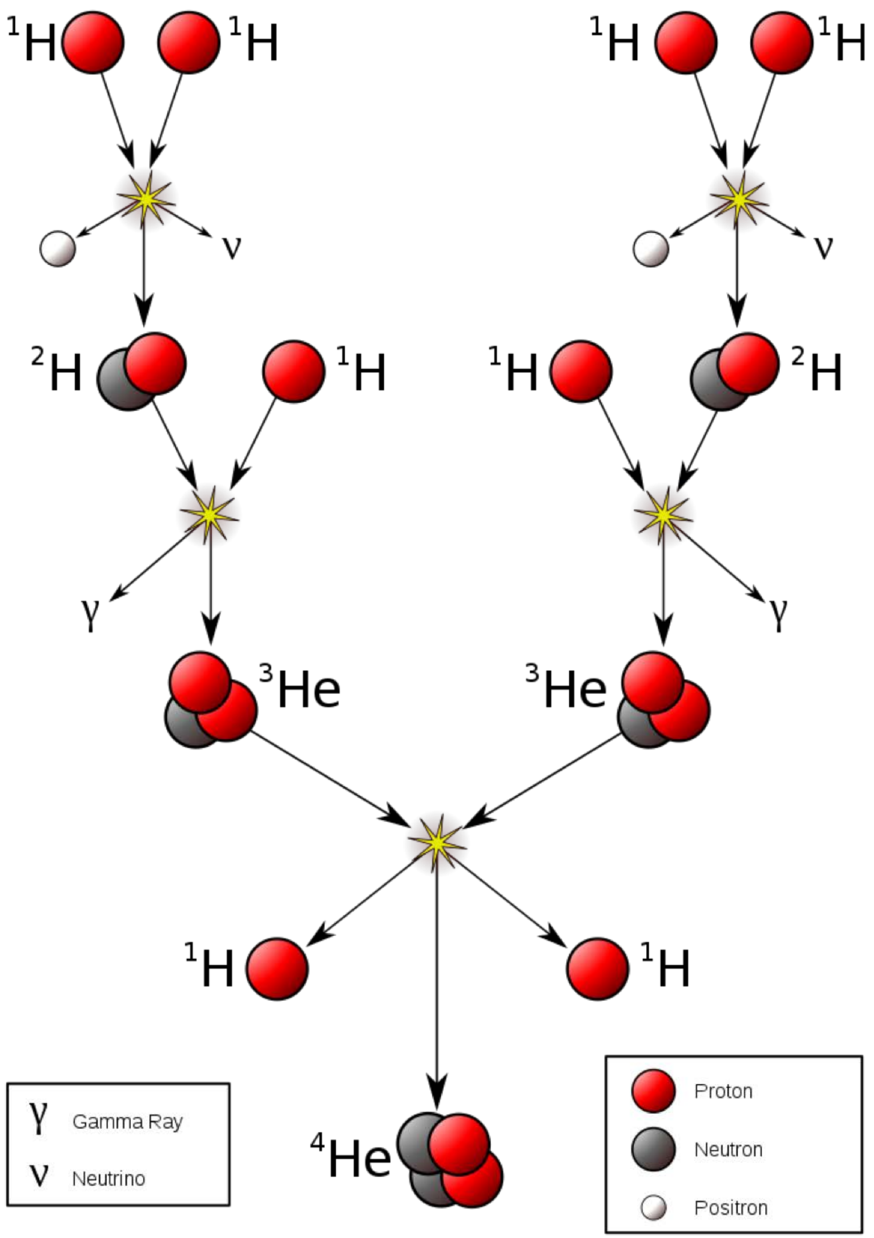
$$^2\text{H} + p^+ \rightarrow {}^3\text{He} + \gamma + \text{energy}$$

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

Overall:

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

pp process occurs when the core temperature is >14 million K



pp Process 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:
$c = 3\times10^8$ m/s

pp Process Calculations (cont'd)

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

Luminosity, L

Reactions per second

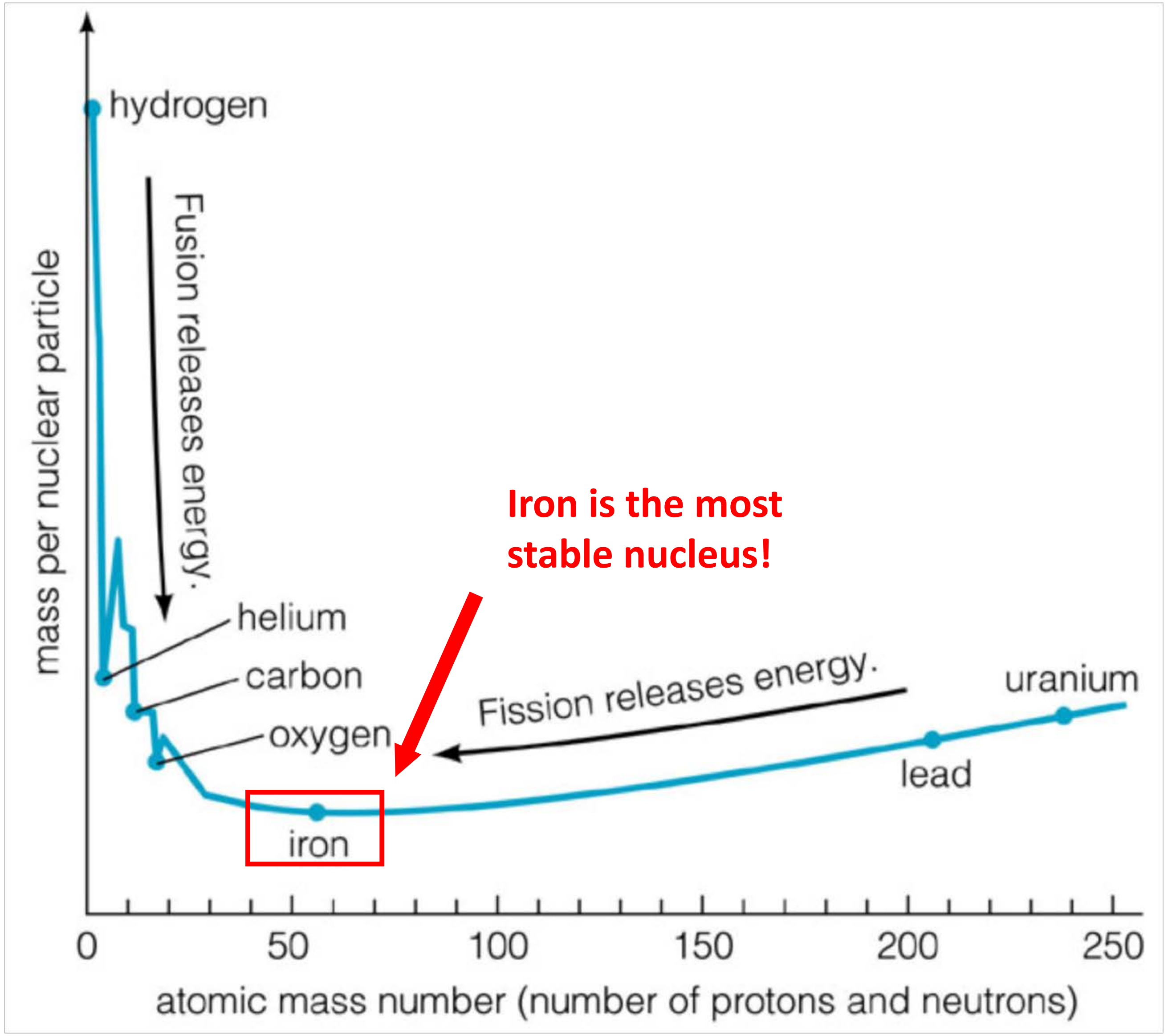
$\boldsymbol{E = 3.994{\times}10^{-12}\,\mathrm{J}}$

$$\frac{\text{Energy}}{\text{second}} = N * E \Longrightarrow N = \frac{E}{\text{L}} = 9.58{\times}10^{37}\text{ reactions per second}$$

$\boldsymbol{L_\odot = 3.83{\times}10^{26}\,\mathrm{J/s}}$

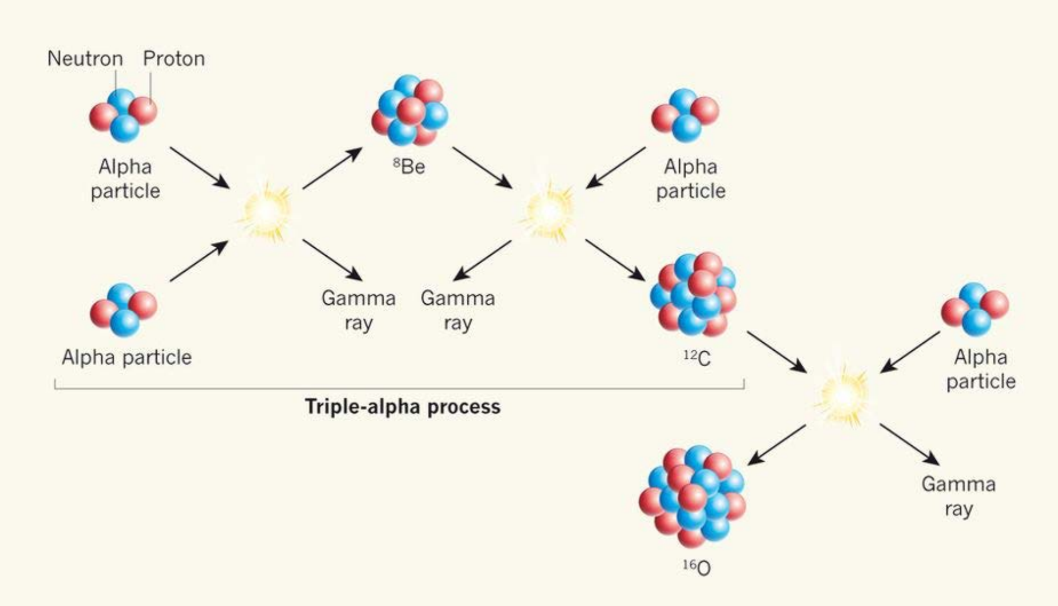
Fission vs. Fusion

- Fusion will occur in the core of stars, if they have a high enough mass, until they produce **iron**.
- Iron is the most stable nucleus, so there is no energetically *favorable* reaction to produce elements heavier than iron.
  - **Energetically favorable** means a process releases energy.
  - There are **energetically unfavorable** processes, which require energy, and these lead to the production of heavier elements like lead that we see on Earth.

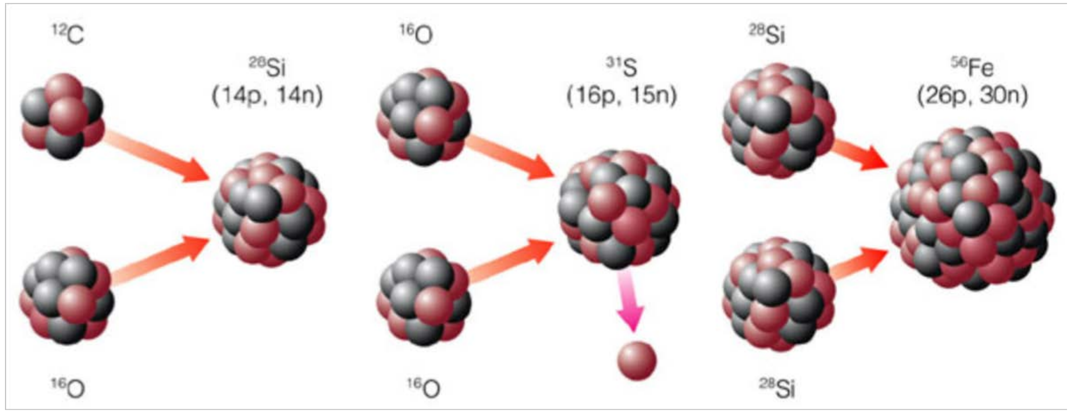


Burning Heavier Elements

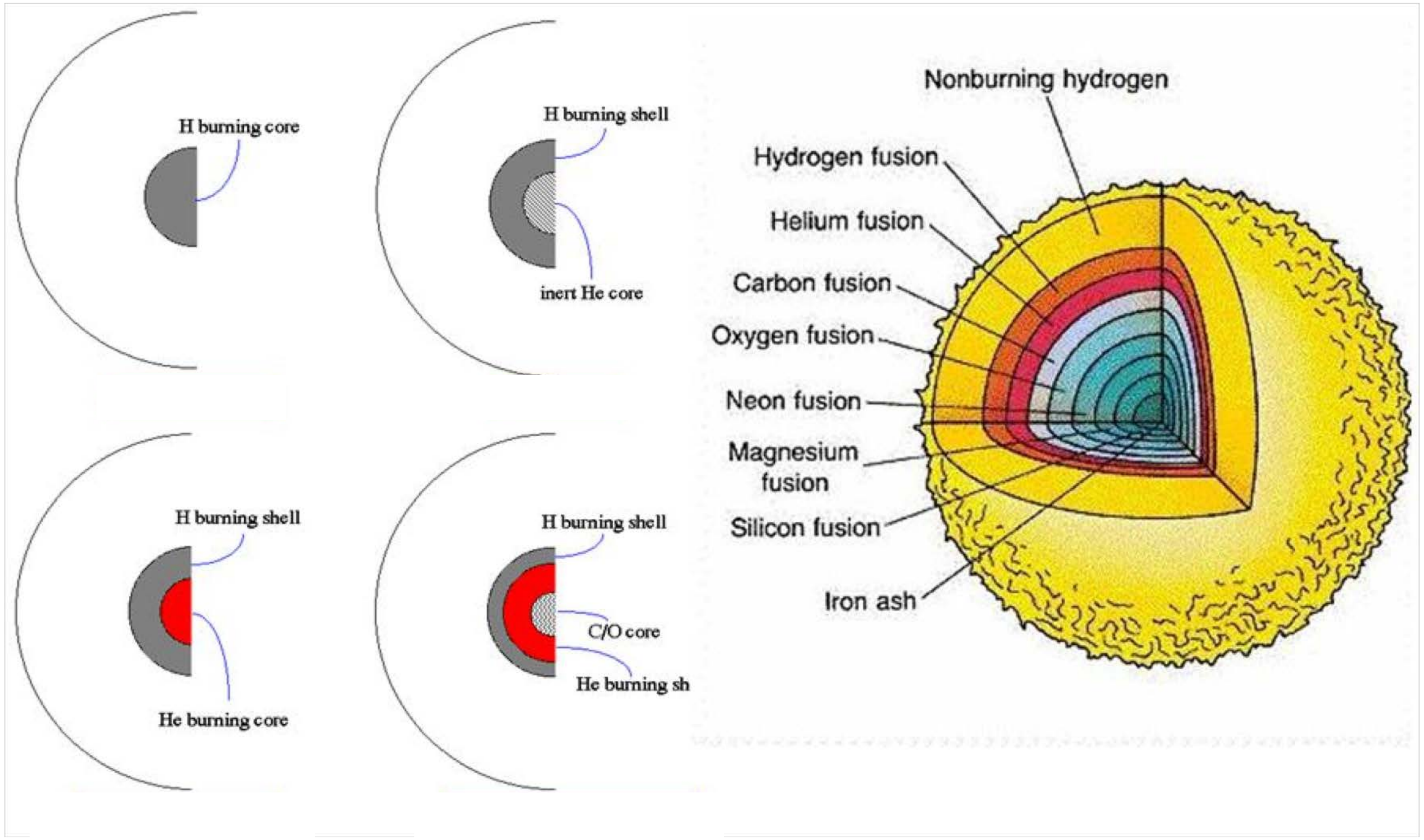
Triple-α process, burns He into C. Secondary process burns C into O. Requires a temperature > 100 million K.



Other processes burn C+O into Si (**oxygen burning**), requiring temperatures > 1.5 billion K, and Si into Ni **(silicon burning),** which decays into Fe, requiring temperatures > 3 billion K.

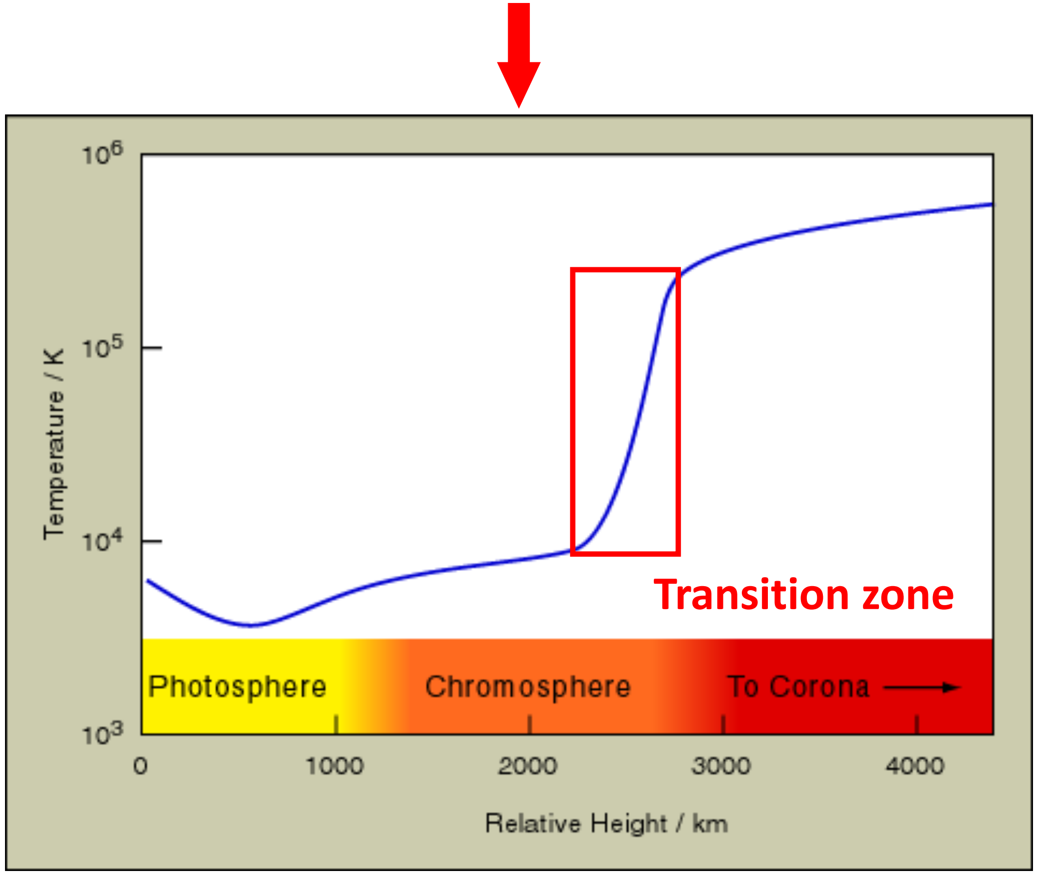


Summary of Evolution of Stellar Core



Solar Atmosphere

Atmosphere contradicts temperature trend



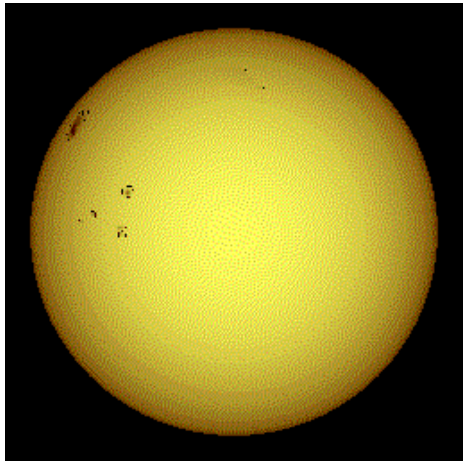
2nd Law of Thermodynamics:

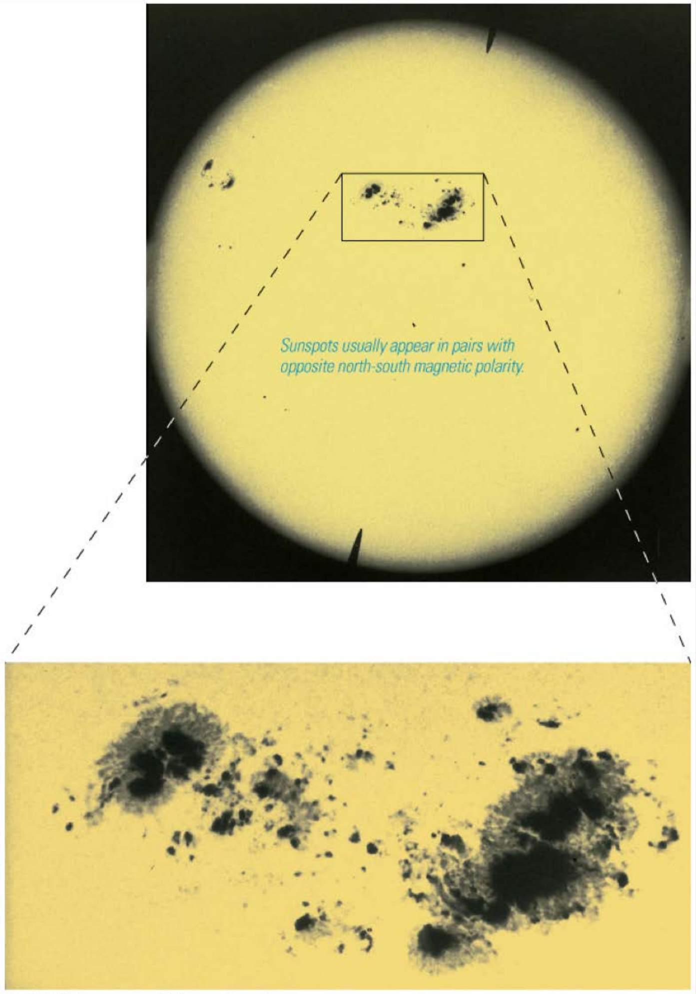
Heat flows from hot to cold, never from cold to hot.

Coronal heating problem!

Possible solution: magnetic recombination

Sunspots





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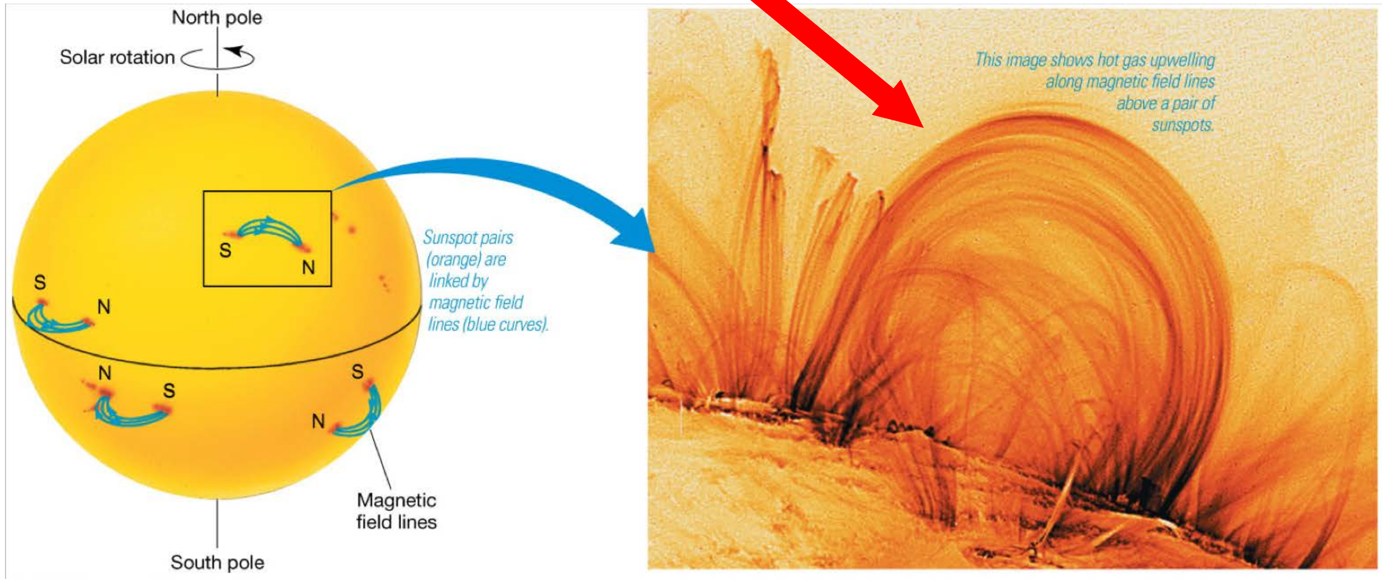
These looping magnetic fields are known as "prominences"



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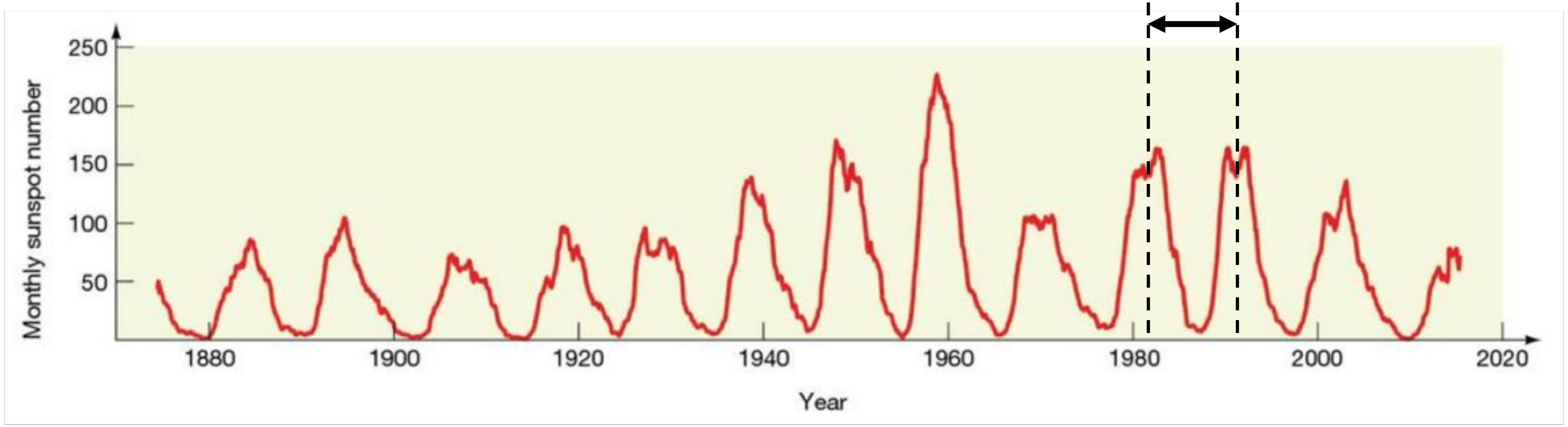
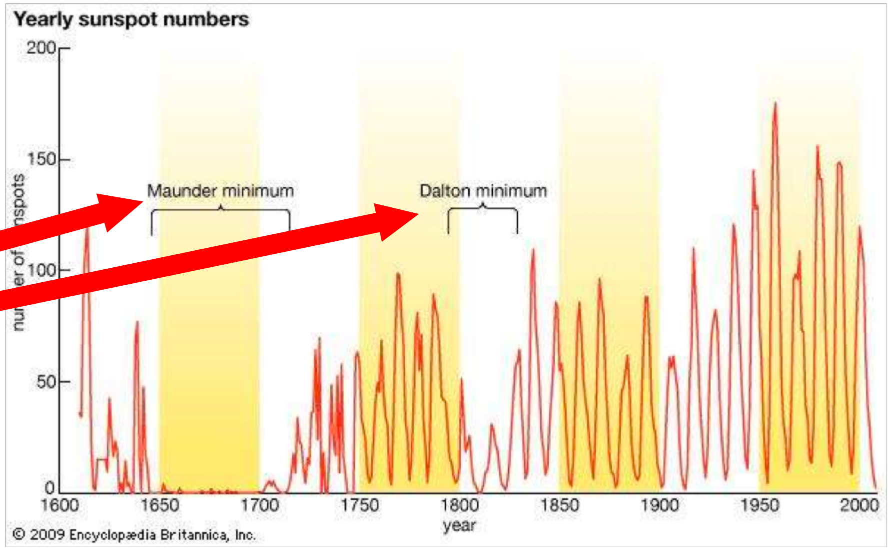
Sunspot Frequency is Periodic

Period $T = 11$ years

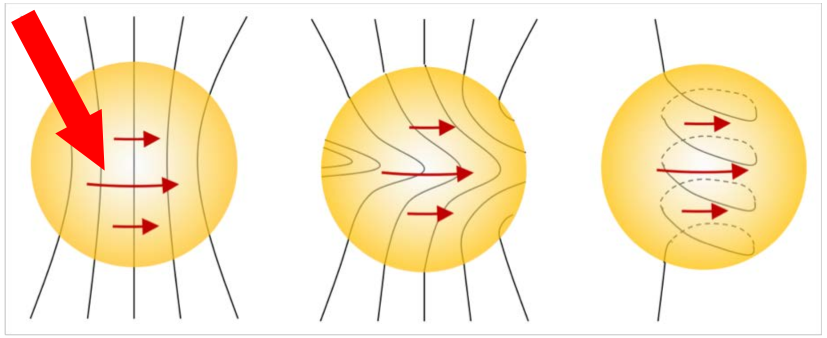


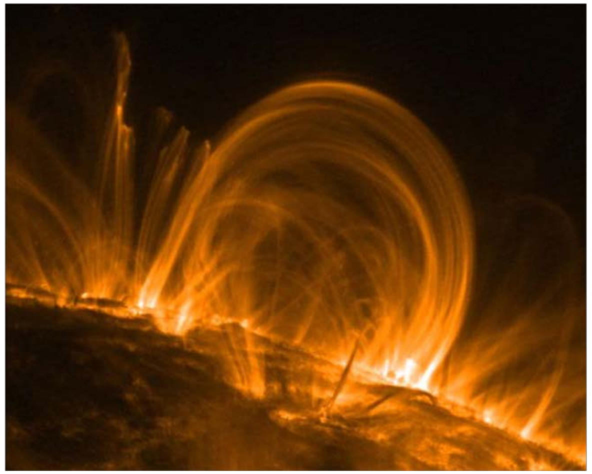
Periods of unusually low sunspot activity are called “minima”

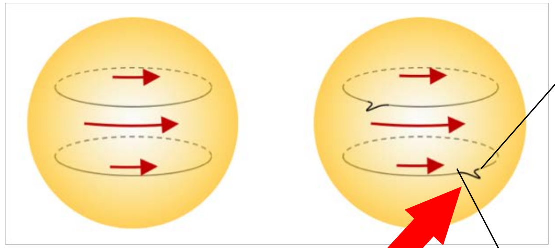


Magnetic Reconnection

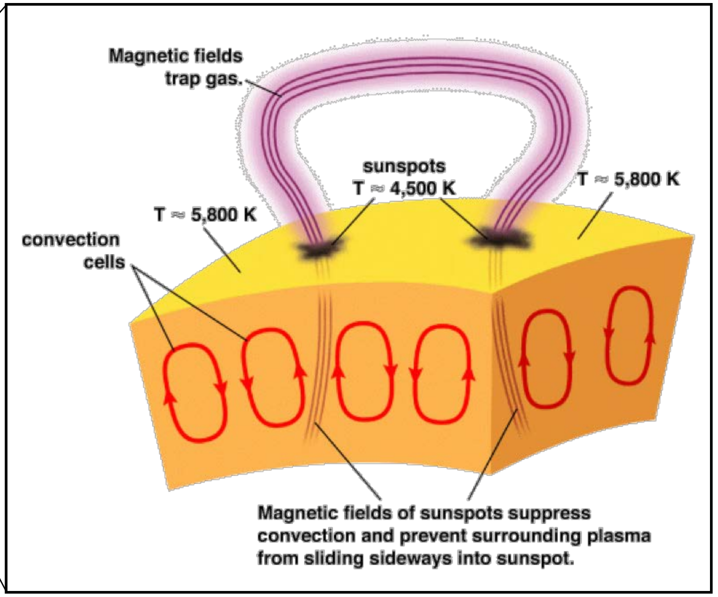
Equator rotates faster than poles



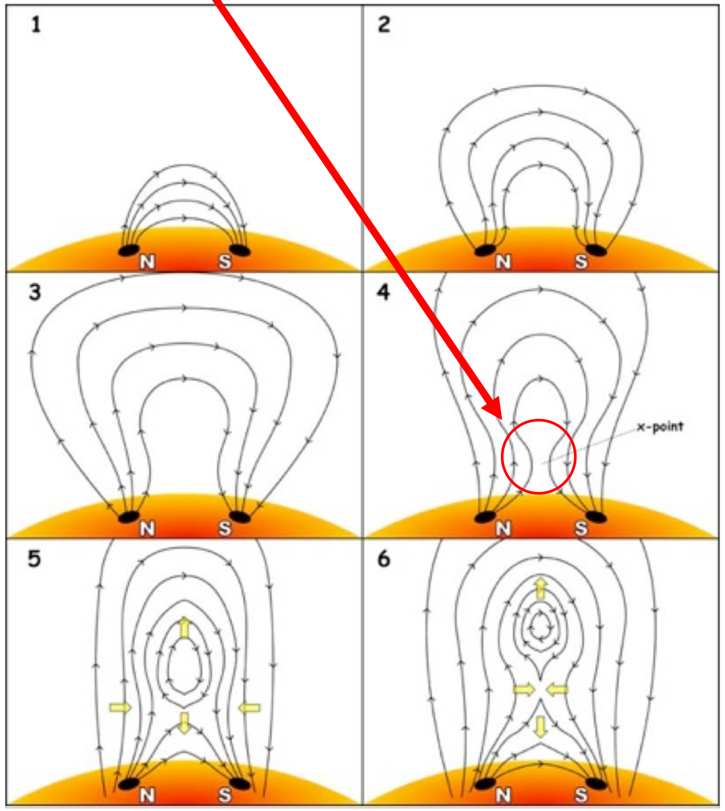




Magnetic loops develop kinks that poke out of Sun's surface

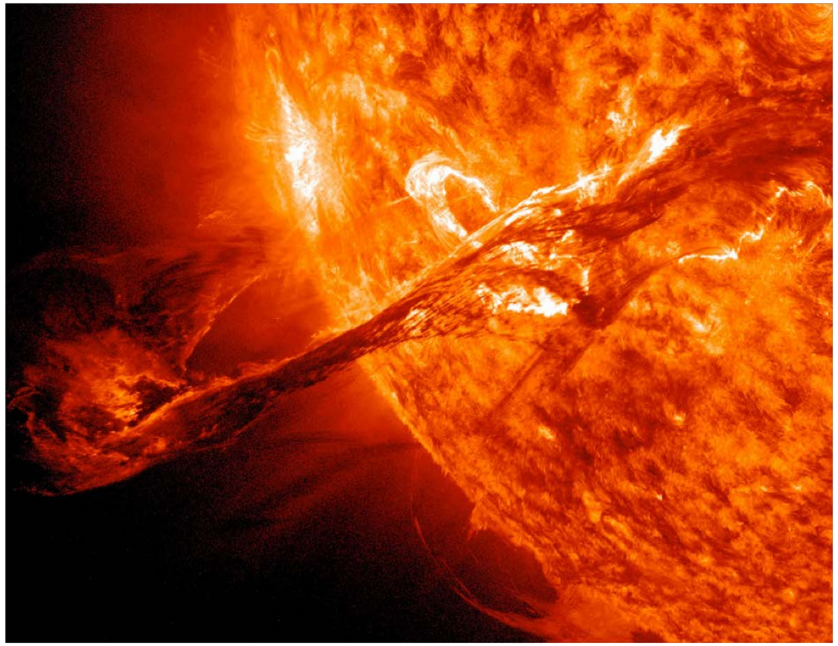


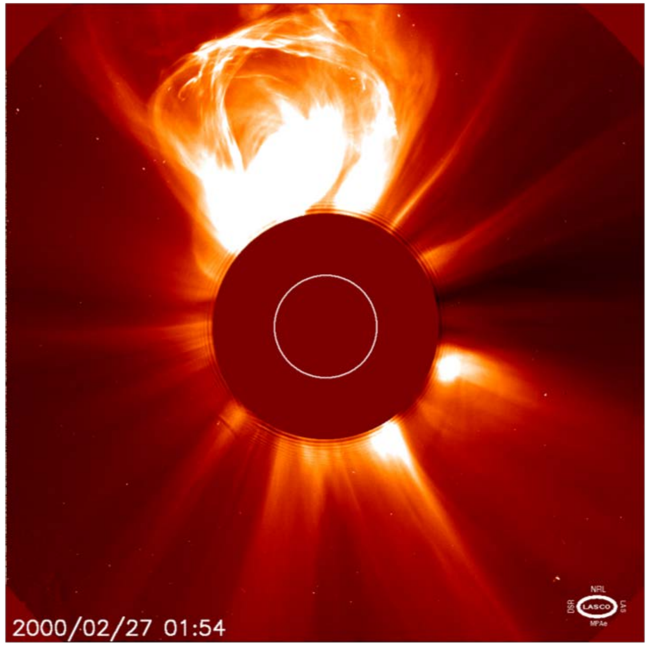
Reconnection point



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

Solar Flares vs. Coronal Mass Ejections



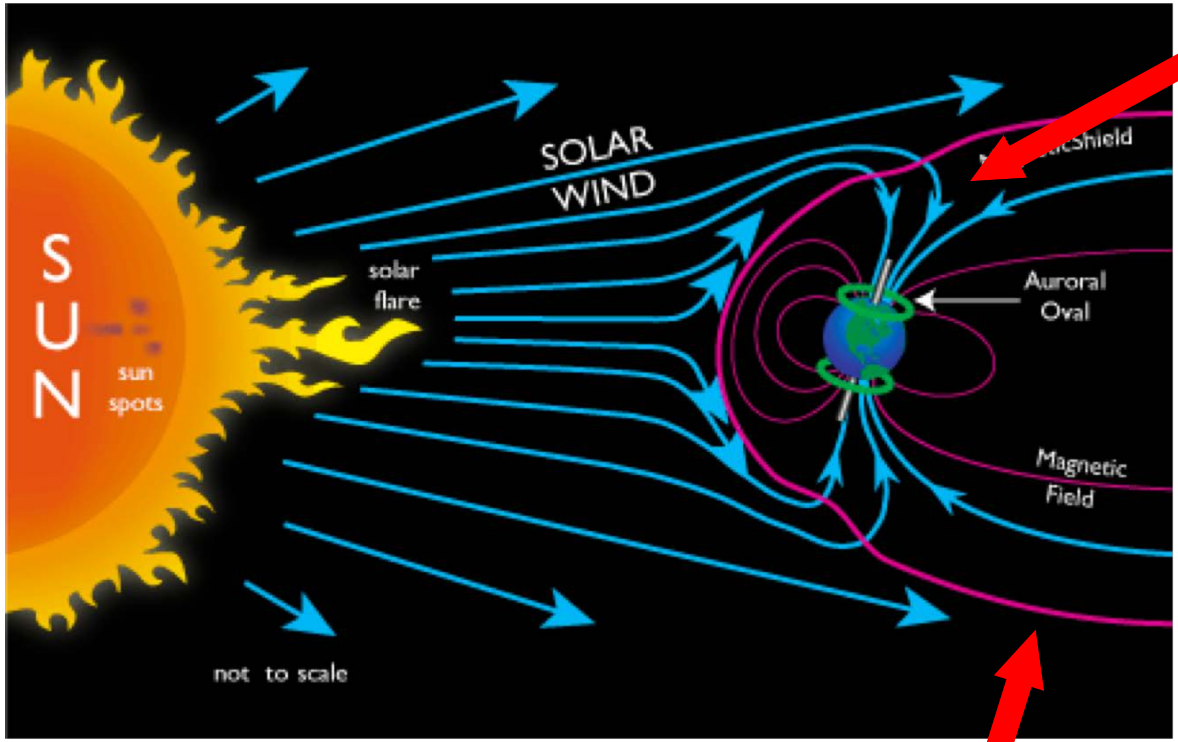


In a solar flare, prominence is still trapped by Sun's magnetic field

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

Magnetosphere and Aurora



The magnetic field lines guide the charged particles in the solar wind to the poles, creating the Auroras.

Charged particles from solar wind collide with particles in the atmosphere, creating the light seen in the Auroras.

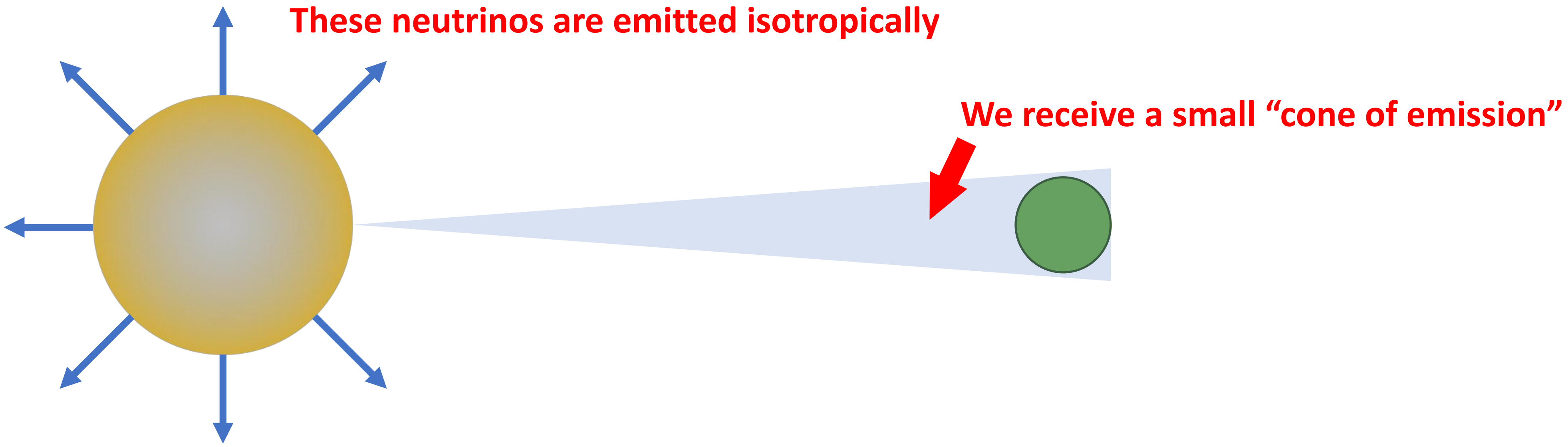
Earth's magnetic field creates a "magnetosphere," which protects us from solar radiation, called solar wind.

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.