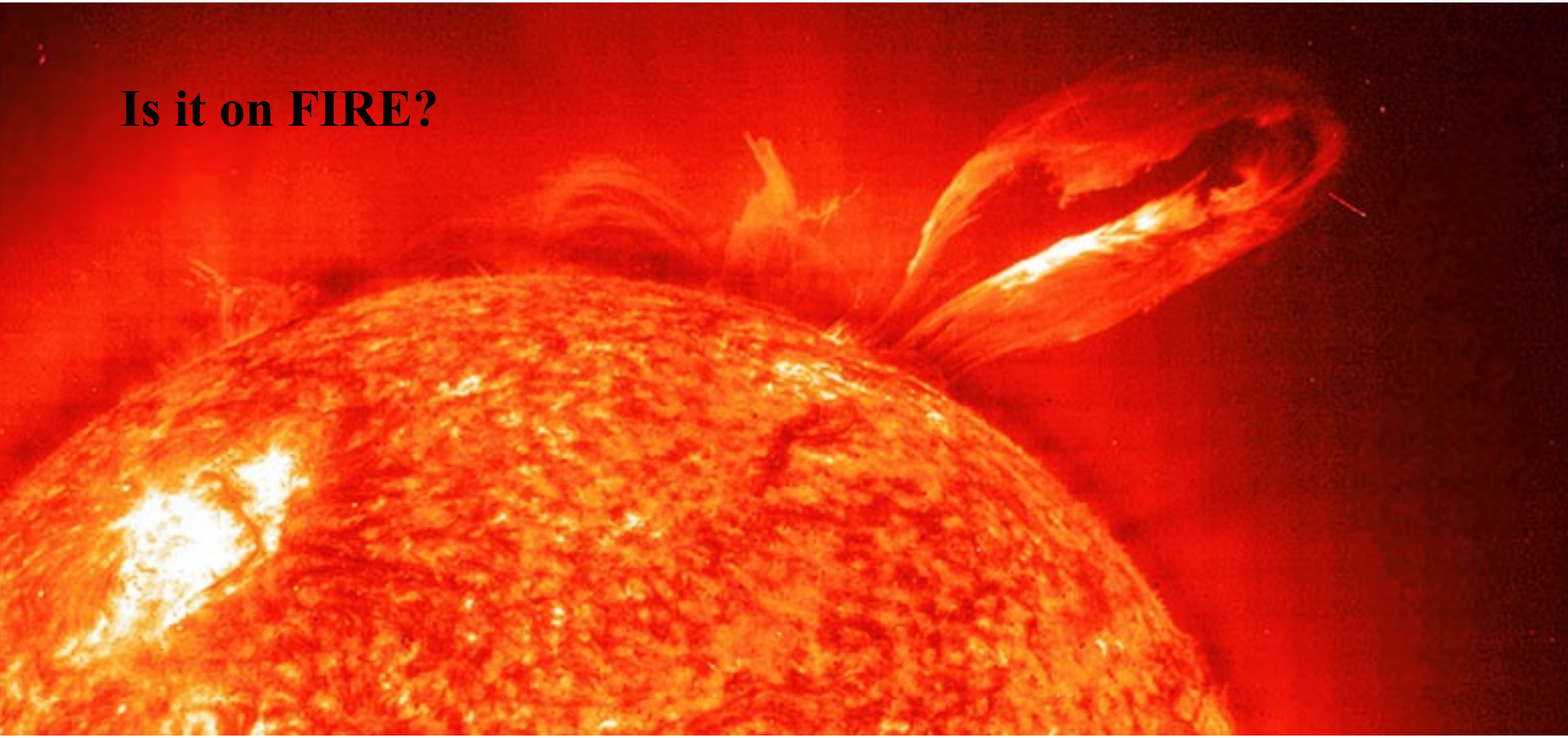
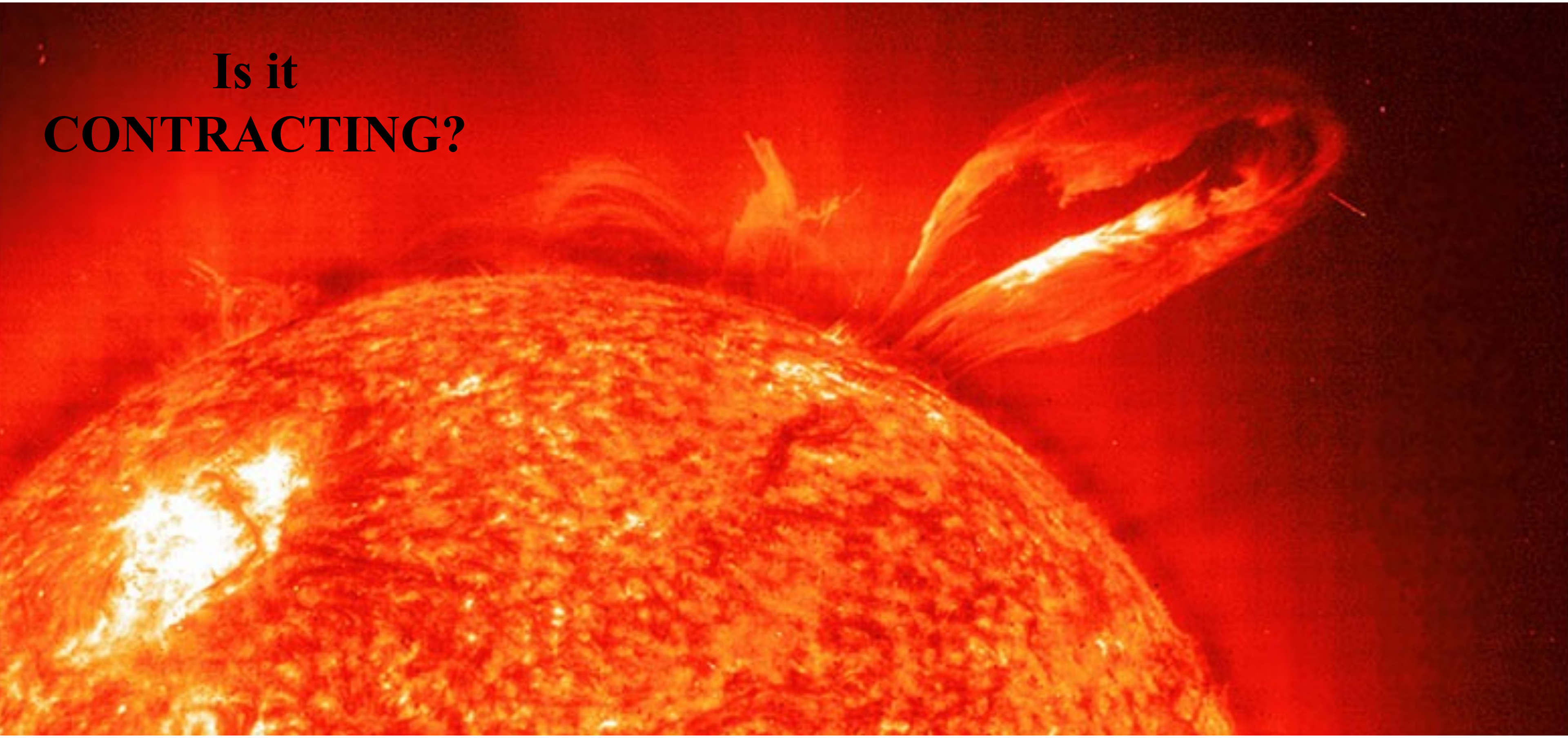
Lecture 13
Our Star, The Sun

Why does the Sun shine?



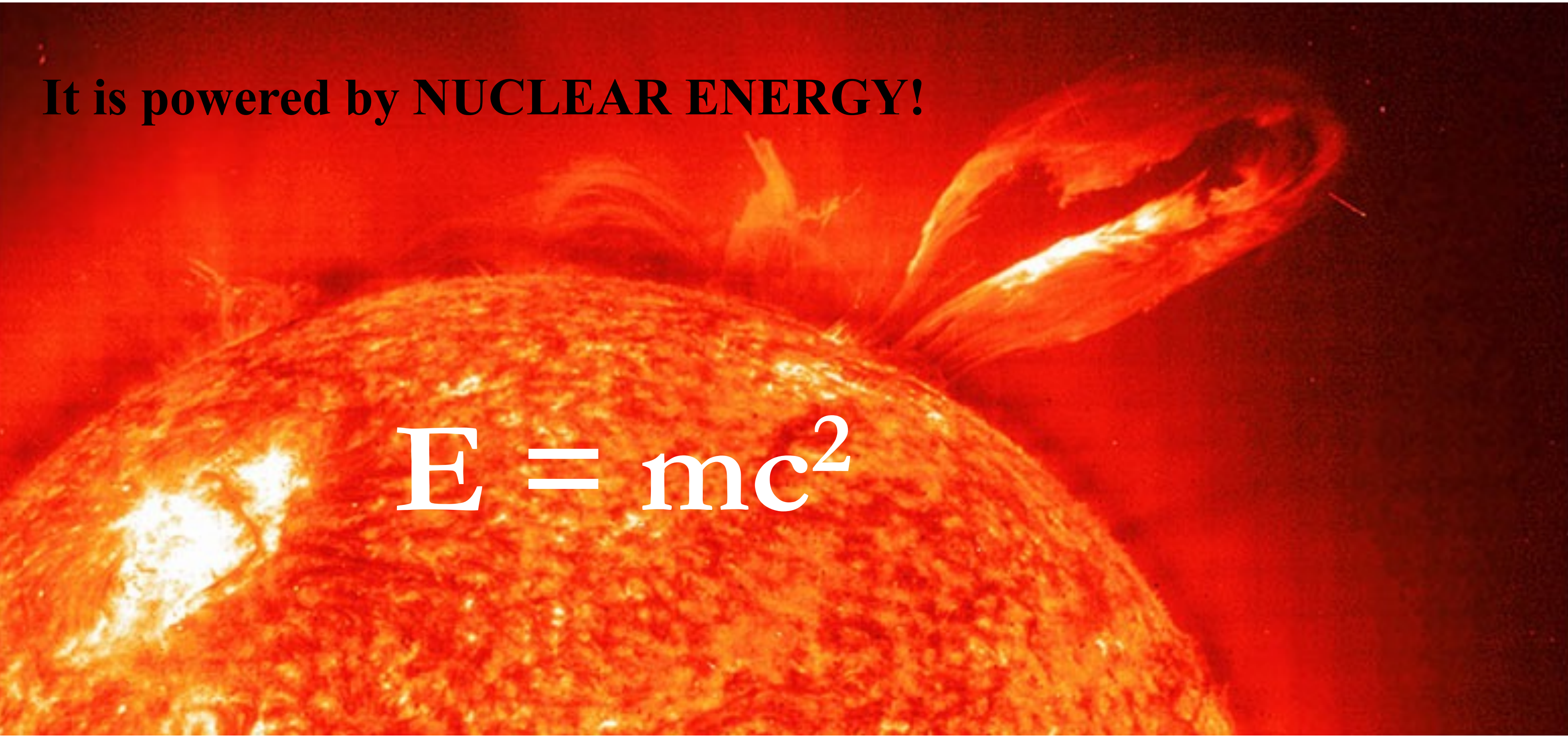
$$\frac{\text{Chemical Energy Content}}{\text{Luminosity}} \sim 10{,}000 \text{ years}$$

Why does the Sun shine?



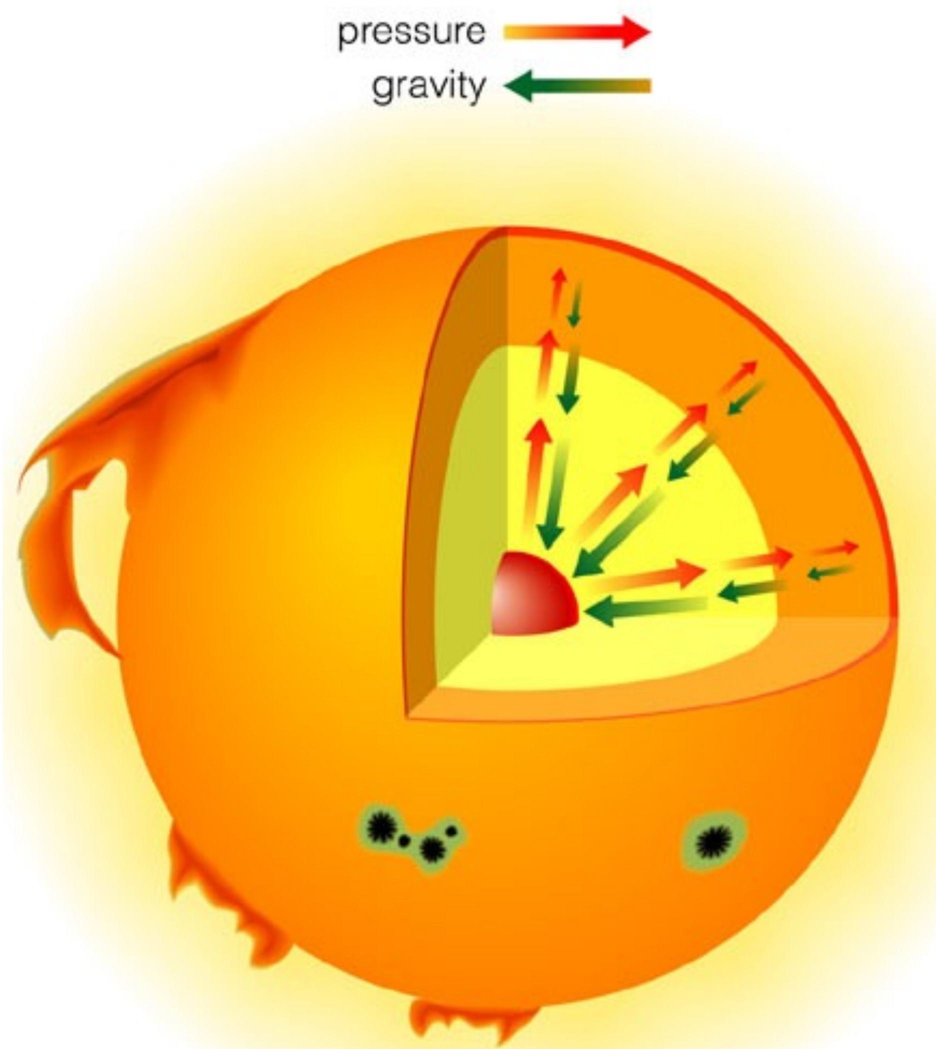
$$\frac{\text{Gravitational Potential Energy}}{\text{Luminosity}} \sim \text{25 million years}$$

Why does the Sun shine?



$$\frac{\text{Nuclear Potential Energy (core)}}{\text{Luminosity}} \sim 10 \textit{ billion} \text{ years}$$

The Sun is in *gravitational equilibrium:*

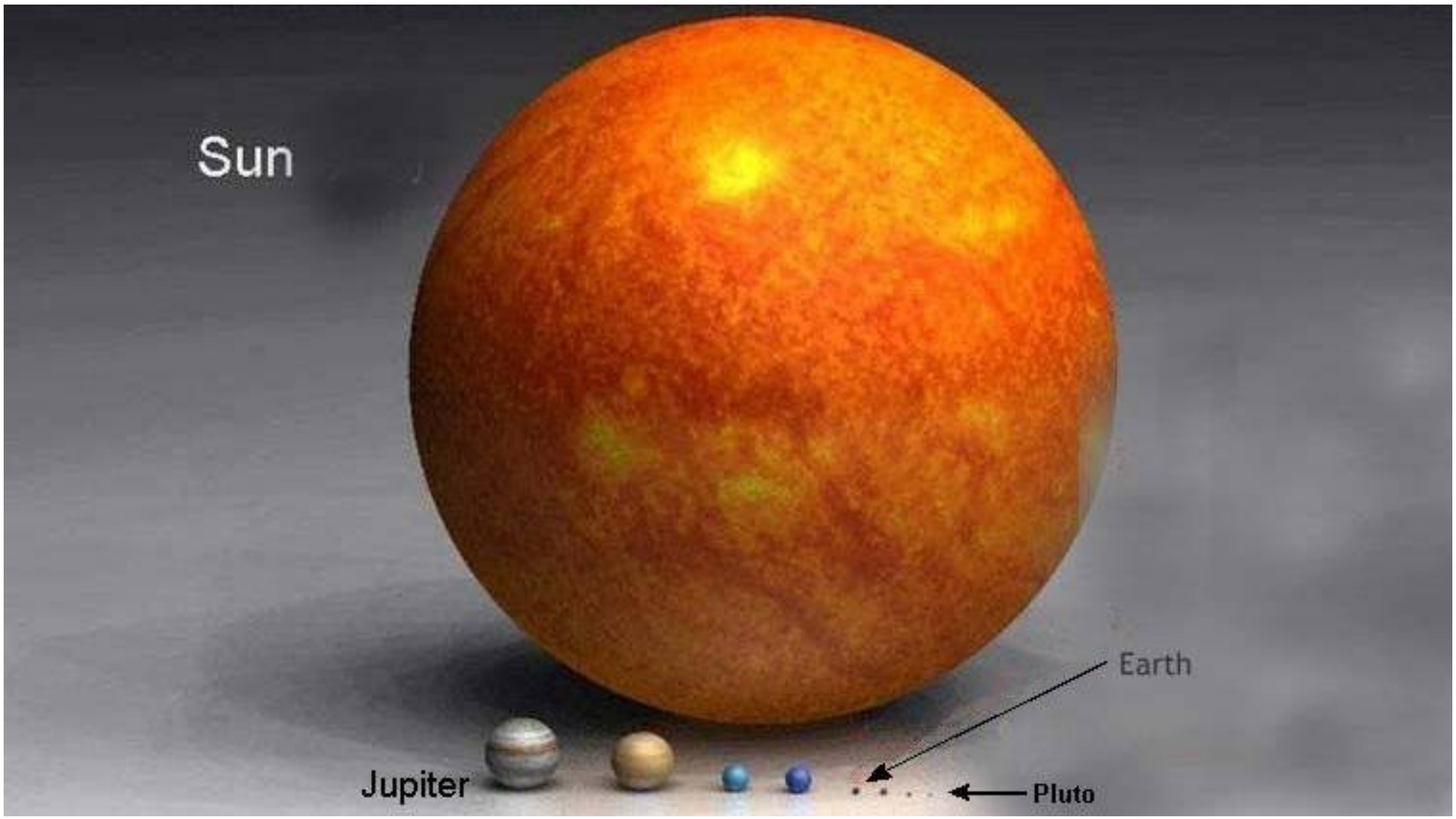


- The Sun's immense gravity tries to contract it
- Energy from fusion provides the outward pressure to counterbalance gravity.

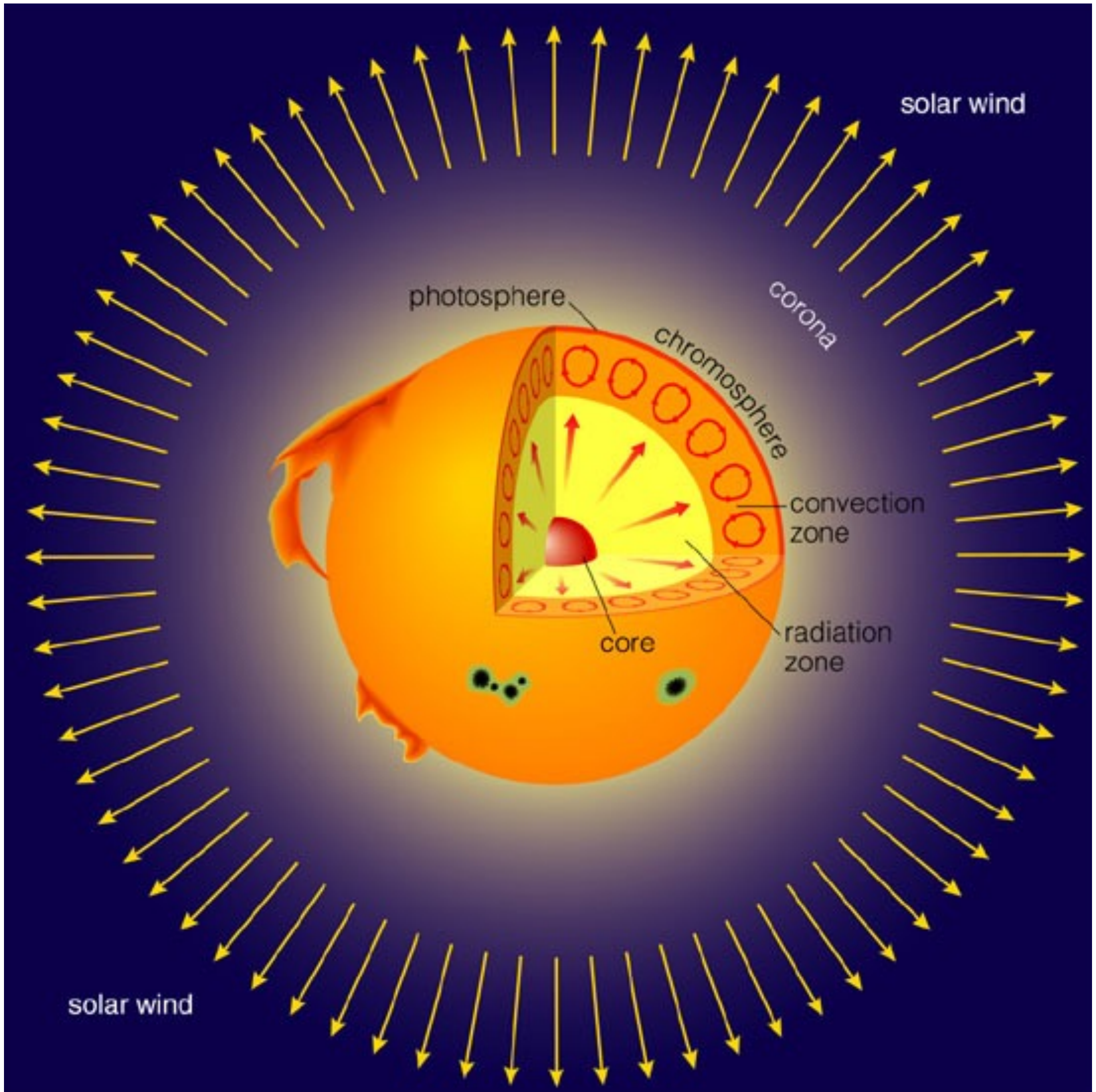
How big is the Sun?

Radius: 6.9×10^5 km ***Mass:*** 2×10^{30} kg ***Luminosity:*** 3.8×10^{26} watts

(109 times Earth) (330,000 Earths)



What is the Sun's internal structure?

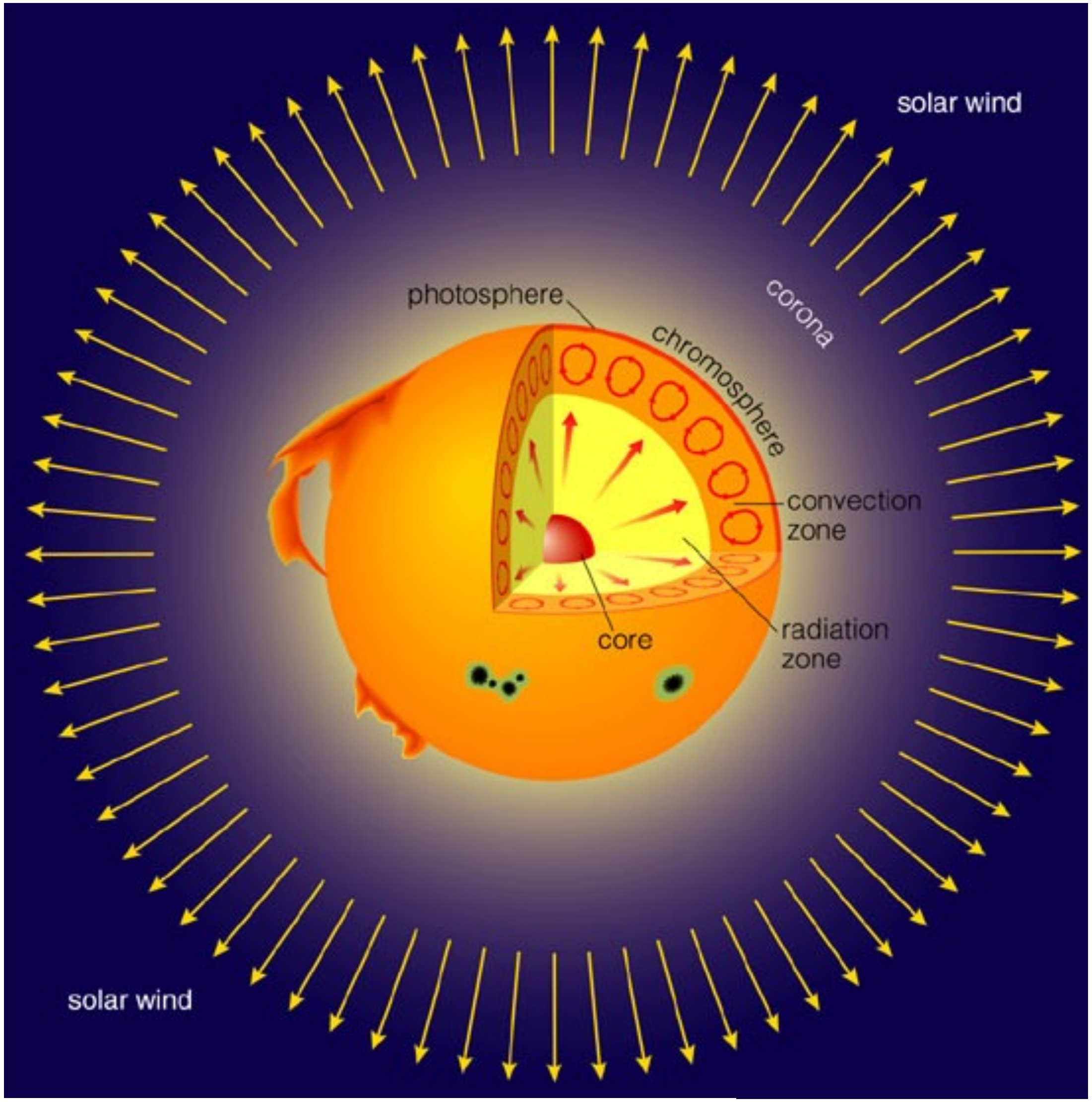


Core:

Energy generated by nuclear fusion

T ~ 15 million K

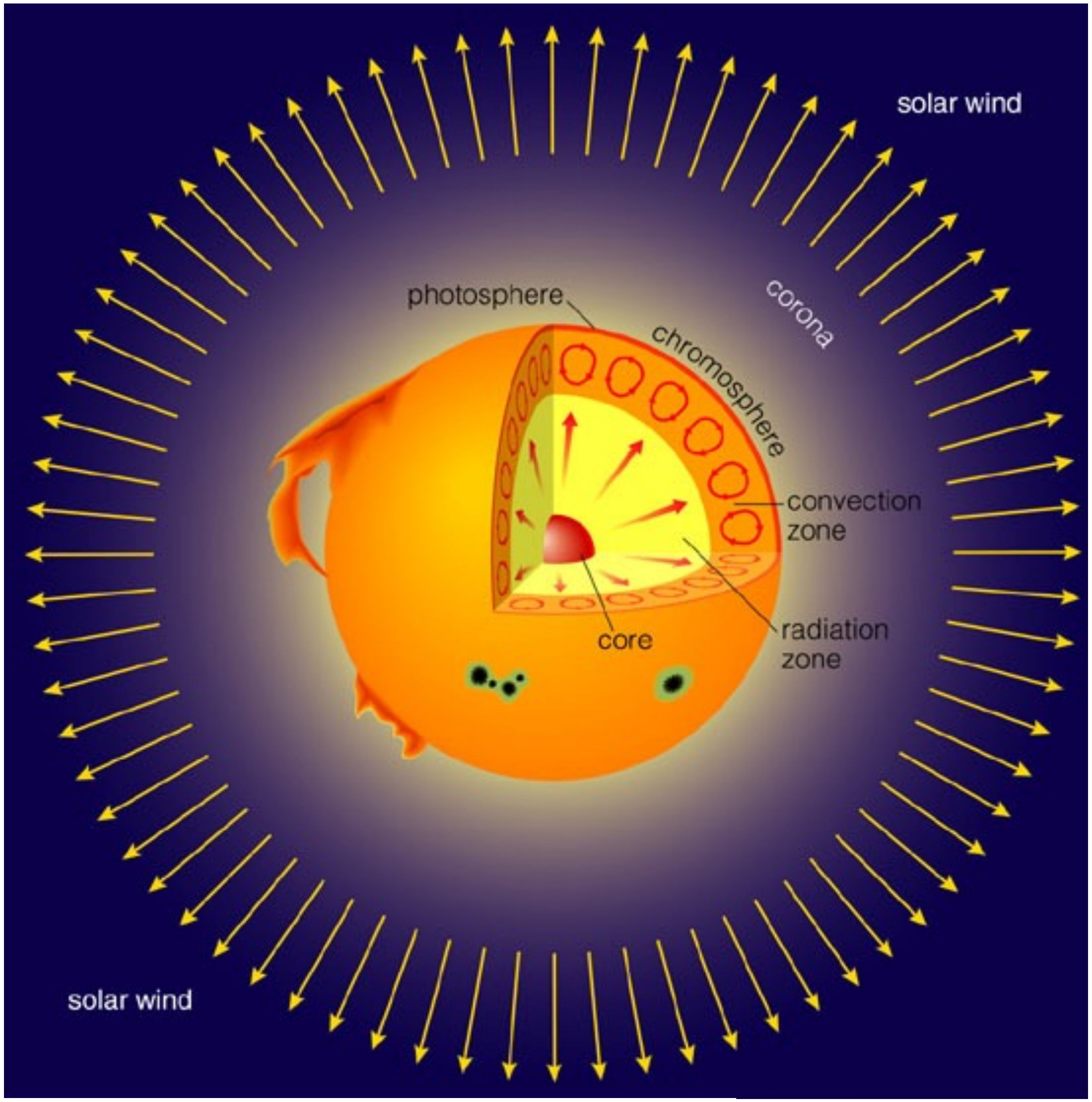
What is the Sun's internal structure?



Radiation zone:

Energy transported upward by photons

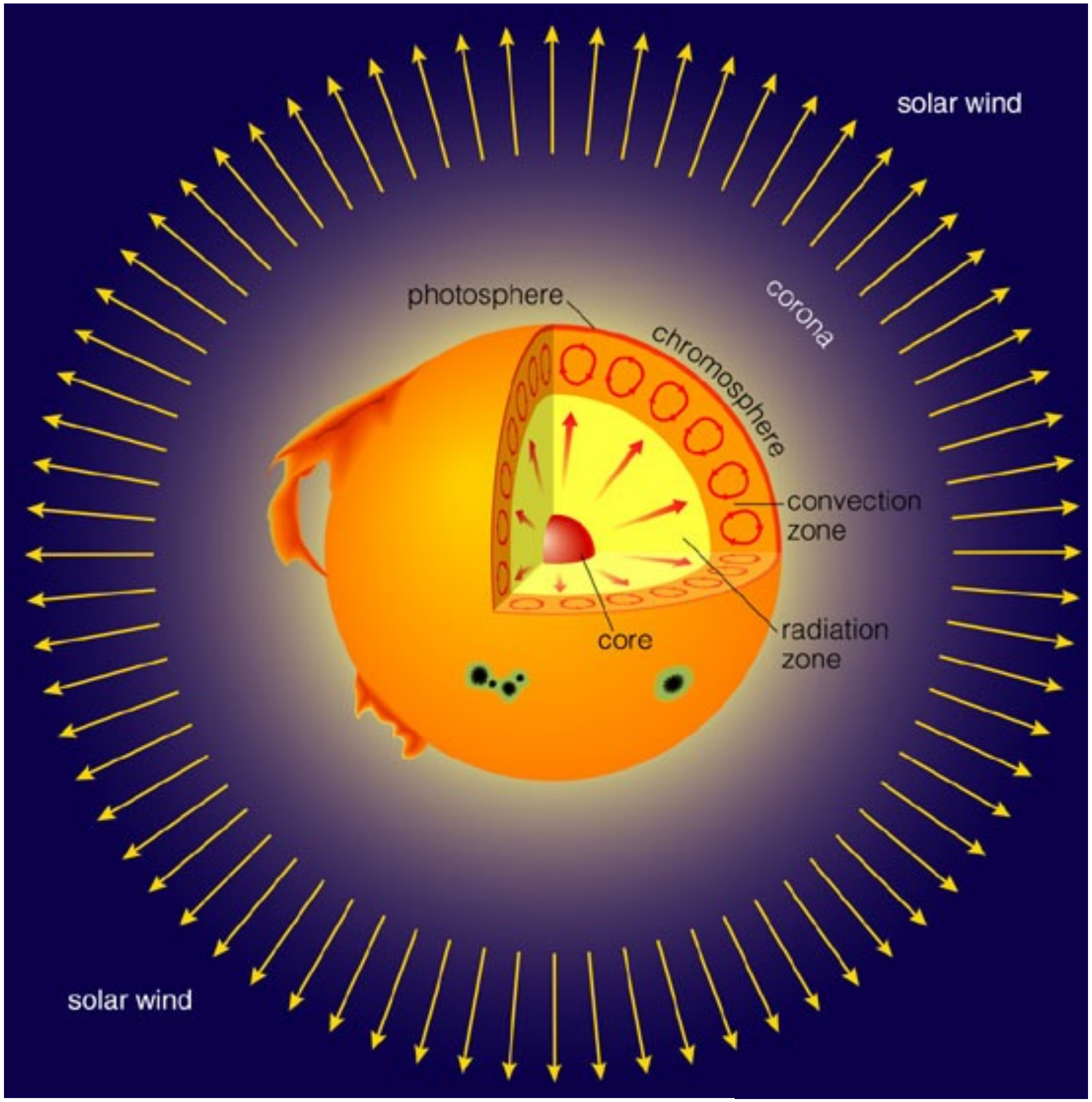
What is the Sun’s internal structure?



Convection zone:

Energy transported upward by rising hot gas

What is the Sun’s atmospheric structure?

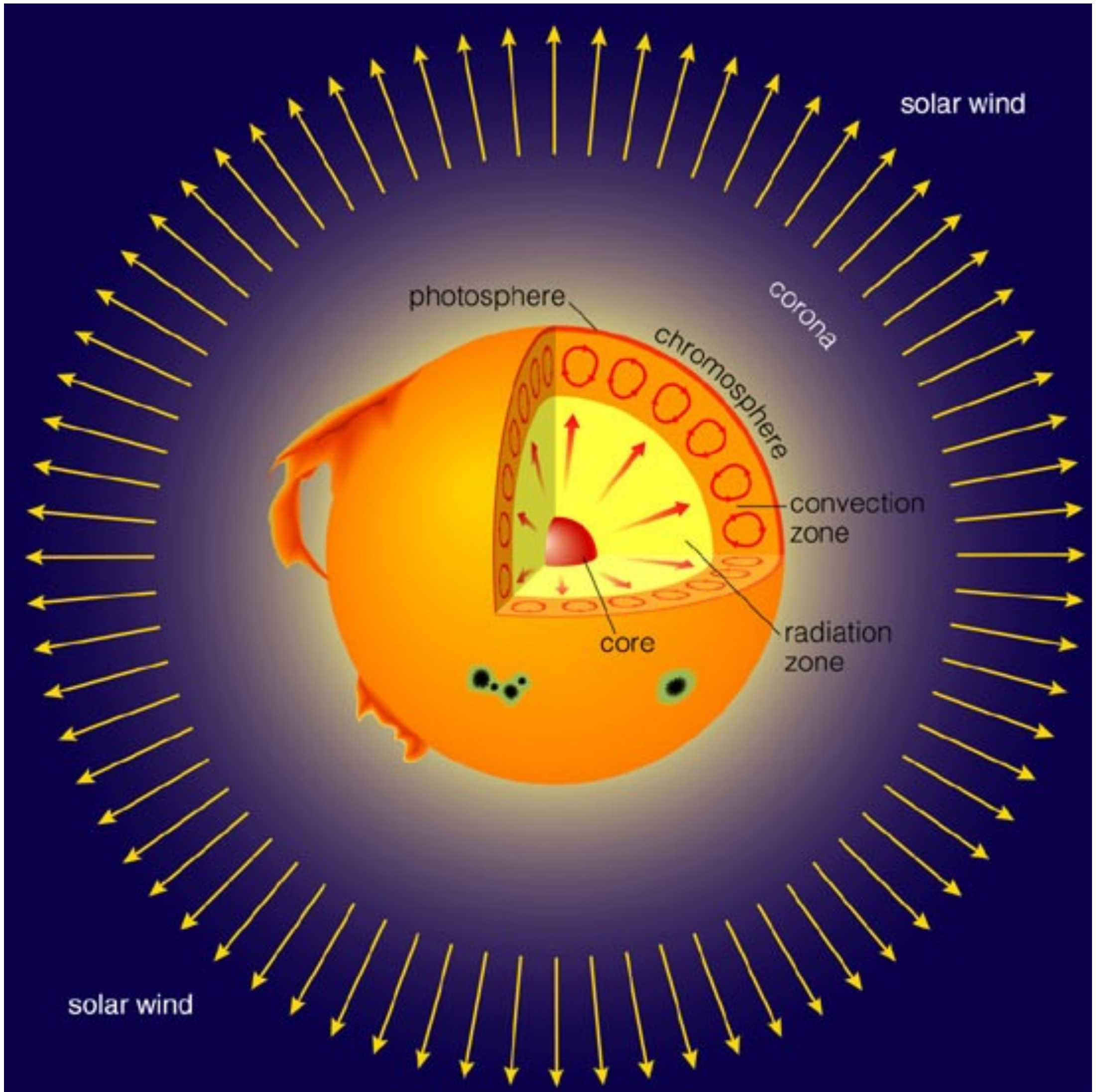


Photosphere:

Visible surface of Sun

T ~ 6,000 K

What is the Sun's atmospheric structure?

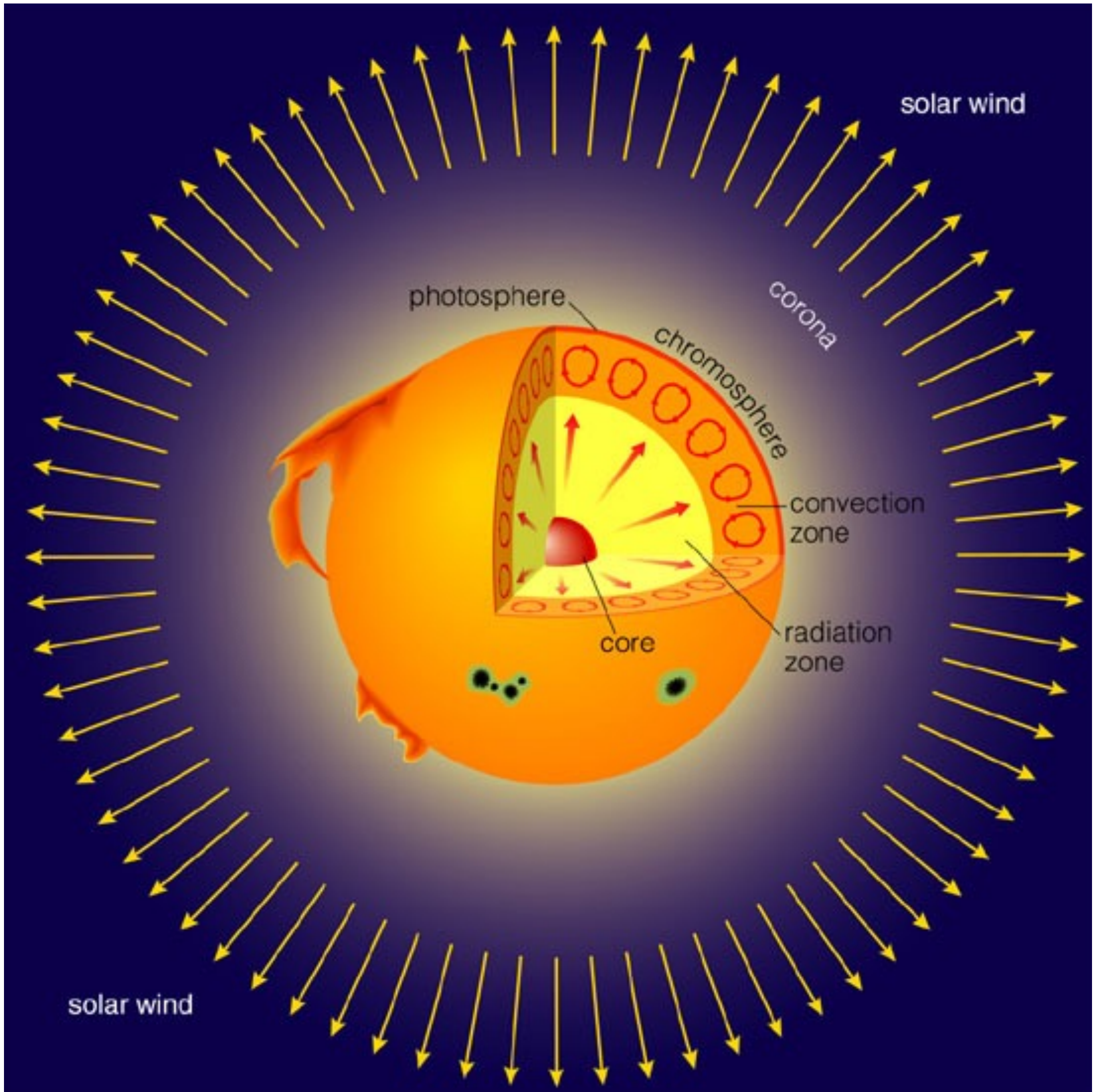


Chromosphere:

Middle layer of solar atmosphere

T ~ 10^4–10^5 K

What is the Sun's atmospheric structure?

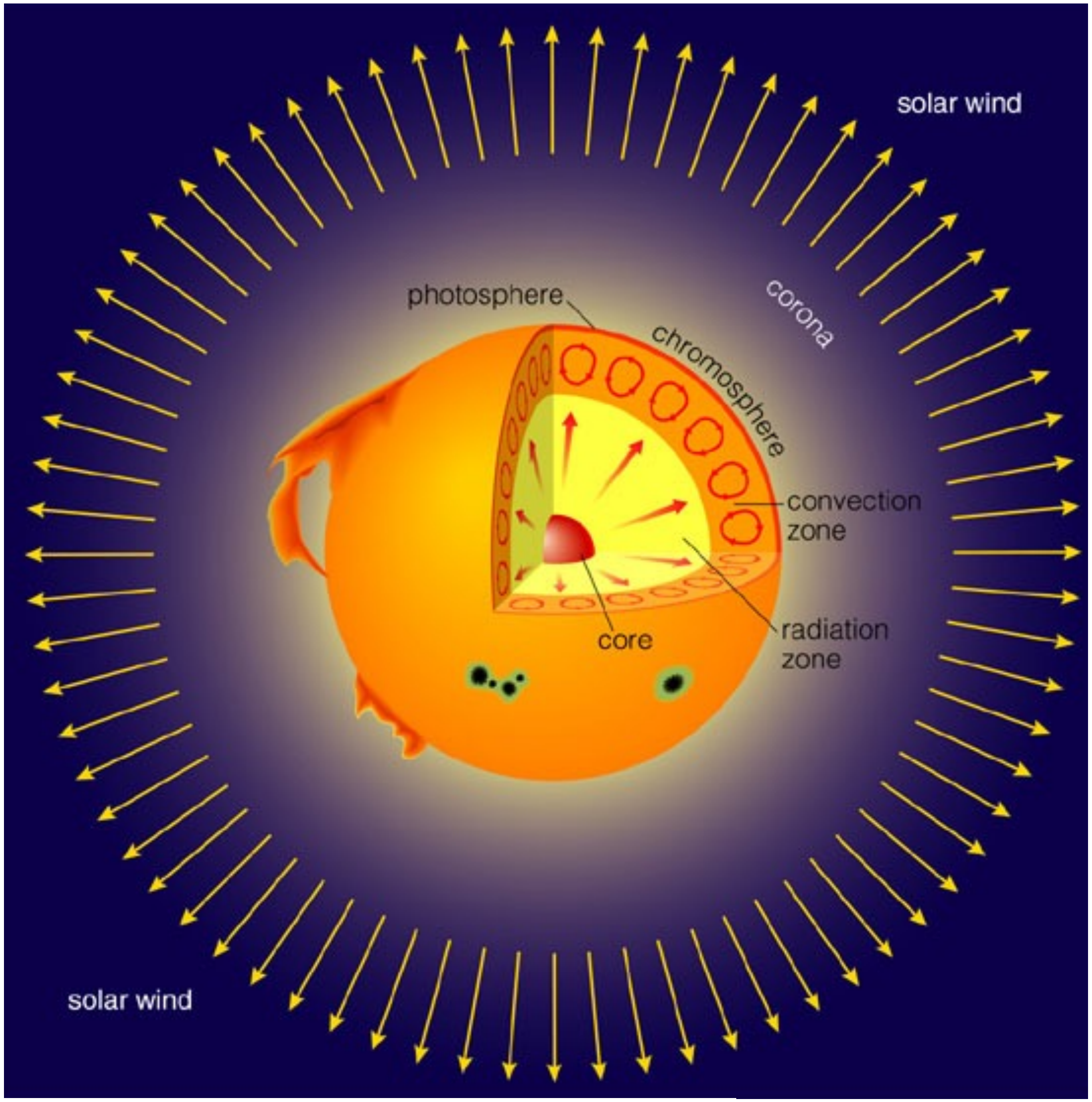


Corona:

Outermost (very low density) layer of solar atmosphere

T ~1 million K

What is the Sun’s atmospheric structure?



Solar wind:

A flow of charged particles (protons, electrons, etc.) from the surface of the Sun

What have we learned?

Begin 3 minute review

What have we learned?

Why does the Sun shine?

* Chemical and gravitational energy sources can not explain the Sun's luminosity.

* The Sun shines because **gravitational equilibrium** keeps its core hot and dense enough to release energy through **nuclear fusion**.

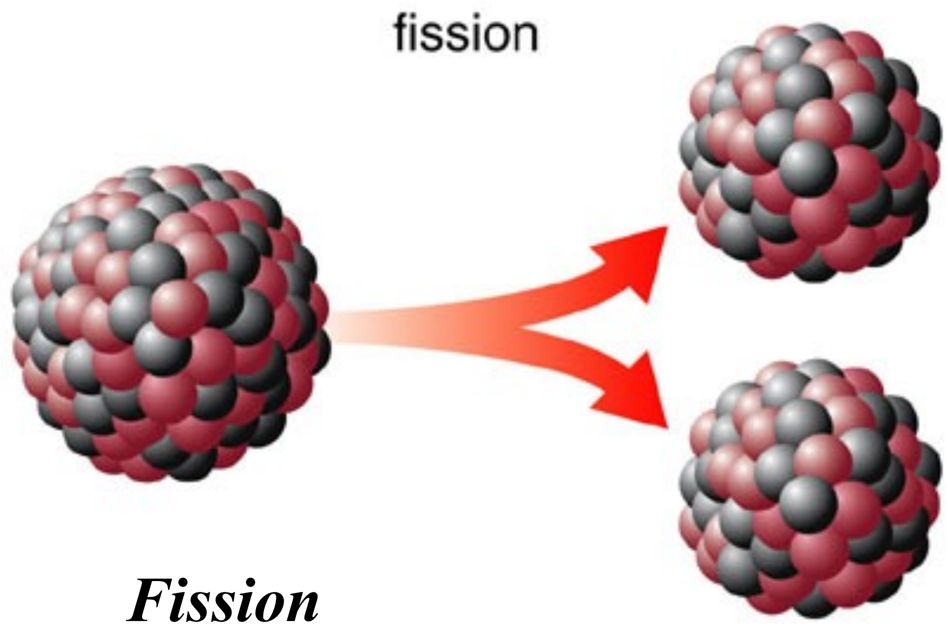
What have we learned?

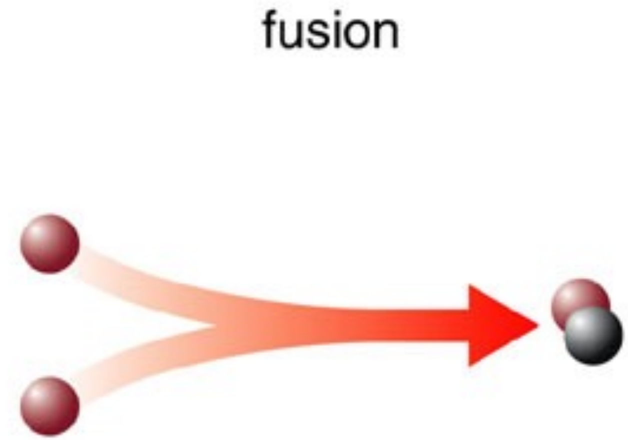
What is the Sun's structure?

From inside out, the layers are:

- Core
- Radiation zone
- Convection zone
- Photosphere
- Chromosphere
- Corona
- Solar wind

Nuclear energy processes





Fission

A big nucleus splits into smaller nuclei with a release of energy.

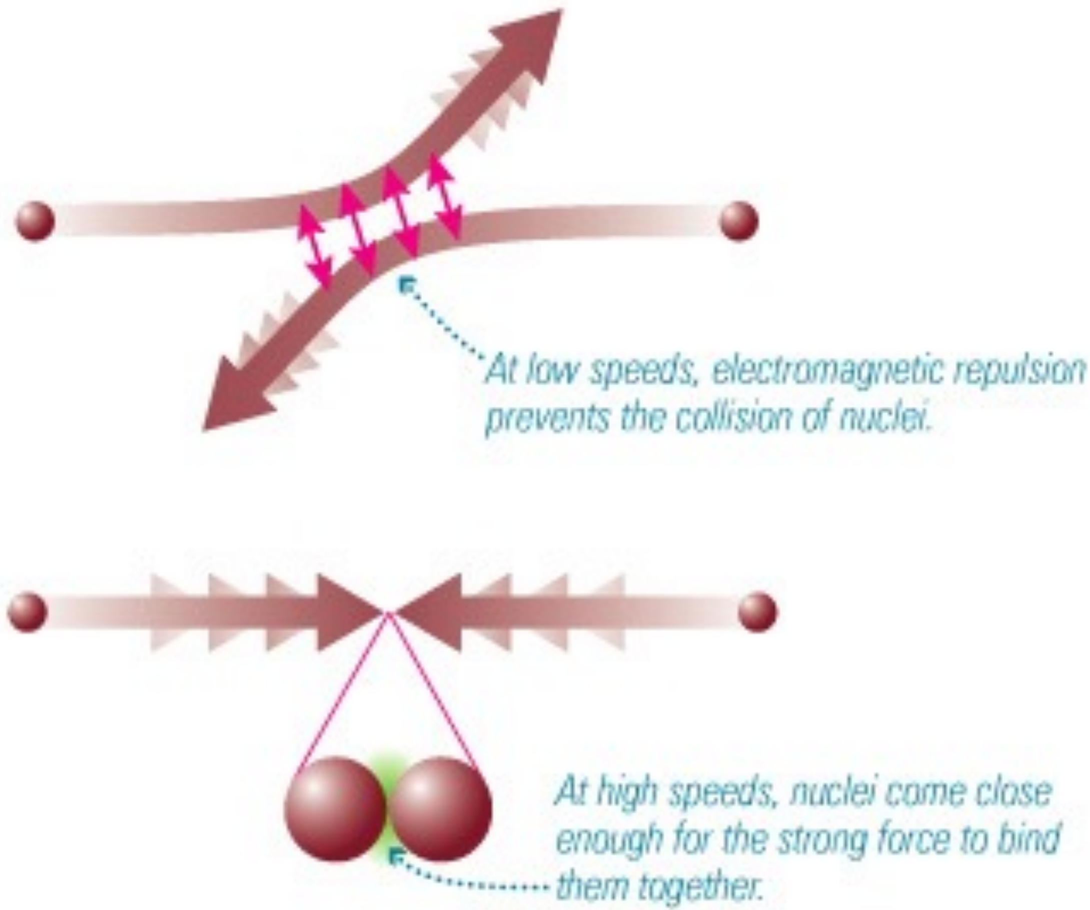
(Nuclear power plants)

Fusion

Small nuclei stick together to make a larger nucleus with a release of energy.

(Sun, stars)

How does nuclear fusion occur in the Sun?

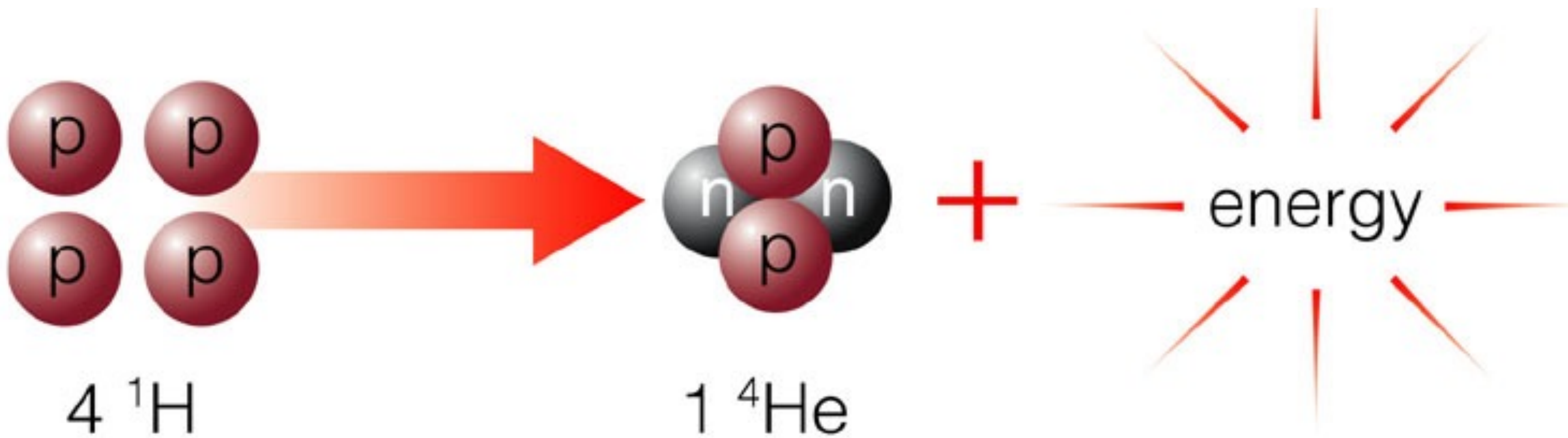


- Extremely high *pressure* and *temperature* (15 million K) enable nuclei to collide

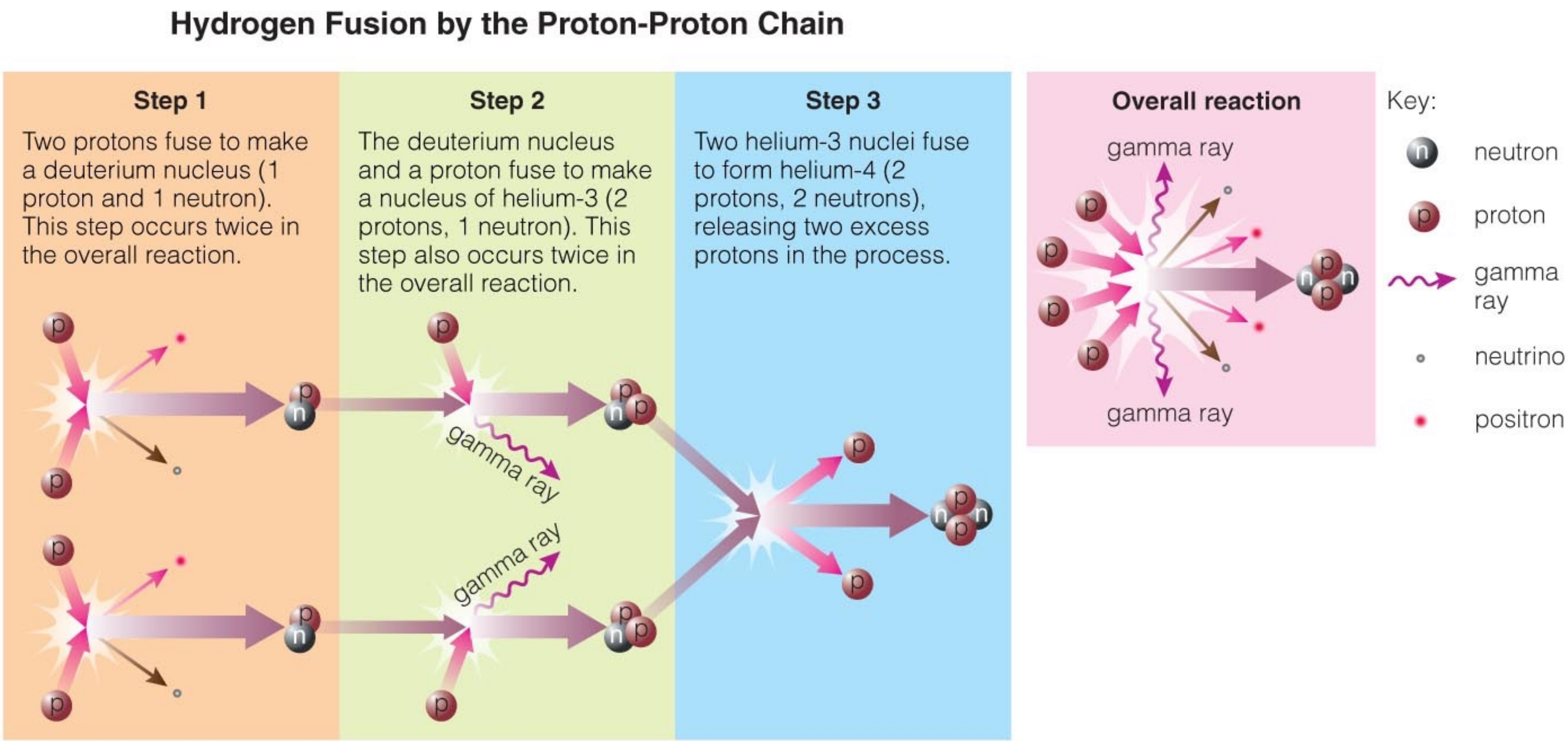
- Nuclear fusion occurs in the core due to strong force overcoming the electromagnetic force.

- Very small % of particles have enough energy to overcome the electromagnetic repulsion barrier and bind together, but there are many particles, so the total energy released is high.

How does nuclear fusion occur in the Sun?



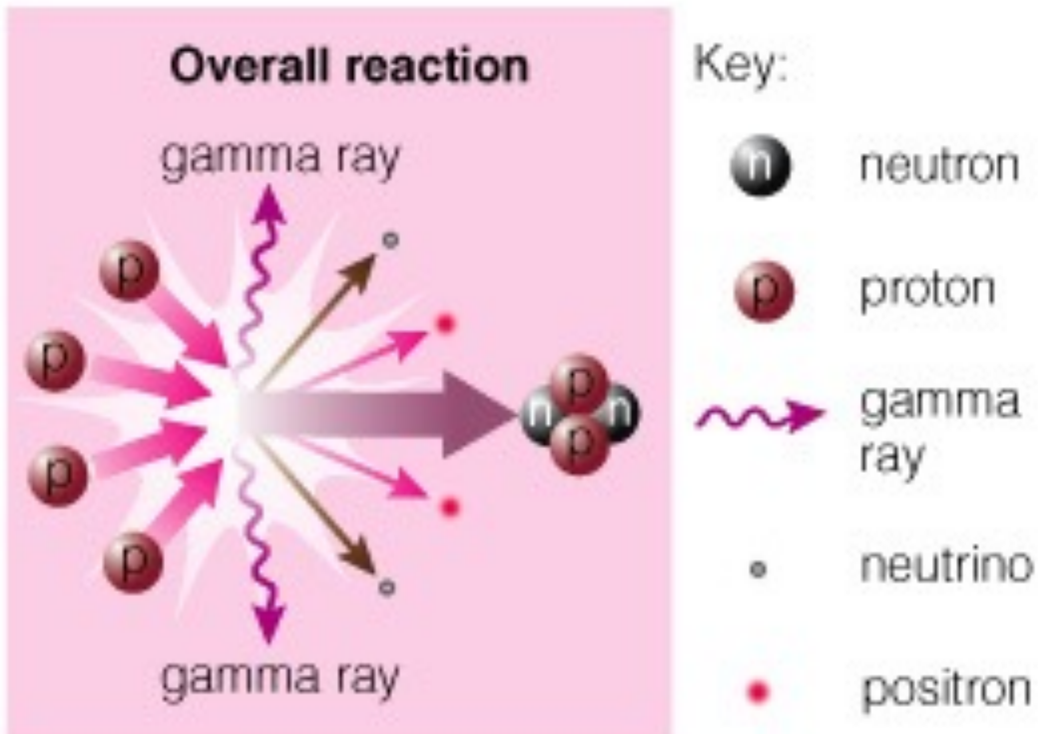
Sun releases energy by fusing four hydrogen nuclei into one helium nucleus. This is called the **proton-proton chain**.



Interactive Figure

The **proton–proton chain** is how hydrogen fuses into helium in Sun.

How does nuclear fusion occur in the Sun?



IN

4 protons

OUT

^{4}He nucleus

2 gamma rays

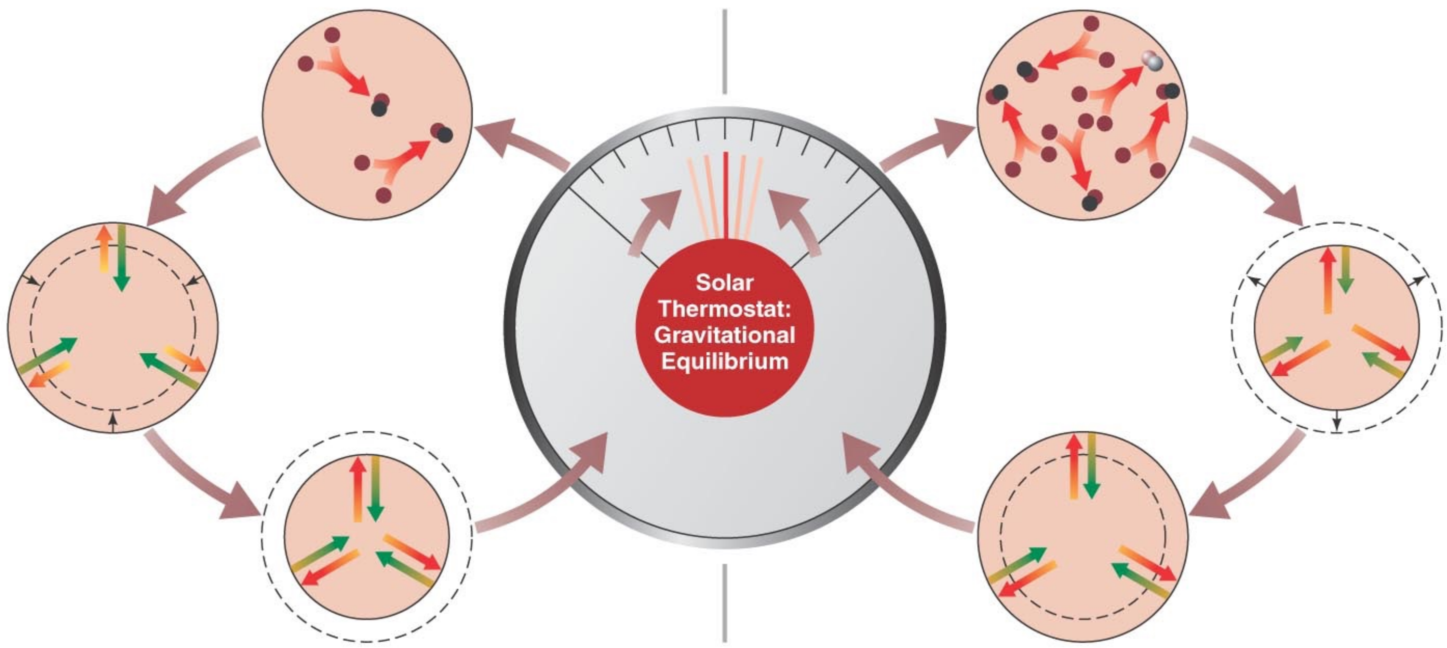
2 positrons

2 neutrinos

Total mass is 0.7% lower – this is converted to energy!

$$E_{released} = \Delta mc^2$$

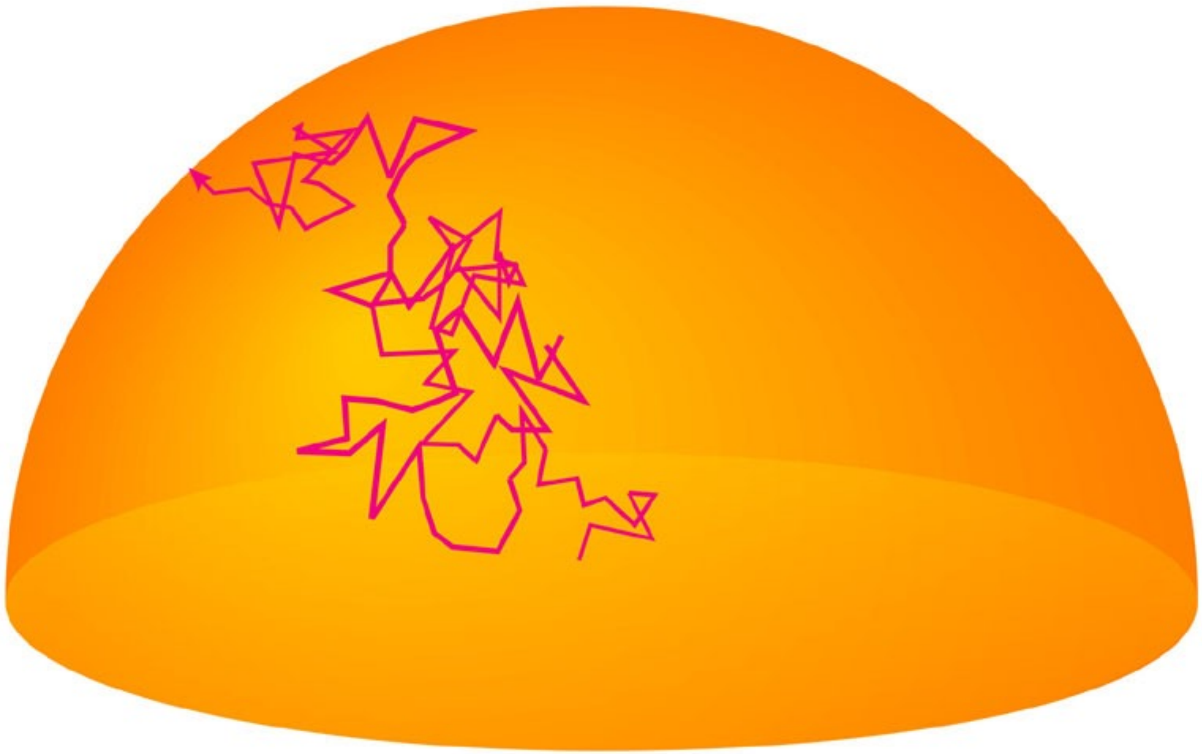
“Solar Thermostat” maintains stability



Decline in core temperature causes fusion rate to drop, so core contracts and heats up.

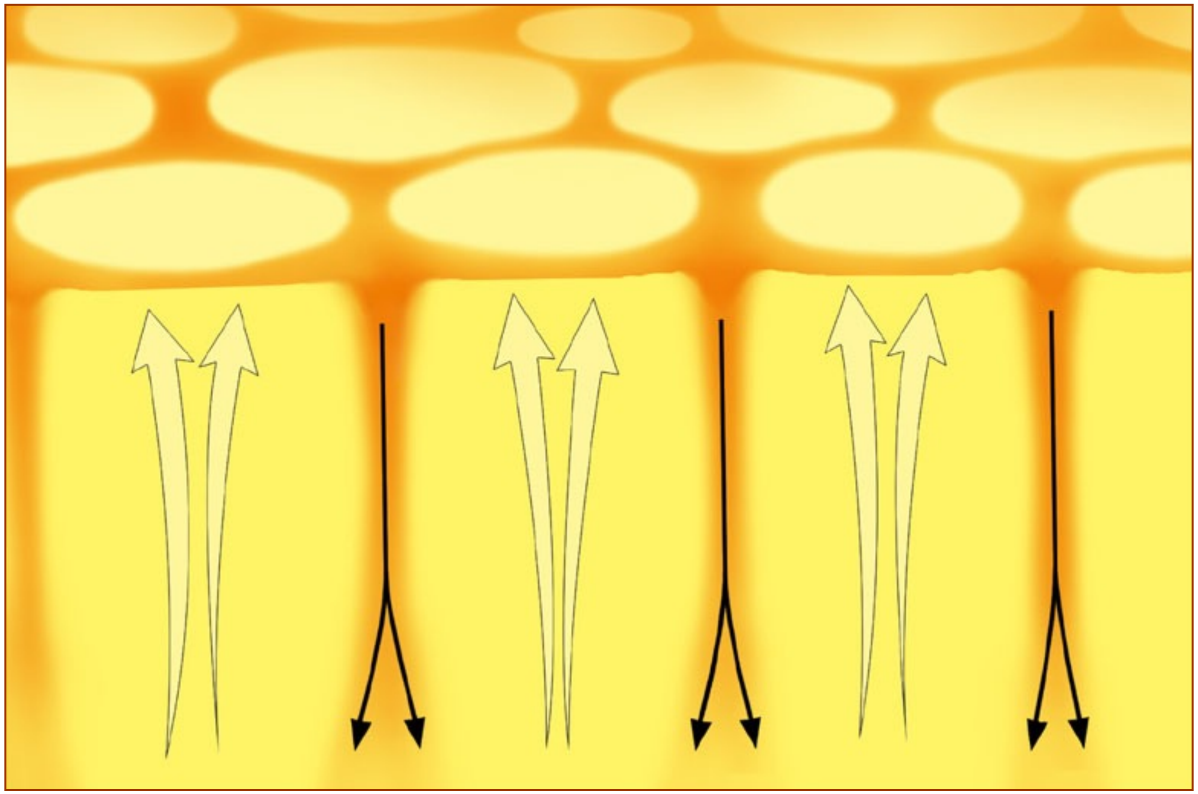
Rise in core temperature causes fusion rate to rise, so core expands and cools down.

How does the energy from fusion get out of the Sun?



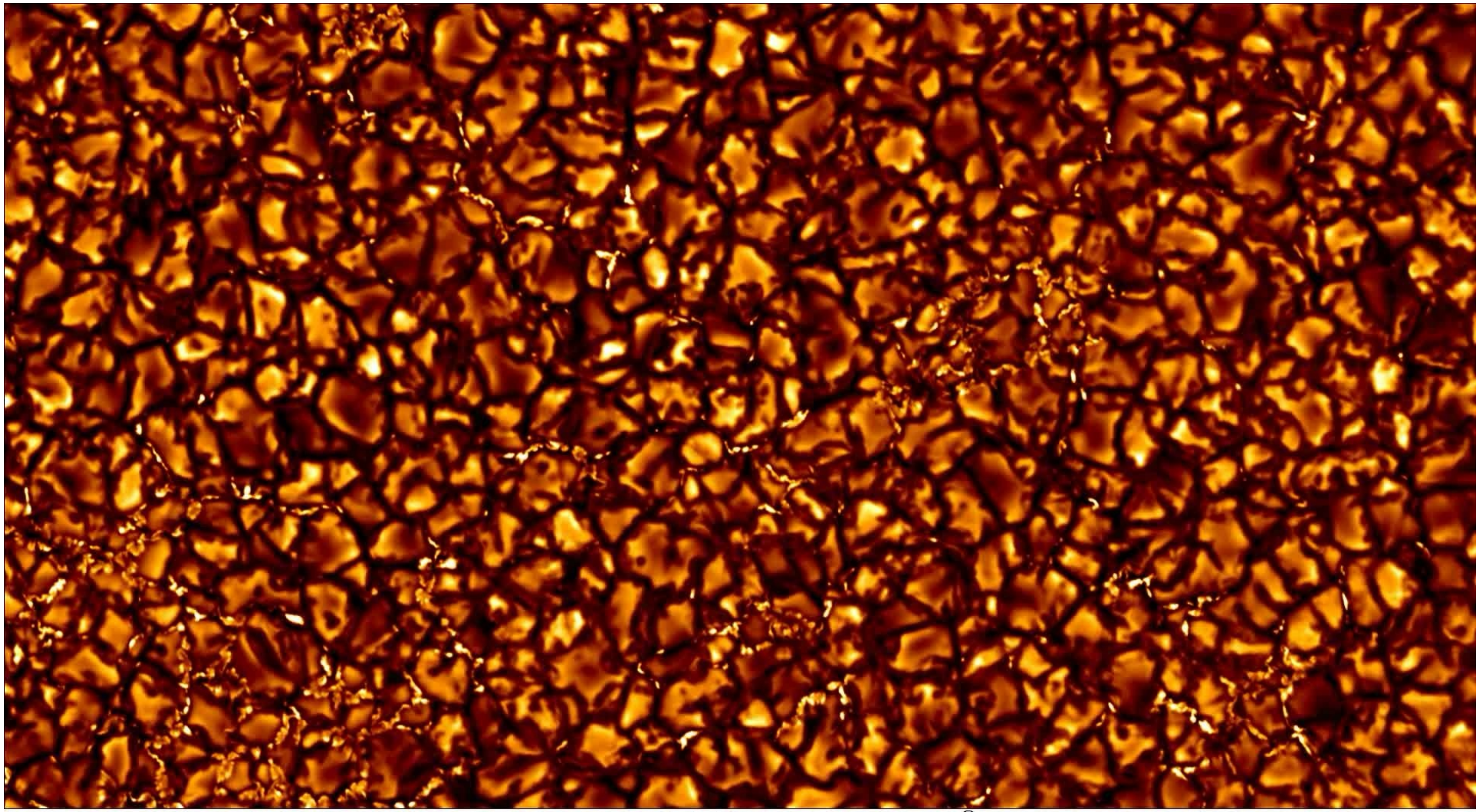
- Energy *gradually* leaks out of the radiation zone as photons randomly colliding with electrons.
- As they lose energy, their wavelength changes (How?)

How does the energy from fusion get out of the Sun?



At about 2 million K, gas absorbs photons, *convection* (rising hot gas) transports energy to the surface.

How does the energy from fusion get out of the Sun?



Swedish 1-m Solar Telescope (SST), CHROMIS Wideband 395.0 nm, 25-May-2017, (x,y)=(36",-91"), 01:08:02 duration 12742 km

Blobs on photosphere where hot gas reaches the surface – bright centers are rising, dark edges are falling.

Photons escape as sunlight!

How does the energy from fusion get out of the Sun?

https://images.app.goo.gl/3bHd3M
zuppDRNNSY6

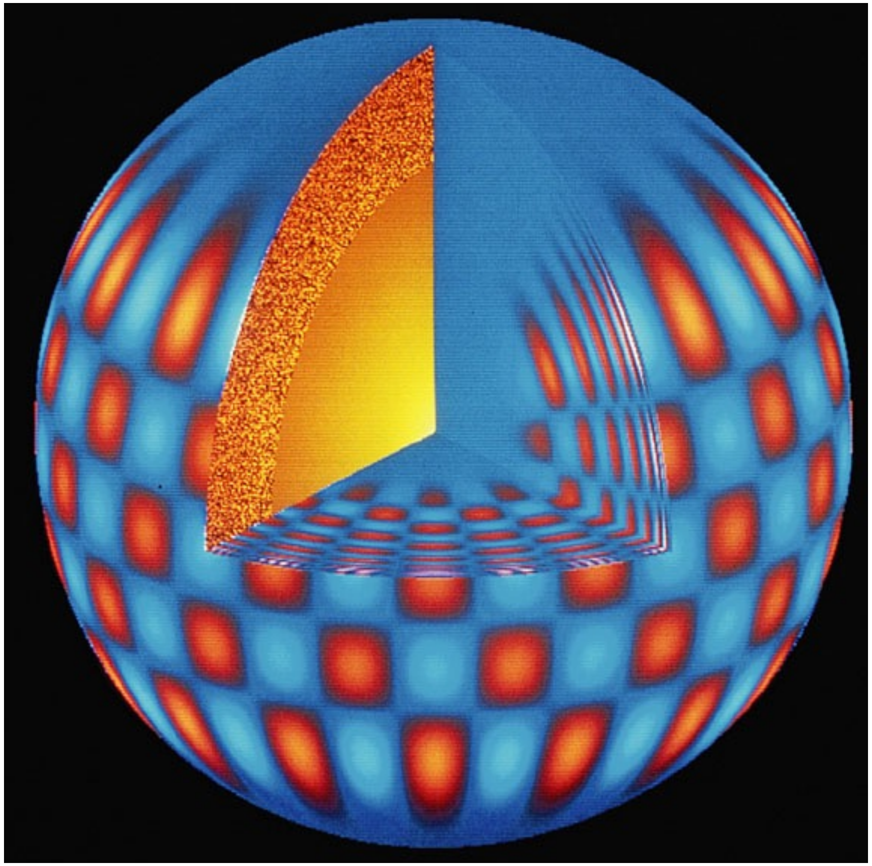
Blobs on photosphere where hot gas reaches the surface – bright centers are rising, dark edges are falling.
Photons escape as sunlight!

How do we know what is happening inside the Sun?

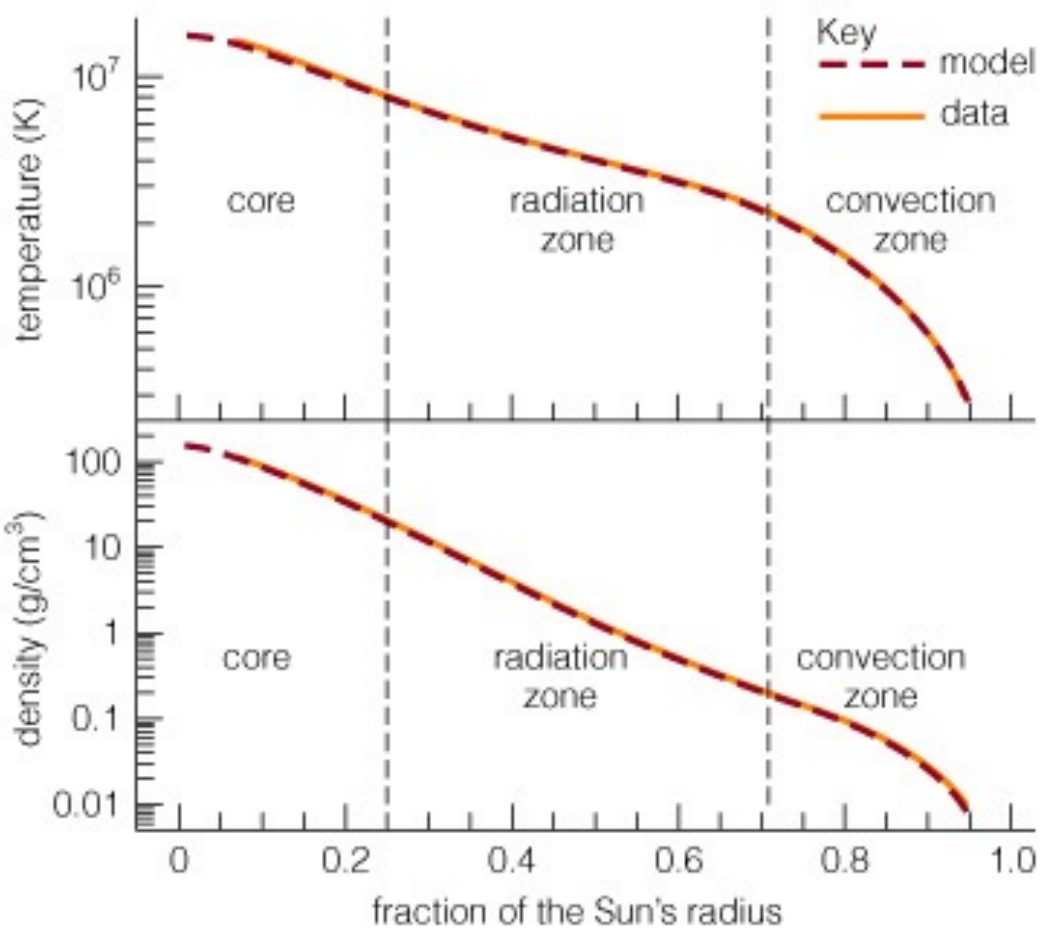
We learn about the inside of the Sun by:

1. observing solar vibrations
2. making mathematical models.
3. observing solar neutrinos.

Patterns of *vibration* (Doppler shifts) on the surface tell us about what the Sun is like inside.

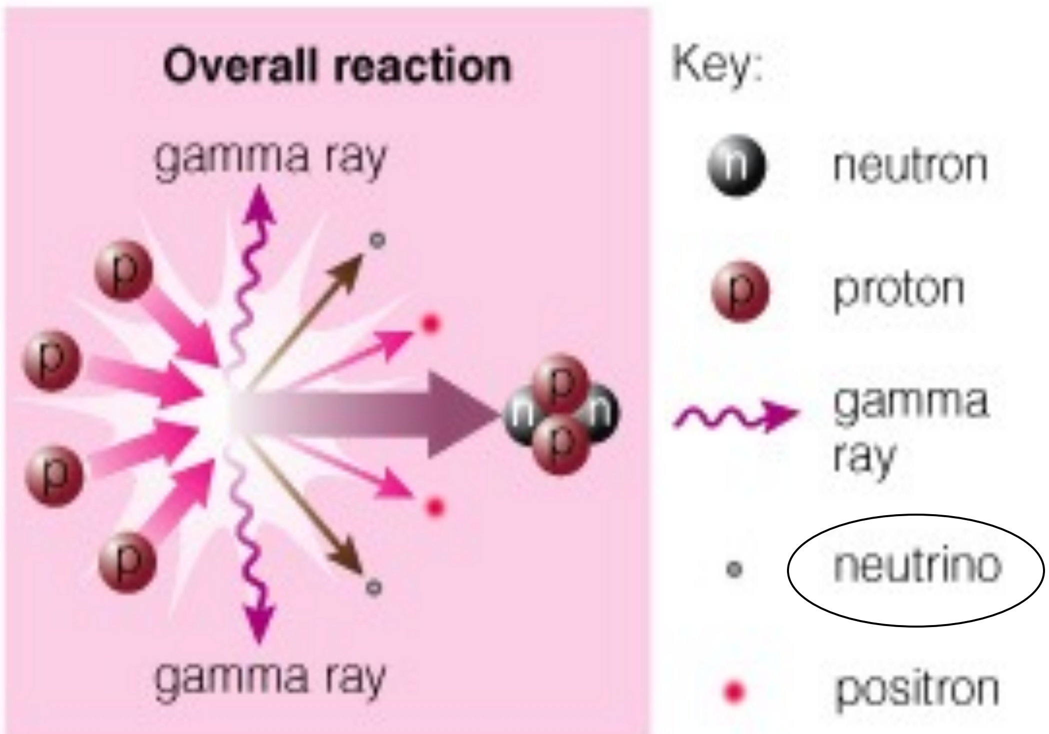


How do we know what is happening inside the Sun?



- *Mathematical models* of solar interior are based on laws of physics
- Solar radius, temperature, and luminosity observations agree with models
- Data on solar vibrations agree with models of solar interior.

How do we know what is happening inside the Sun?



- **Neutrinos** created during fusion fly right through Sun.
- Observations of these solar neutrinos tell us what's happening in the core.
- Neutrino detectors help improve knowledge of Sun

Think/Pair/Share

For the Sun to produce energy, what is required in its core?

A. High temp, low density, and the weak nuclear force
B. Low temp, high density, the strong nuclear force.
C. High temp, high density, the strong nuclear force
D. Low temp, low density, and the weak nuclear force

Think/Pair/Share

For the Sun to produce energy, what is required in its core?

A. High temp, low density, and the weak nuclear force
B. Low temp, high density, the strong nuclear force.
C. High temp, high density, the strong nuclear force
D. Low temp, low density, and the weak nuclear force

What have we learned?

Begin 3 minute review

What have we learned?

How does nuclear fusion occur in the Sun?

* The core's extreme temperature and density allow the nuclear fusion of hydrogen to helium through the **proton–proton chain**.
* Gravitational equilibrium acts as a thermostat to regulate the core temperature because fusion rate is very sensitive to temperature.

What have we learned?

How does the energy from fusion get out of the Sun?

* Photons carry it directly through the radiation zone.
* Rising hot plasma carries energy through the convection zone to the photosphere.

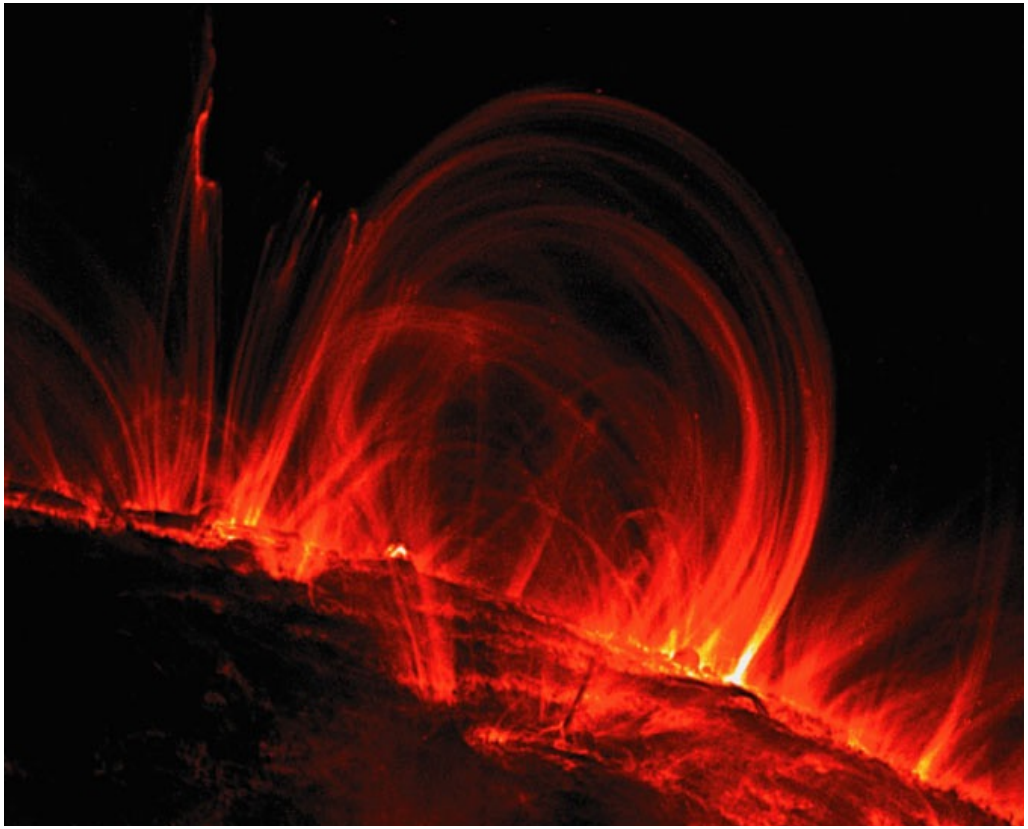
How do we know what is happening inside the Sun?

* Mathematical **models** agree with observations of **solar vibrations** and solar **neutrinos**.

Solar activity

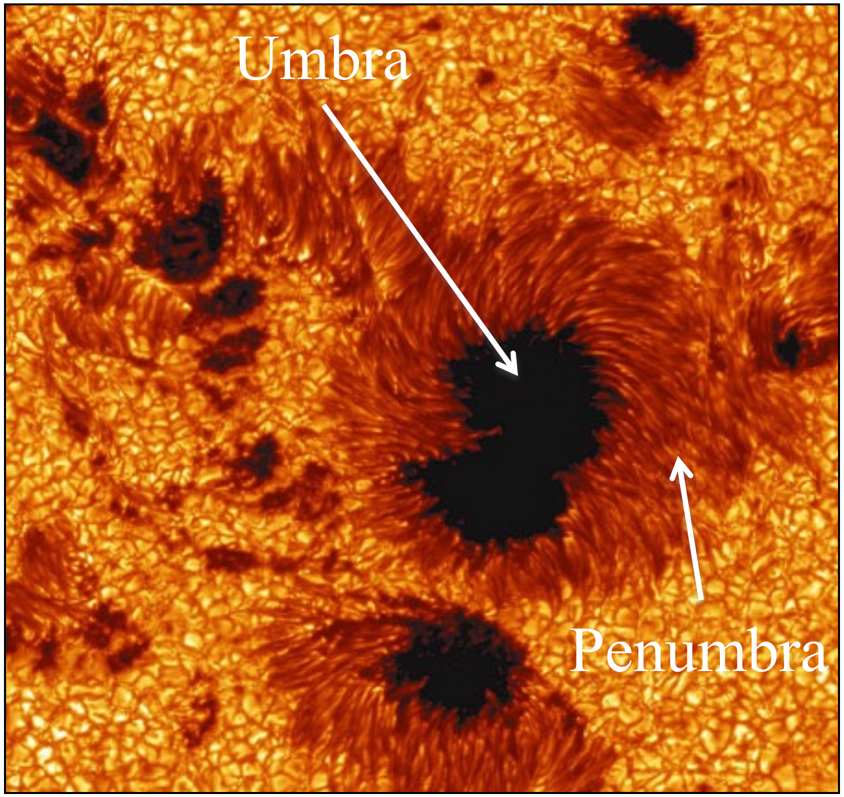
- Sunspots
- Solar flares
- Solar prominences

All related to magnetic fields.



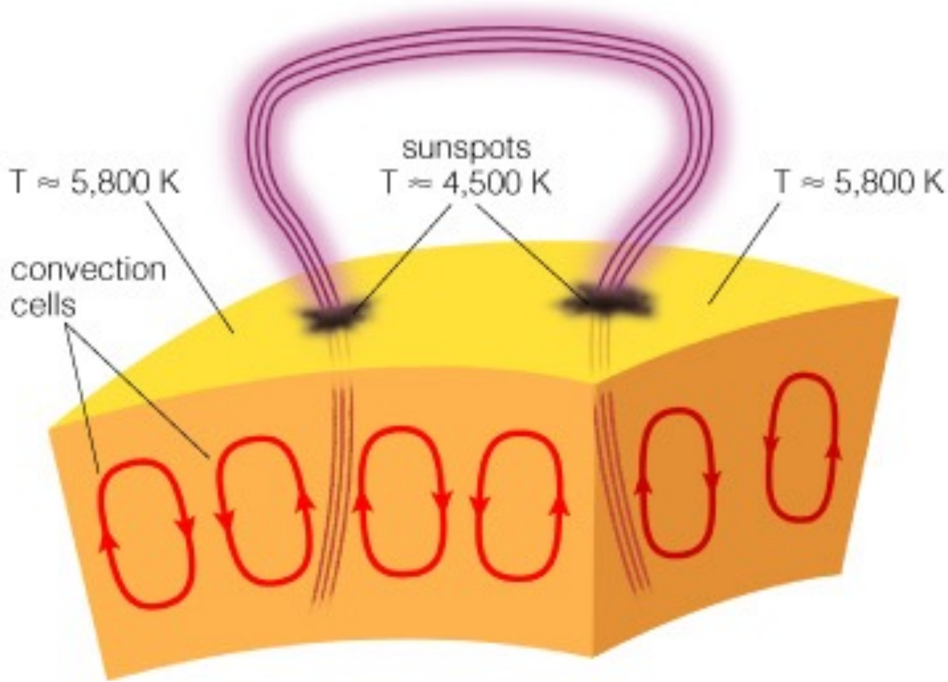
Sunspots

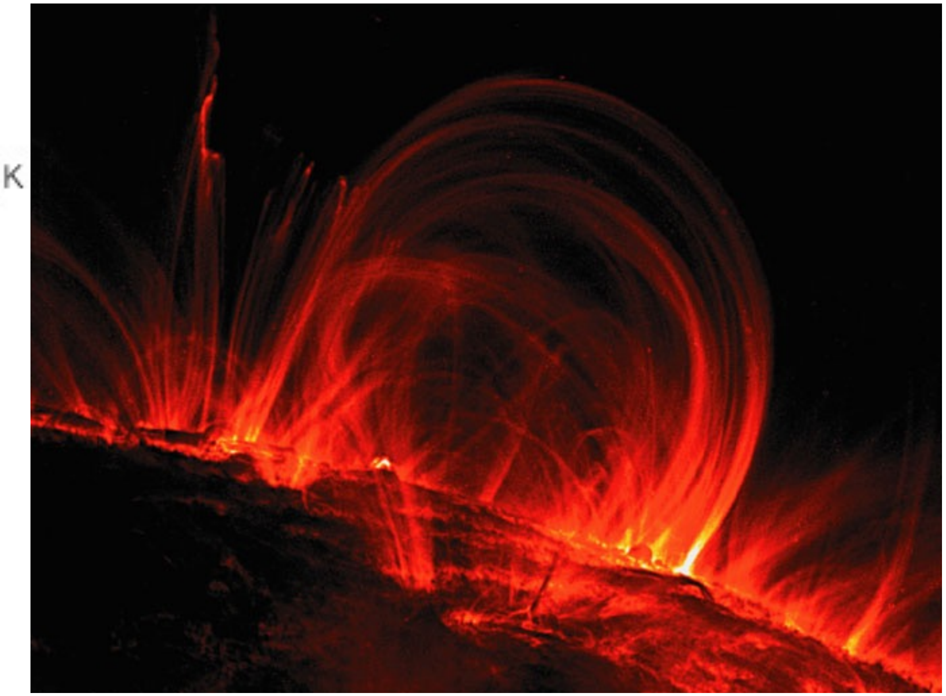
• Cooler (4000K) than other parts of the Sun's surface (5800K).
• Regions with strong magnetic fields.



• *Strong fields suppress convection, prevent energy from escaping.*

Sunspots





Loops of bright gas (**prominences**) often connect sunspot pairs.

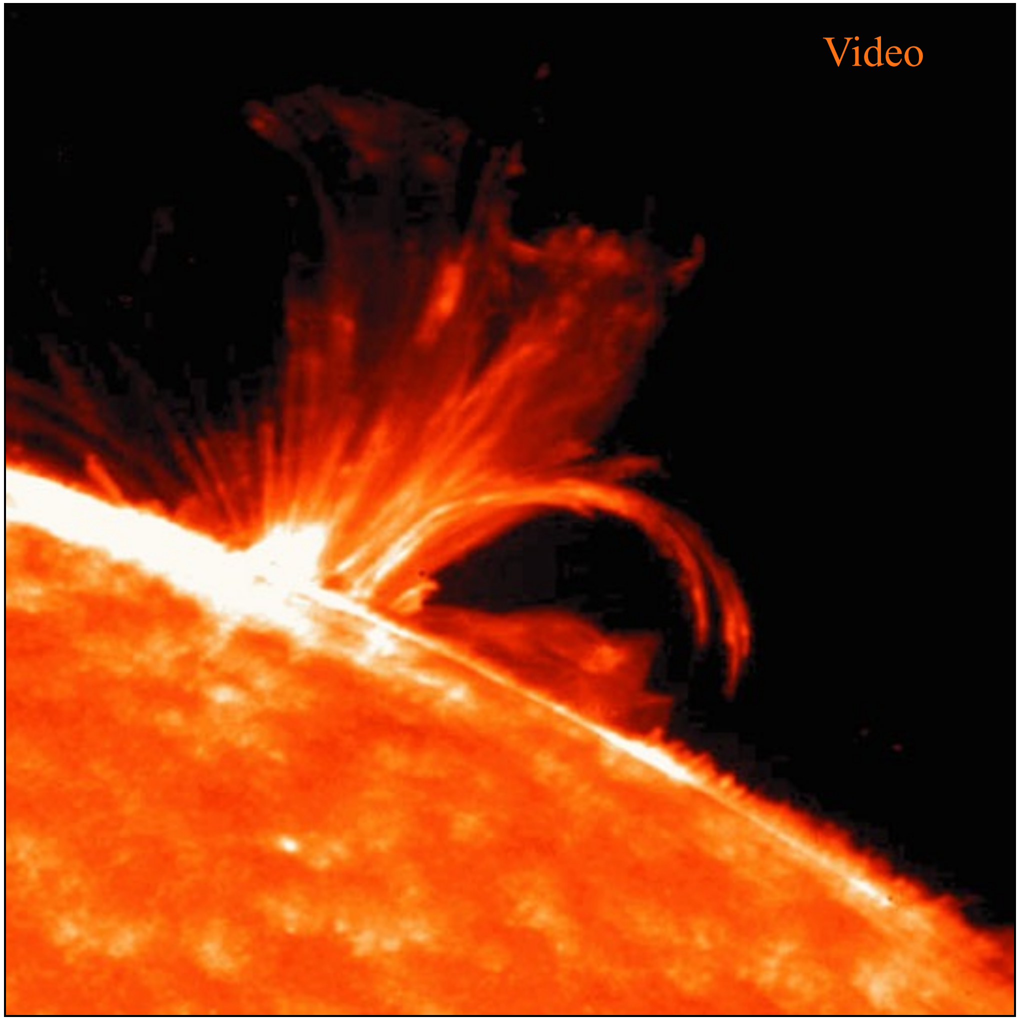
Solar prominences

Magnetic activity also causes solar prominences to erupt high above the Sun's surface.

Solar flares

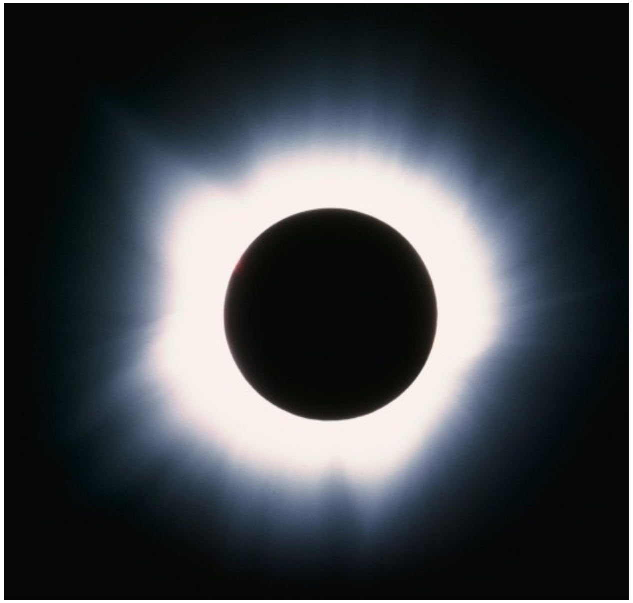
• Magnetic field lines become so twisted they snap open.

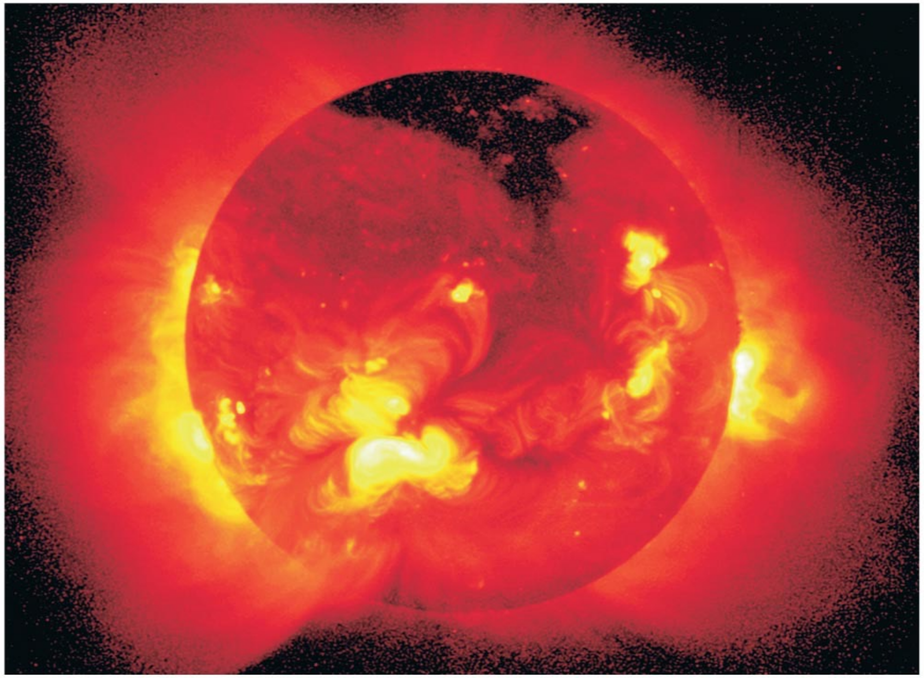
• This causes ***solar flares*** that send X-rays and charged particles into space.



The Corona

- The corona is only seen at visible wavelengths during solar eclipses when light from the photosphere is blocked.

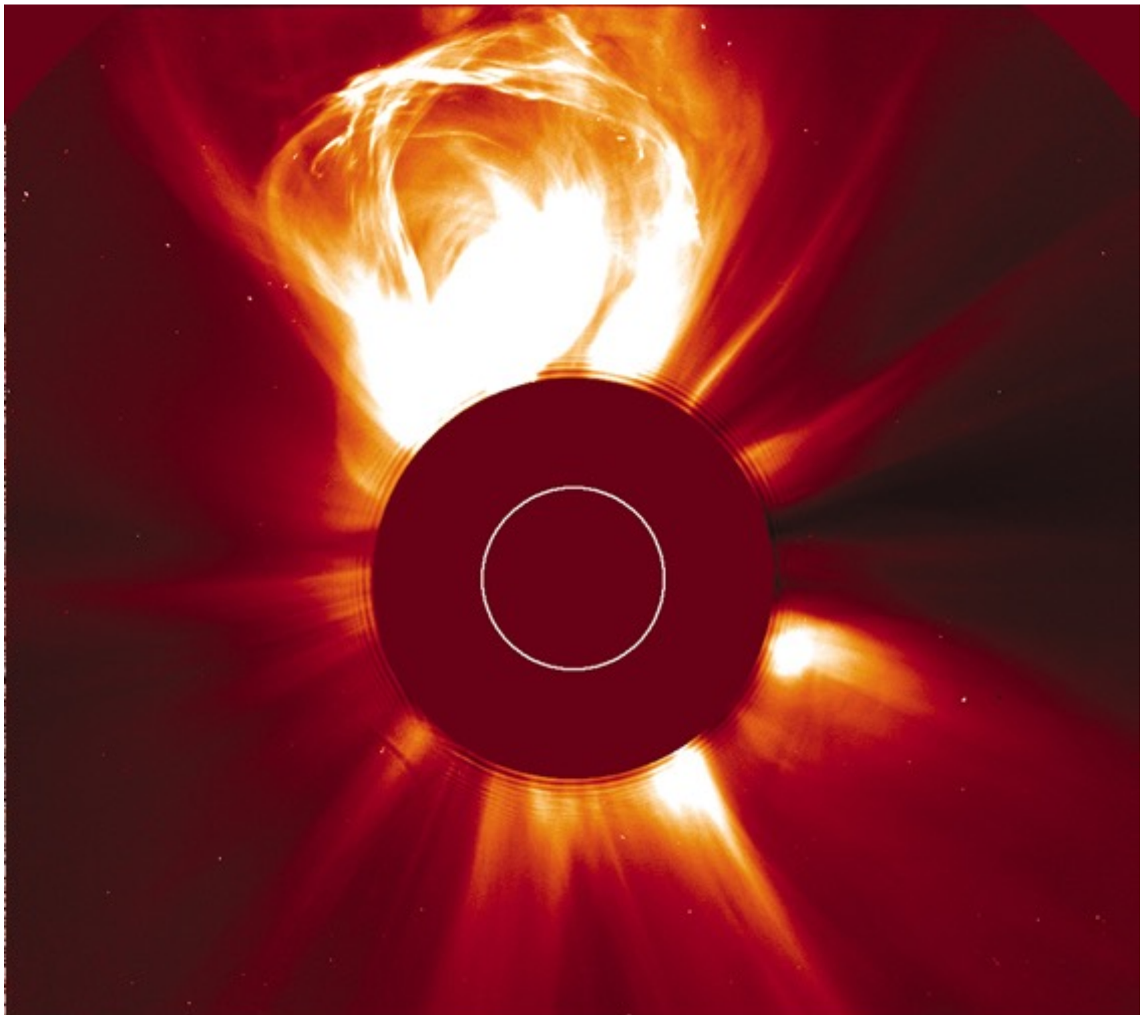




- The corona appears bright in X-ray photos in places where magnetic fields trap hot gas.

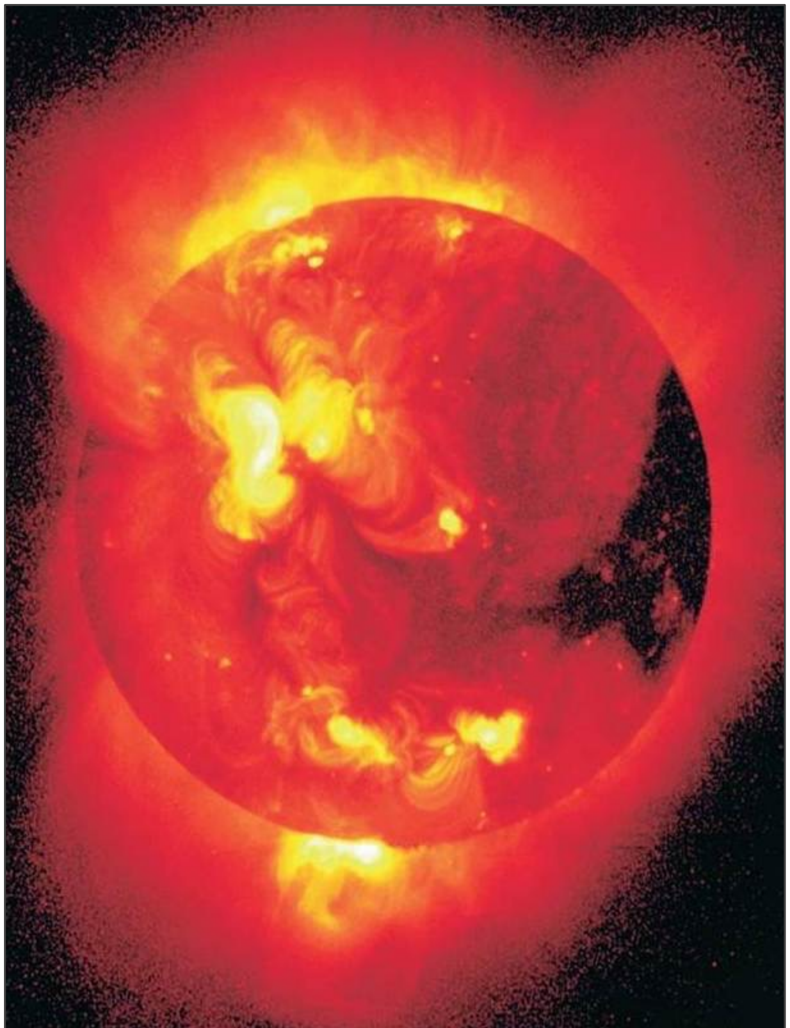
Interactive Figure

Coronal mass ejections



Coronal mass ejections send bursts of energetic charged particles out through the solar system.

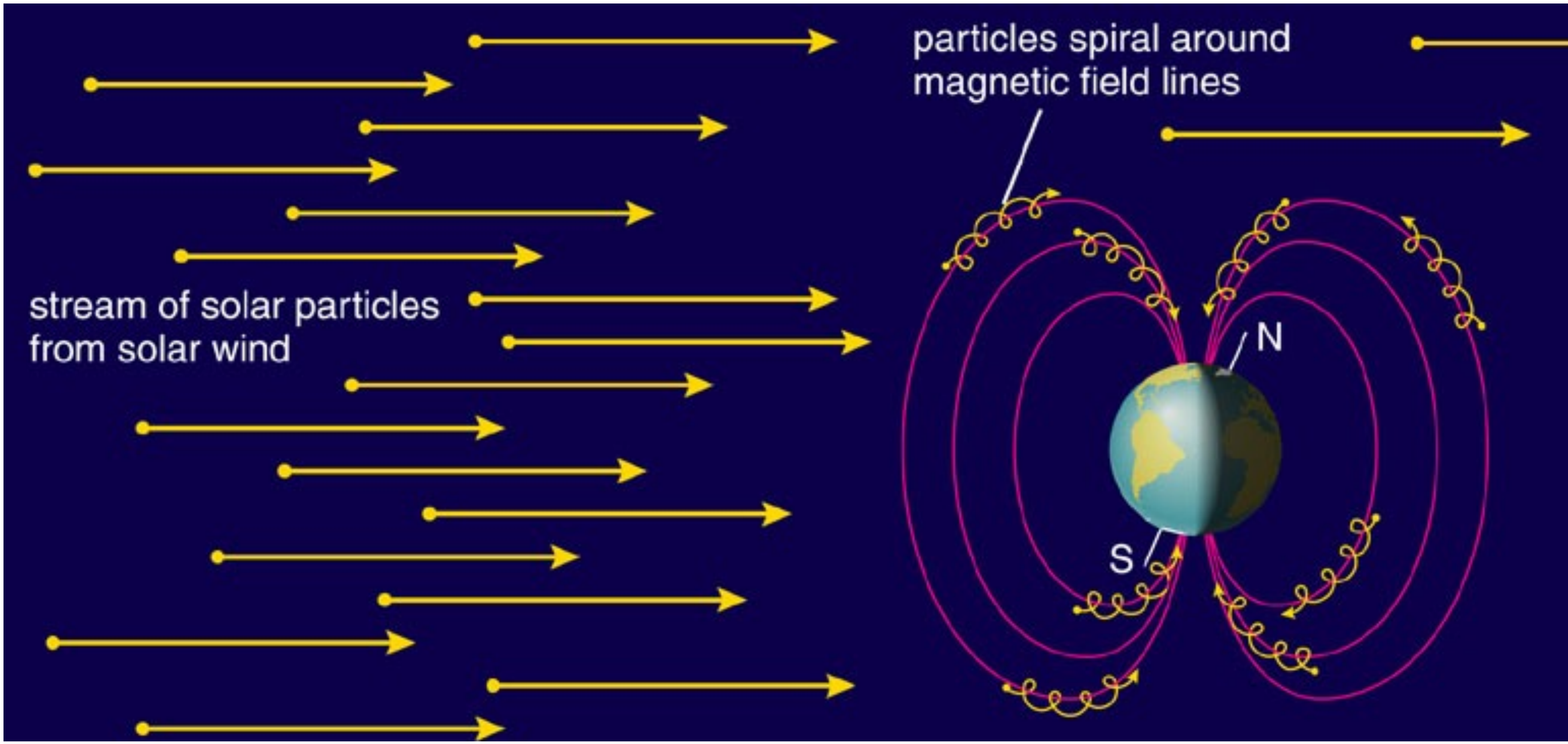
Multiwavelength views of Sun



- Comparing the Sun at different wavelengths tells us about different regions.
- Solar prominences and CMEs can be spectacular!

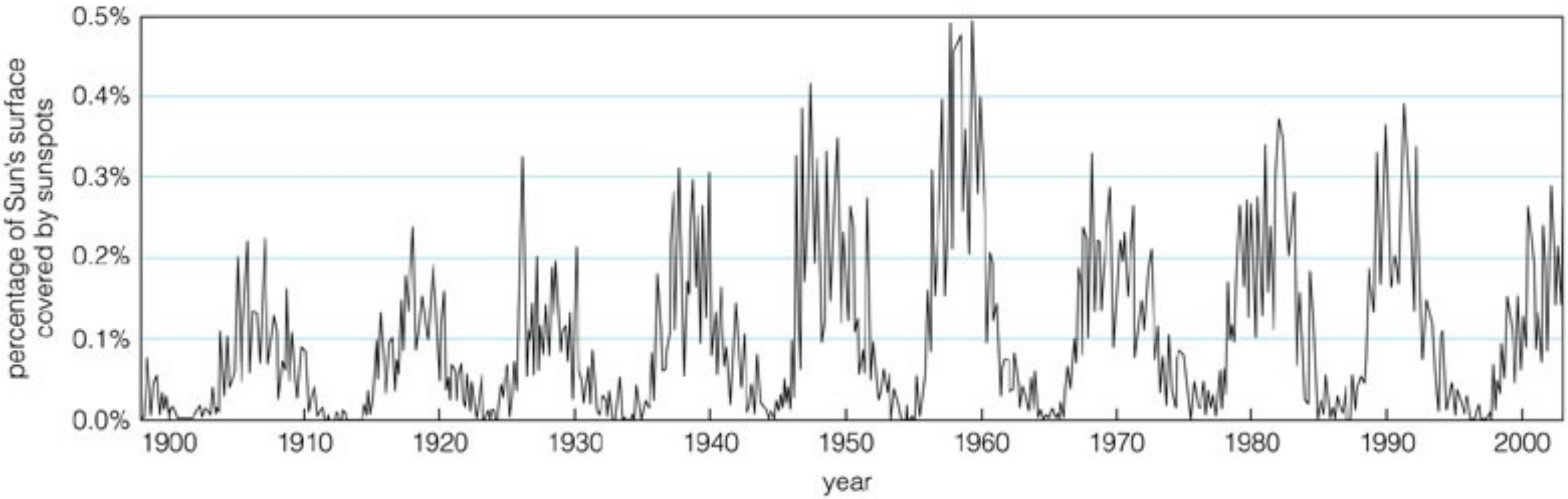
NASA Video

How does solar activity affect humans?



Charged particles from the Sun can disrupt electrical power grids and disable communications satellites.

How does solar activity vary with time?

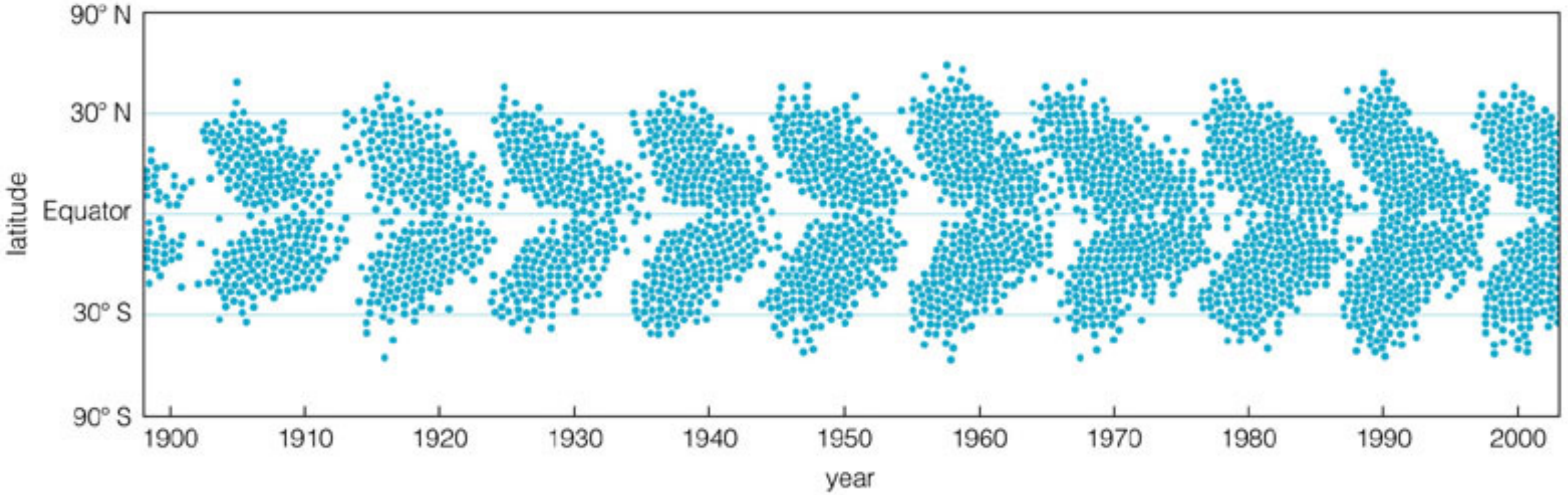


- The *number* of sunspots rises and falls in 11-year cycles (frequency of prominences, flares, and CMEs also cycles).

- Number of sunspots varies in each cycle.

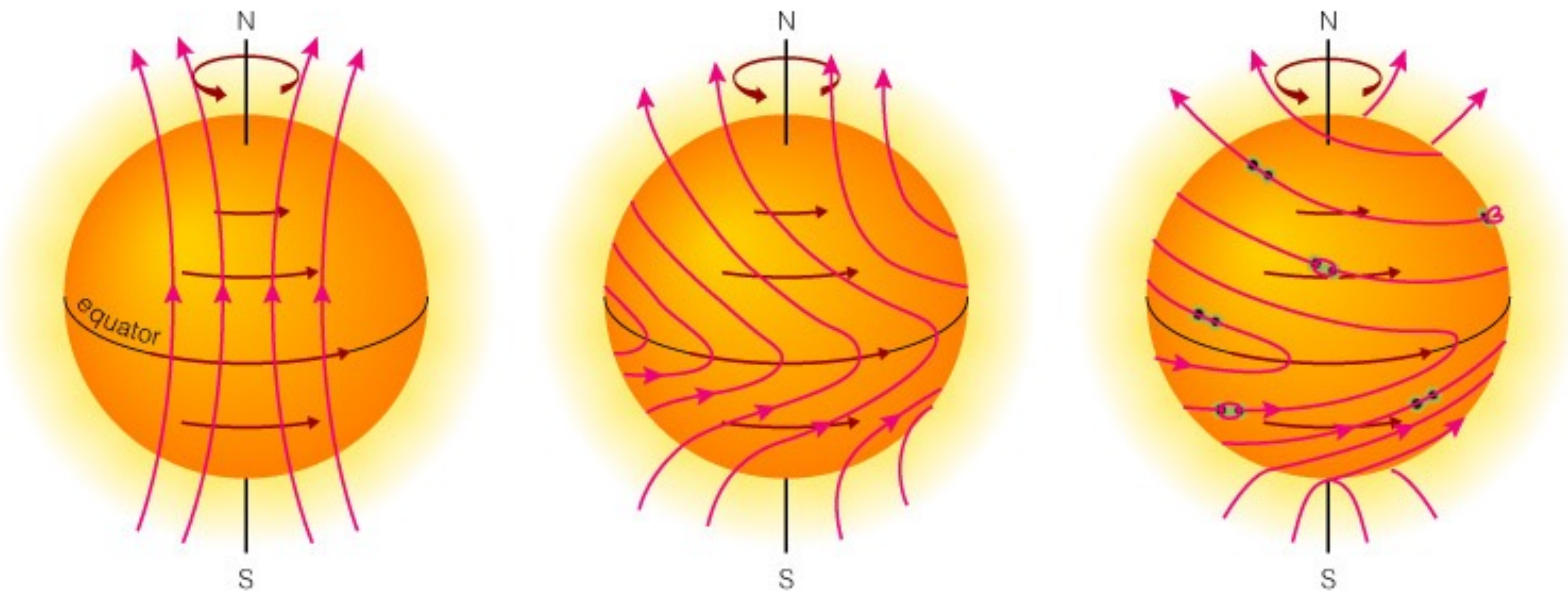
How does solar activity vary with time?

"Butterfly diagram"



- The *latitude* of sunspots rises and falls in 11-year cycles
  - At sunspot minimum, spots begin at latitude 30-40 degrees
  - As cycle progresses, spots appears at lower latitudes

The Sunspot cycle



The sunspot cycle results from the winding and twisting of the Sun's magnetic field due to *differential rotation*.

- Lower latitudes rotate faster than high latitudes.
- Overall field "winds up" like a rubberband.

What have we learned?

Begin 3 minute review

What have we learned?

What causes solar activity?

* The concentration and stretching and twisting of magnetic field lines near Sun's surface causes solar activity.

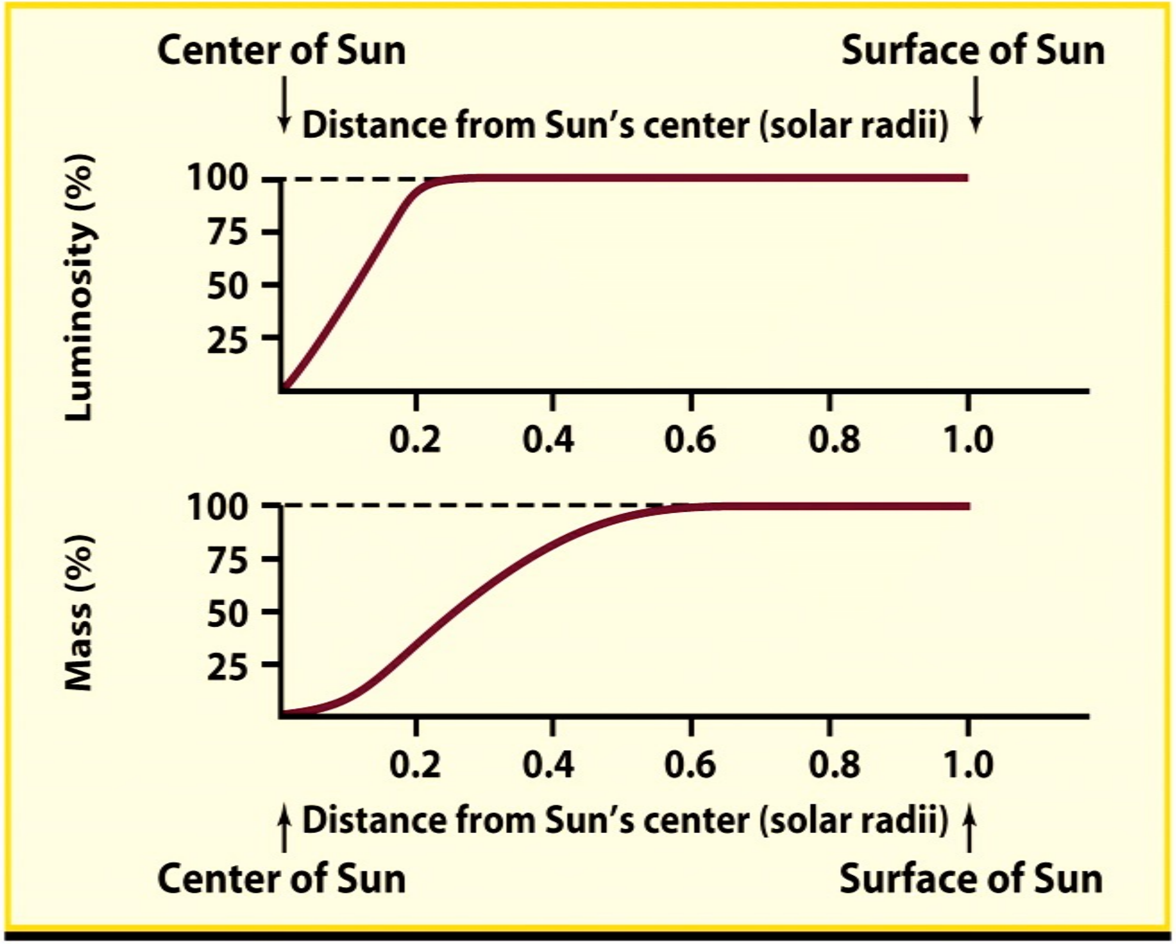
How does solar activity affect humans?

* Bursts of charged particles from the Sun can disrupt communications, satellites, and electrical power generation.

How does solar activity vary with time?

* Activity rises and falls in 11-year cycles.
* The **number** and **latitude** change.

Luminosity & Mass



Temp & Density