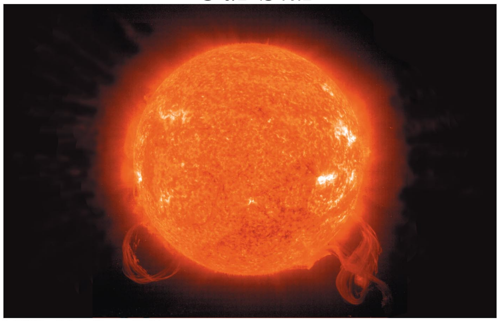
Chapter 14
Our Star



Facts about the Sun...

- Diameter:
  - 1.4 million km (109 × Diameter of Earth)
- Mass:
  - 2×10^{30} kg (300,000 × Mass of Earth)
- Composition:
  - 70% H, 28% He, 2% heavier elements
- Temperature:
  - 5800 K at "surface", 15 million K at core
- Energy Output (Luminosity):
  - 3.8×10^{26} Watts
- Rotation rate:
  - 25 days (equator) to 30 days (poles)

The Sun is the Largest Object in the Solar System

- The Sun contains more than 99.85% of the total mass of the solar system
- If you put *all* the planets in the solar system together, they would not fill up the volume of the Sun
- 110 Earths or 10 Jupiters fit across the diameter of the Sun

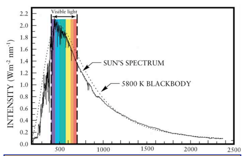
The Sun's Energy Output

- Sun's energy output $=3.8 \times 10^{26}$ Watts
  - How much is that?
- In 100 Watt light bulbs:
  - Could power about 4 trillion trillion light bulbs!

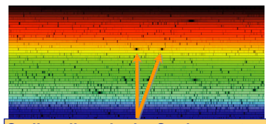
- 1 second of the energy output from the Sun is enough to meet current human energy demands for the next 500,000 years

Learning from Sunlight

- Sun's photosphere glows because it is **hot**
  - Average temp: 5,800 K
  - Emits **blackbody (or thermal) radiation**
- Absorption lines in the Sun's spectrum are caused by atoms in its atmosphere
  - Lines can tell us about the Sun's composition

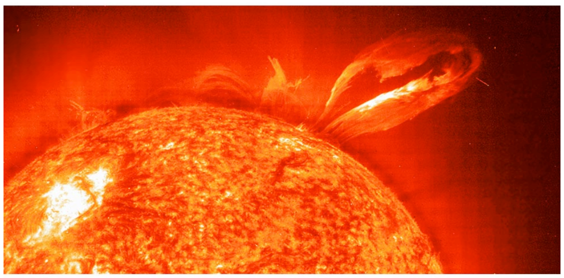


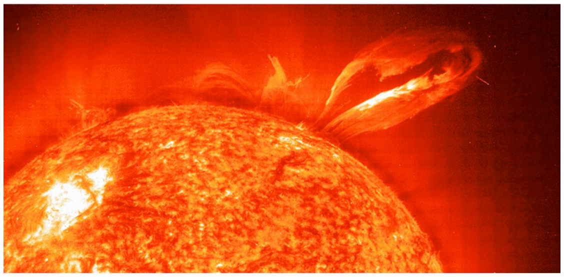
The Sun's spectrum compared to a perfect 5800 K blackbody



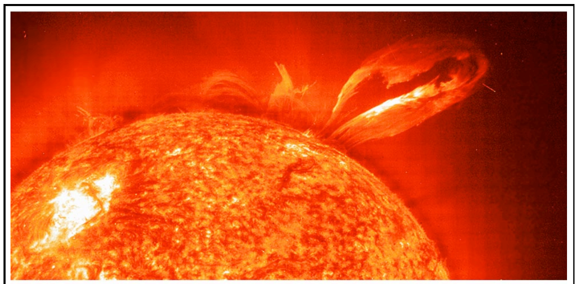
Sodium lines in the Sun's spectrum

Why does the Sun shine?

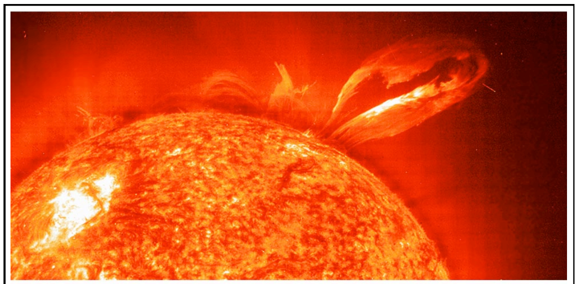




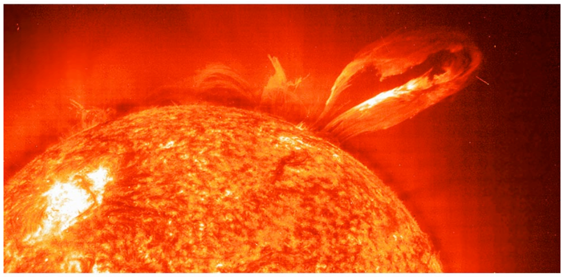
Is it on FIRE?



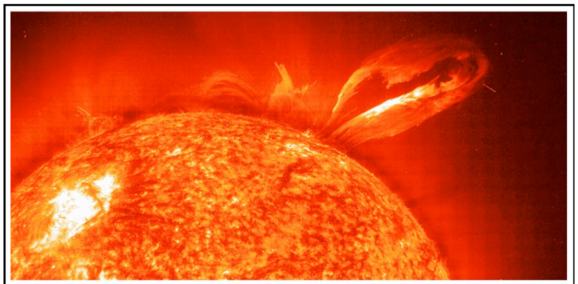
Is it burning coal or wood?



Is it burning coal or wood? … NO!

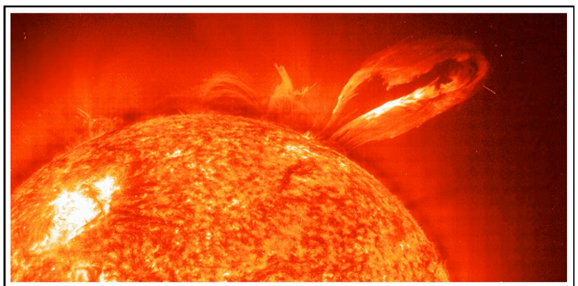


Is it CONTRACTING?



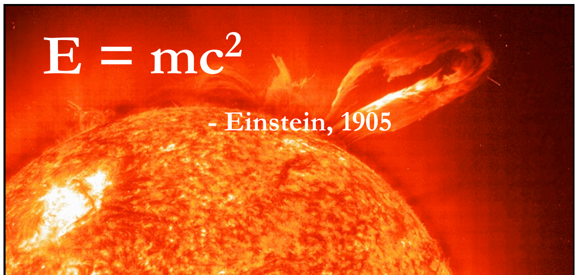
Is it CONTRACTING?

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



Is it CONTRACTING? … NO!

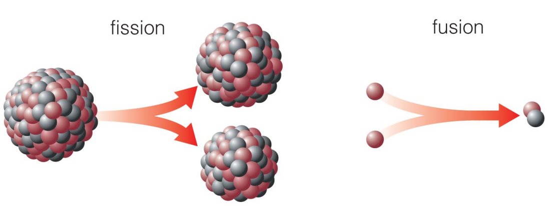
$$\frac{\text{Gravitational Potential Energy}}{\text{Luminosity}} \sim \text{25 million years}$$



It can be powered by NUCLEAR ENERGY!

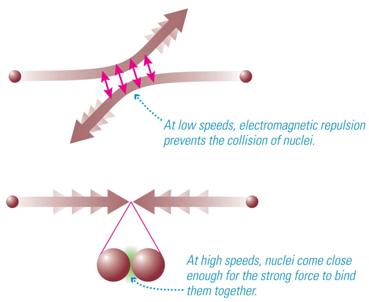
$$\frac{\text{Nuclear Potential Energy (core)}}{\text{Luminosity}} \sim \text{10 billion years}$$

How does nuclear fusion occur in the Sun?

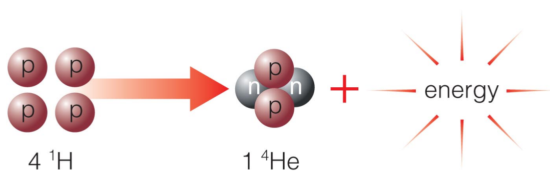


Fission
Big nucleus splits into smaller pieces
(Nuclear power plants)

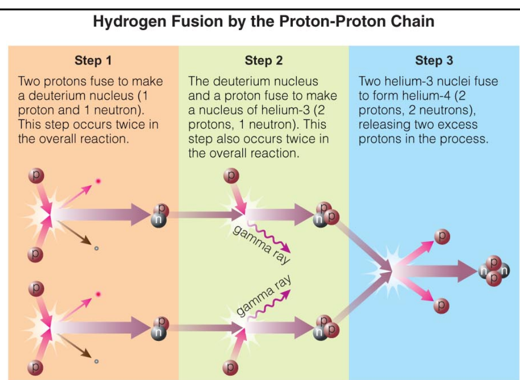
Fusion
Small nuclei stick together to make a bigger one
(Sun, stars)



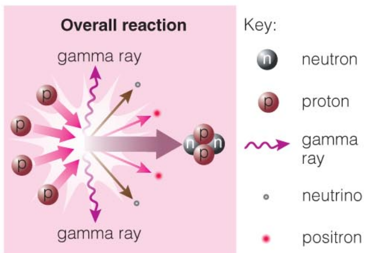
High temperature enables nuclear fusion to happen in the core



Sun releases energy by fusing four hydrogen nuclei into one helium nucleus



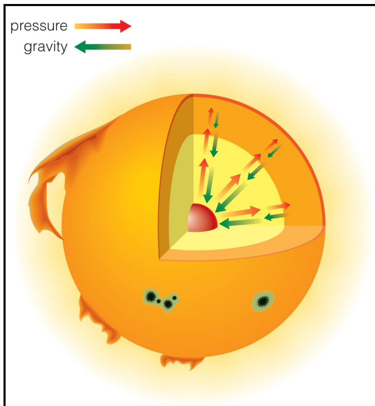
Proton-proton chain is how hydrogen fuses into helium in Sun



IN
4 protons

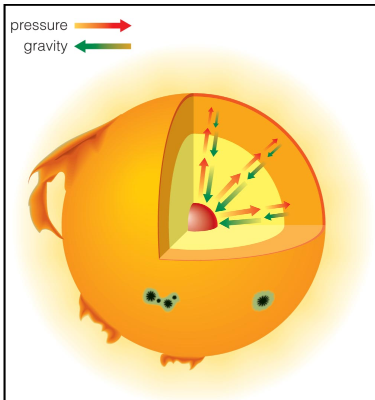
OUT
^{4}He nucleus
2 gamma rays
2 positrons
2 neutrinos

Total mass is 0.7% lower



Gravitational equilibrium:

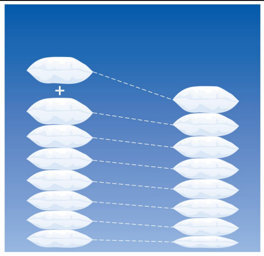
Energy provided by fusion maintains the pressure



Gravitational contraction:

Provided the energy that heated the core as Sun was forming

Contraction stopped when fusion began

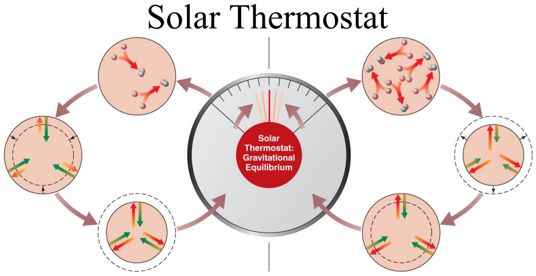


Weight of upper layers compresses lower layers

What would happen inside the Sun if a slight rise in core temperature led to a rapid rise in fusion energy?

A. The core would expand and heat up slightly
B. The core would expand and cool
C. The Sun would blow up like a hydrogen bomb

Solar Thermostat

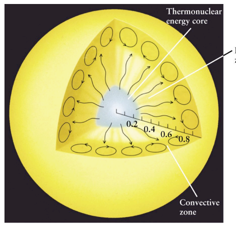


Decline in core temperature causes fusion rate to drop, so core contracts and heats up

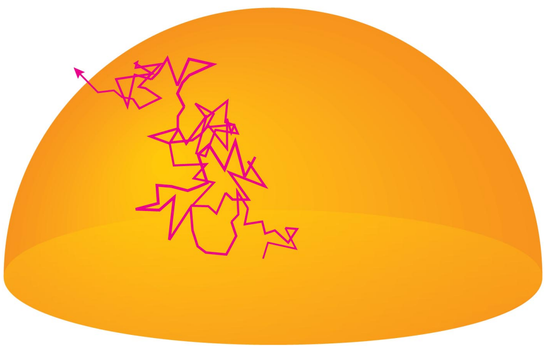
Rise in core temperature causes fusion rate to rise, so core expands and cools down

The Sun’s Interior

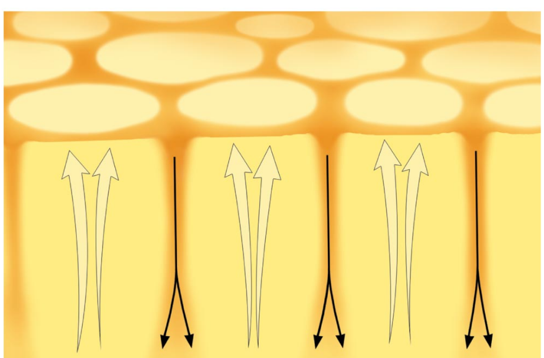
- Core
- Radiation zone
- Convection zone



Energy generated in the core of the Sun propagates outward through these different layers, and finally, through the atmosphere of the Sun. This process takes tens of thousands of years or more.



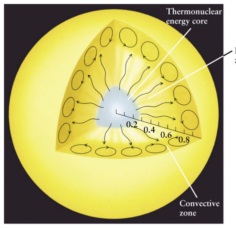
Energy gradually leaks out of radiation zone in form of randomly bouncing photons



Convection (rising hot gas) takes energy to surface

Heat Flow in the Sun

- Every square millimeter of the photosphere radiates more energy than a 60-watt light bulb
- Energy in the form of heat is flowing outward from the sun's interior



Heat energy flows outward from the Sun's interior to keep the photosphere hot - 5,800 K!

The Sun's "Atmosphere"

- **Photosphere** – inner
  - About 500 km thick
  - Average temp: 5,800 K
- **Chromosphere** – middle
  - Roughly 1,000 times fainter than the photosphere
  - Temps: 10,000 K
- **Corona** – outer
  - Temps up to 1,000,000 K!
  - Most of Sun's X rays

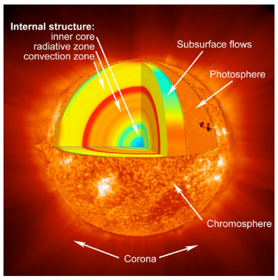
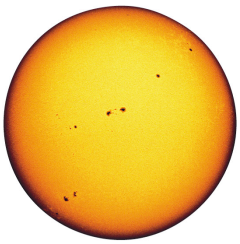


Diagram of the Sun, showing the layers of its atmosphere

The Sun's "surface"

- The Sun's disk looks like a mostly smooth layer of gas
- The apparent surface of the Sun is called **the photosphere**
  - A layer of gas about 500 km deep
  - Average temp: 5800 K
  - The source of most of the sunlight received by Earth



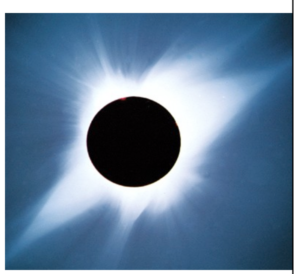
The photosphere is the Sun's apparent "surface", but it is 3,000 times less dense than the air you breathe!

The Chromosphere

- The deep red layer (hydrogen line at 656nm)
- About 10,000 km
- About 10,000 K
- Radiates most of the Sun's ultraviolet light

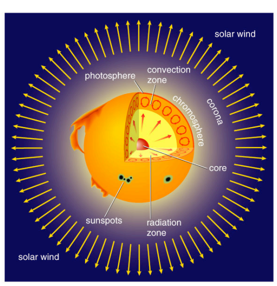
The Corona

- Outermost layer of the Sun's atmosphere
- Extends several million kilometers
- High temperature and low density

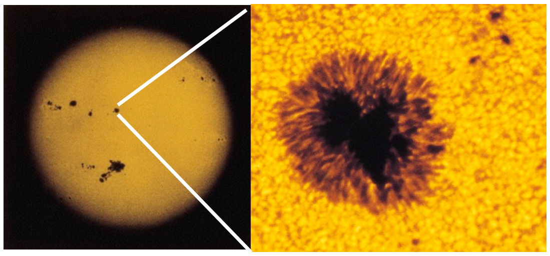


The Solar Wind

- The stream of charged particles blown away from the sun is called the **solar wind**
- The low-density gases of the solar wind blow past Earth at 300 to 800 km/s—with gusts as high as 1,000 km/s



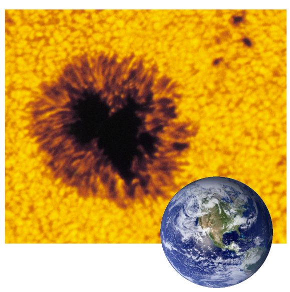
Surface of the Sun



http://earthobservatory.nasa.gov/Library/SolarMax/solarmax_sunspot.html

Sunspots

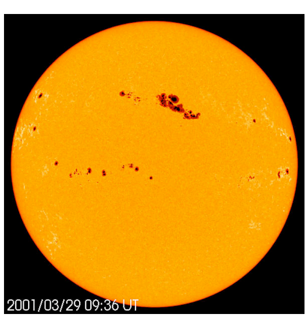
- Sunspots are regions of the photosphere that appear darker
- Cooler than the rest of the surface
  - About 1000 K cooler on average
- Sizes: 1500 – 50,000 km



Earth's radius = 6378 km

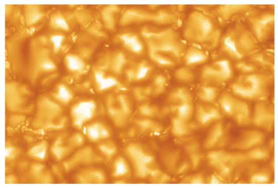
Features of Sunspots

- Cooler than the rest of the photosphere
  - 4,500 K vs. 5,800 K
- Typical sizes: 1,500 – 50,000 km
- Last a few days to weeks (sometimes months)
- Tend to form in groups
- Change over time
  - Grow, shrink, merge, rotate



Granulation

- In good images, the photosphere has a mottled appearance
- This is because it is made up of dark-edged regions called **granules**
  - Each granule is about 1000 km across
  - Each lasts about 10-20 minutes

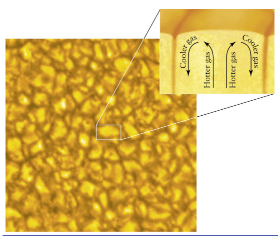


solar granulation

http://www3.kis.uni-freiburg.de/~pnb/movies/gran_mov27M_99_crea.mpg

Convection of hot gas brings energy to the surface

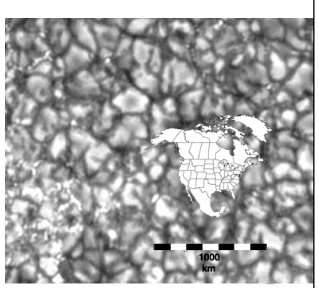
- Granules result from **convection currents** in the hot gas in and just below the photosphere
  - Centers granules are rising columns of hot gas
  - Edges are cooler, sinking gas
  - Brings heat energy to the Sun's surface



Bright blobs on the photosphere are where hot gas is reaching the surface

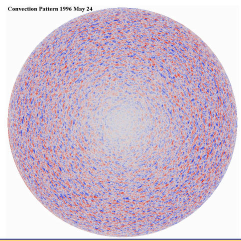
Which best approximates the size of a granule in the Sun's photosphere?

a) Earth
b) The United States
c) Texas
d) Arkansas
e) Chicago



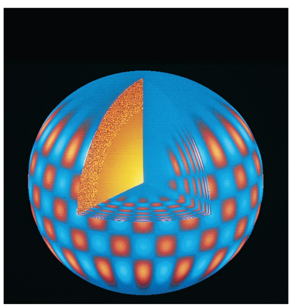
Detecting the motions of gas in the photosphere

- We can observe Doppler shifts in the light from the photosphere
- Allows us to map the convective flows of gas rising up to the Sun's surface



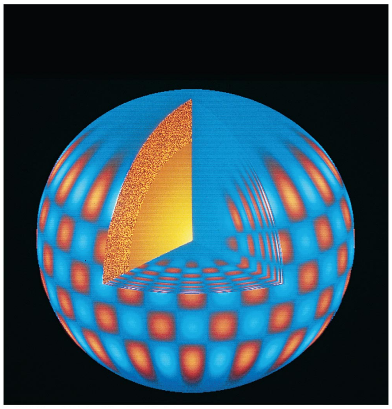
Convective flows in the Sun
Blue: Rising gas
Red: Falling gas

How we know what is happening inside the Sun?

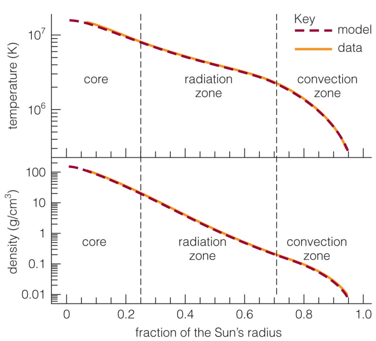


We learn about inside of Sun by …

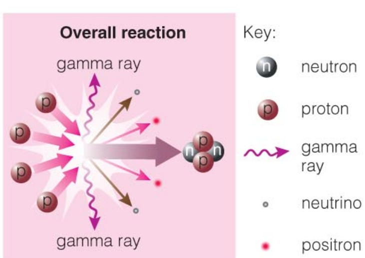
- Making mathematical models
- Observing solar vibrations
- Observing solar neutrinos



Patterns of vibration on surface tell us about what Sun is like inside



Data on solar vibrations agree very well with mathematical models of solar interior

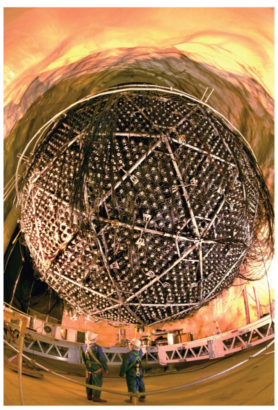


Neutrinos created during fusion fly directly through the Sun

Observations of these solar neutrinos can tell us what's happening in core

Solar neutrino problem:

Early searches for solar neutrinos failed to find the predicted number

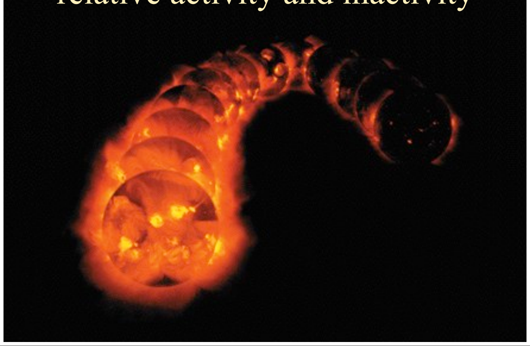


Solar neutrino problem:

Early searches for solar neutrinos failed to find the predicted number

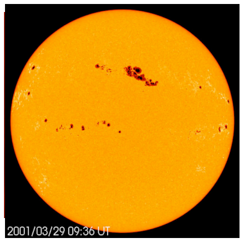
More recent observations find the right number of neutrinos, but some have changed form

The Sun goes through periods of relative activity and inactivity



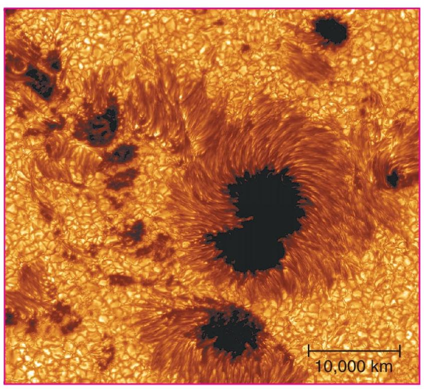
The Active Sun

- Periodic disruptions in the Sun's atmosphere
  - Sunspots
  - Prominences
  - Solar Flares
  - Coronal Mass Ejections
- Connected to each other and the Sun's magnetic field!



Sunspots

prominence



Sunspots

Are cooler than other parts of the Sun's surface (4000 K)

Are regions with strong magnetic fields

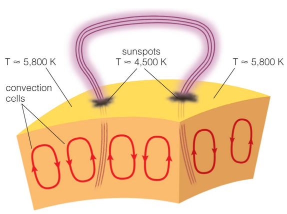
How would sunspots appear if you could magically remove them from the Sun?

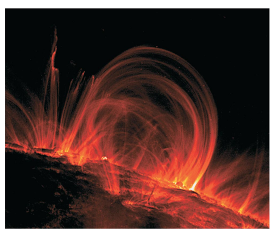
a) They would appear blue-white
b) They would shine only with reflected sunlight
c) Because sunspots are dark spots, they would be invisible against the blackness of space
d) They would shine bright orange in color
e) They would appear the same color as the photosphere

Sunspots and Magnetic Fields

- Sunspots are caused by very strong magnetic fields on the Sun
- When regions of intense of magnetism break the visible surface of the Sun, they produce sunspots

Magnetic field "loops" popping through the photosphere make sunspots

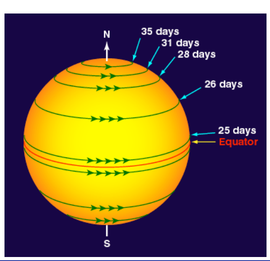




Loops of bright gas often connect sunspot pairs

The Sun rotates *differentially*

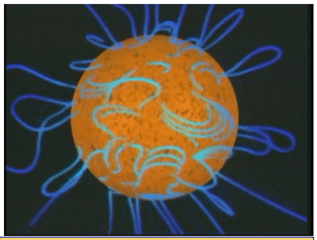
- Sun does not rotate as a rigid sphere
- Equator of the Sun rotates faster than the poles of the Sun
- Called ***differential rotation***
- This has a very interesting effect on the Sun's magnetic field



The Sun rotates fastest at the equator, and slowest at the poles

Sun's rotation twists up the magnetic field

- Differential rotation winds up the Sun's magnetic field
- Creates very intense regions
- When field lines get too twisted, they pop thru the surface
- Make sunspots!



The Sun's rotation makes a tangled mess of magnetic field lines at the surface

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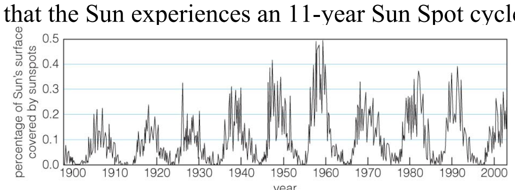
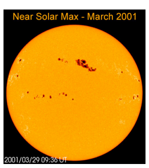
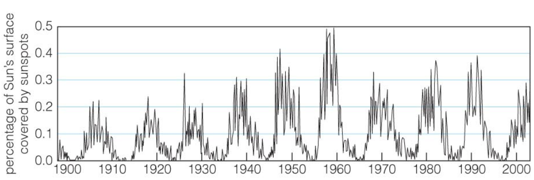
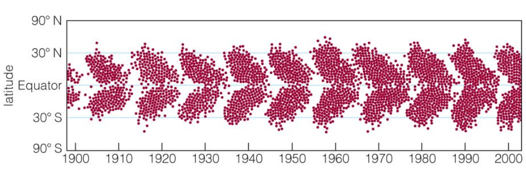
The annual change in numbers of **sunspots** reveals that the Sun experiences an 11-year Sun Spot cycle



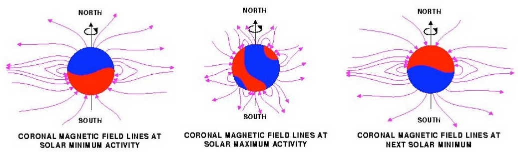




Number of sunspots rises and falls in 11-year cycle

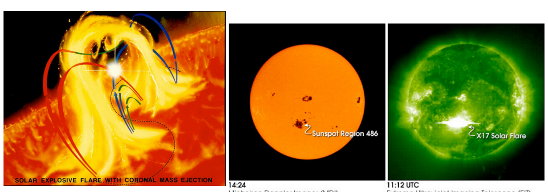


The 11-year sunspot cycle is a really 22-year magnetic cycle!

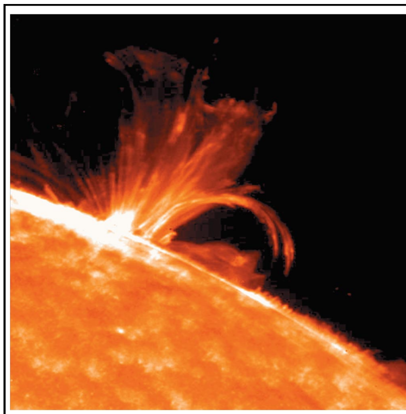


Every 11 years, the field breaks apart and reorders itself - North and south flip!

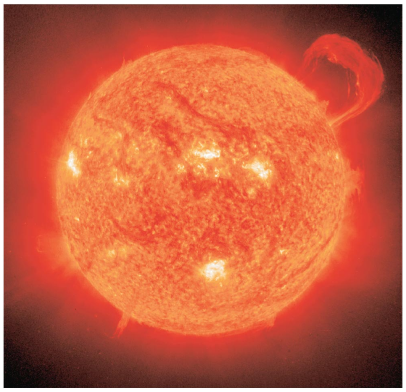
Crossing the Streams: Solar Flares



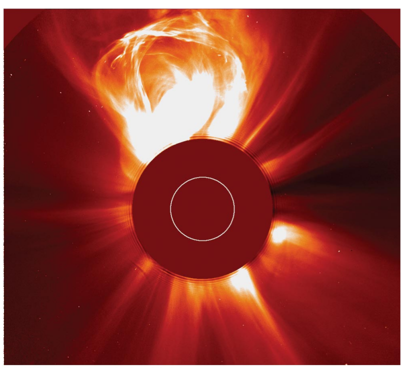
Flares occur when intense magnetic fields on the Sun "short circuit" and release their energy explosively



Magnetic activity causes ***solar flares*** that send bursts of X-rays and charged particles into space



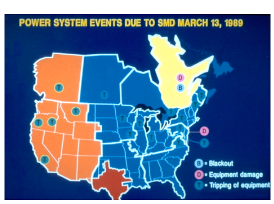
Magnetic activity also causes ***solar prominences*** that erupt high above the Sun's surface

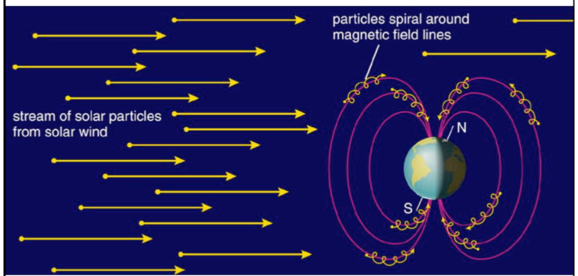


Coronal mass ejections send bursts of energetic charged particles out through the solar system

Blackout of 1989

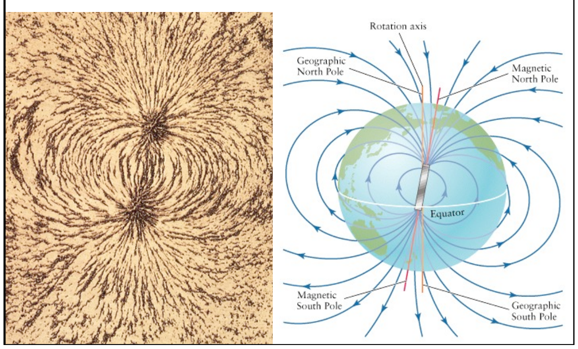
- March 13, 1989 - a CME knocked out a power transformer in Quebec
- Plunged the whole province into darkness!
- Affected power grids across North America

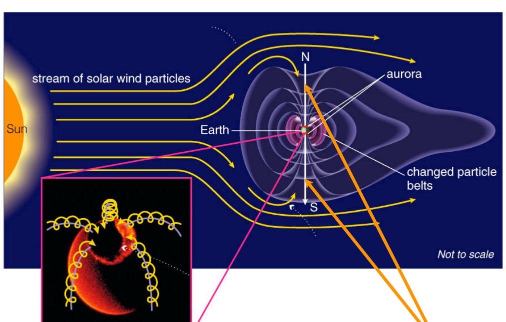




Charged particles streaming from Sun can disrupt electrical power grids and can disable communications satellites

The Earth's magnetic field is caused by movement of material in Earth's interior





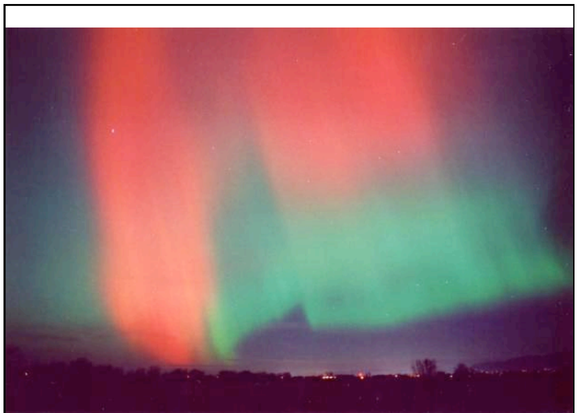
Most solar wind particles are deflected by Earth's magnetic field, but some enter at the poles

Relevance of Earth's protective magnetosphere

- ***Protects against Solar Flares*** - violent explosions on the Sun releasing large burst of charged particles into the solar system
- ***Protects against Solar Wind*** - dangerous stream of charged particles constantly coming from the Sun
- ***Northern Lights*** (Aurora Borealis)

Northern Lights (Aurora Borealis)

As the charged particles from the Sun interact with the magnetic field around Earth, the particles collide with the nitrogen and oxygen atoms in the atmosphere and excite those atoms to emit light



Aurora as seen from space