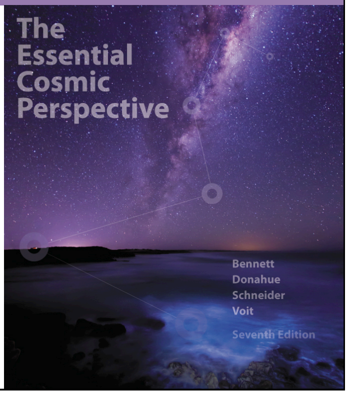
Lecture Outline

Chapter 11: Our Star

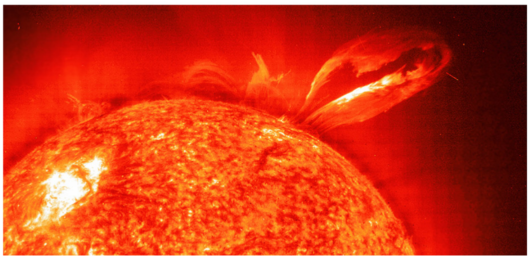


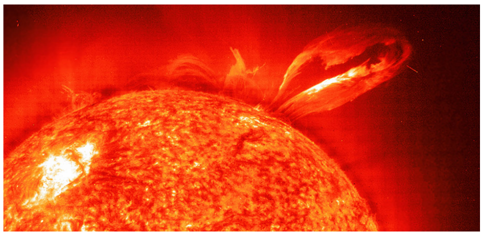
11.1 A Closer Look at the Sun

Our goals for learning:

- Why does the Sun shine?
- What is the Sun's structure?

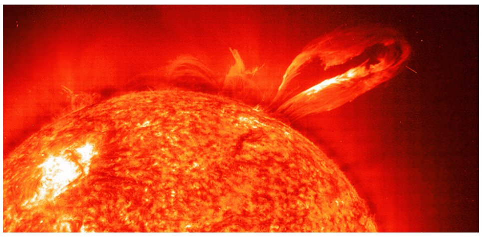
Why does the Sun shine?





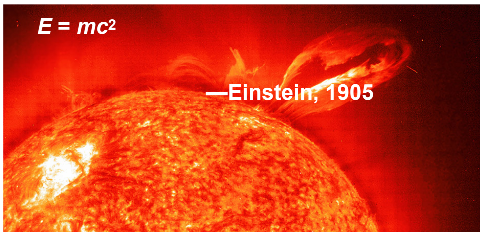
Is it on FIRE?

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



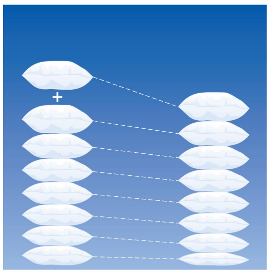
Is it CONTRACTING?

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

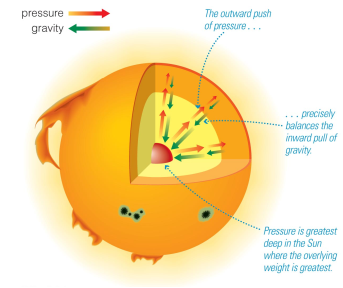


It is powered by NUCLEAR ENERGY!

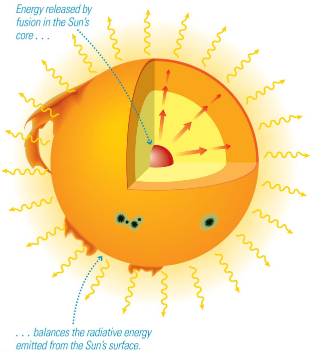
$$\frac{\text{Nuclear Potential Energy (core)}}{\text{Luminosity}} \sim 10 \text{ billion years}$$



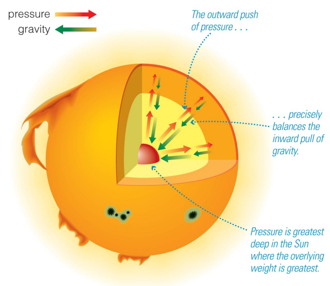
Weight of upper layers compresses lower layers.



Gravitational equilibrium: Gravity pulling in balances pressure pushing out.



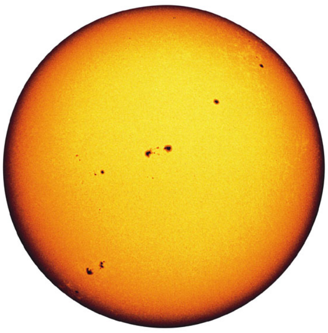
Energy balance: Thermal energy released by fusion in core balances radiative energy lost from surface.



Gravitational contraction… provided energy that heated the core as the Sun was forming.

Contraction stopped when fusion started replacing the energy radiated into space.

What is the Sun's structure?



Radius:

6.9×10^8 m

(109 times Earth)

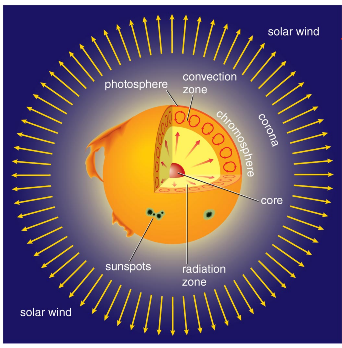
Mass:

2×10^{30} kg

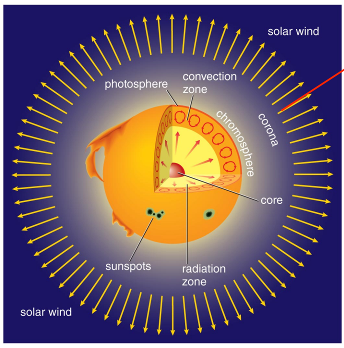
(300,000 Earths)

Luminosity:

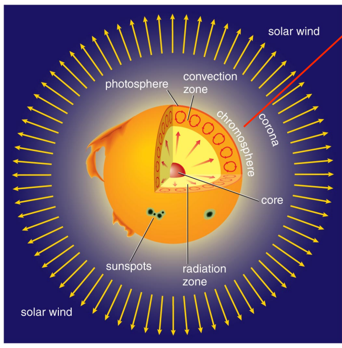
3.8×10^{26} watts



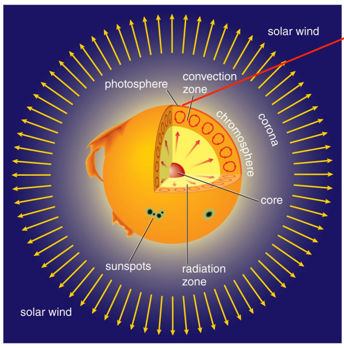
Solar wind: A flow of charged particles from the surface of the Sun



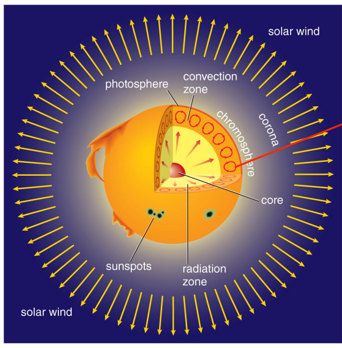
Corona:
Outermost layer of solar atmosphere
~ 1 million K



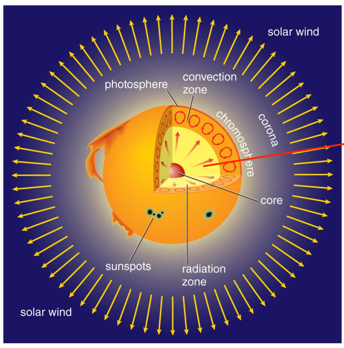
Chromosphere:
Middle layer of solar atmosphere
~ 10^4–10^5 K



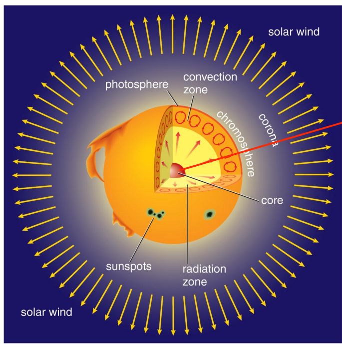
Photosphere:
Visible surface of the Sun
~ 6000 K



Convection zone:
Energy transported upward by rising hot gas



Radiation zone:
Energy transported upward by photons



Core:
Energy generated by nuclear fusion
~ 15 million K

What have we learned?

- Why does the Sun shine?
  - The Sun shines steadily because **nuclear fusion** in the core maintains both **gravitational equilibrium** between pressure and gravity and **energy balance** between thermal energy released in core and radiative energy lost from the Sun's surface.

What have we learned?

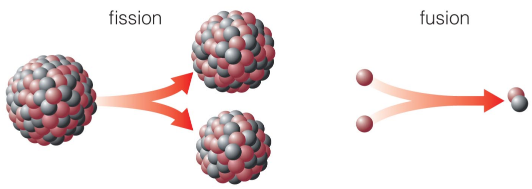
- What is the Sun's structure?
  - From inside out, the layers are
    - Core
    - Radiation zone
    - Convection zone
    - Photosphere
    - Chromosphere
    - Corona

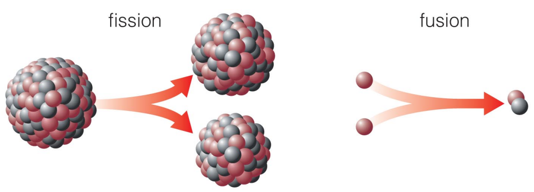
11.2 Nuclear Fusion in the Sun

Our goals for learning:

- How does nuclear fusion occur in the Sun?
- How does the energy from fusion get out of the Sun?
- How do we know what is happening inside the Sun?

How does nuclear fusion occur in the Sun?





Fission

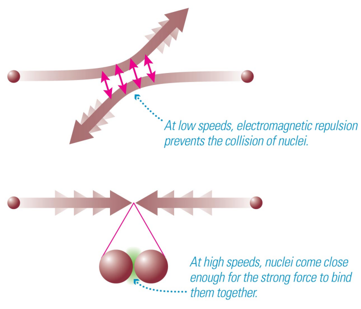
Big nucleus splits into smaller pieces.

(Nuclear power plants)

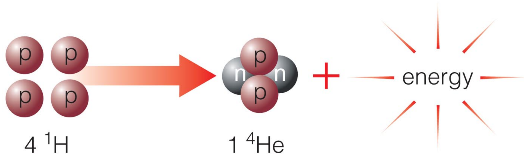
Fusion

Small nuclei stick together to make a bigger one.

(Sun, stars)



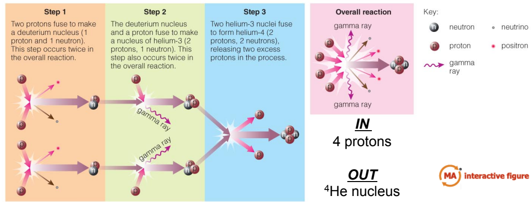
High temperatures enable nuclear fusion to happen in the core.



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

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

Hydrogen Fusion by the Proton–Proton Chain

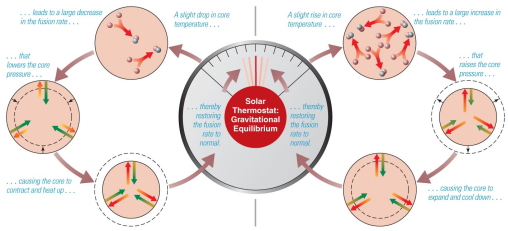


IN
4 protons

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

Total mass is 0.7% lower.

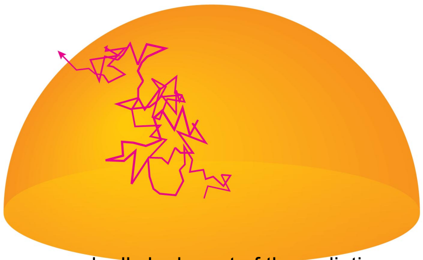
Solar Thermostat



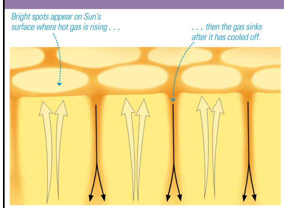
Decline in core temperature causes fusion rate to drop, so core contracts and heats up.

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

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

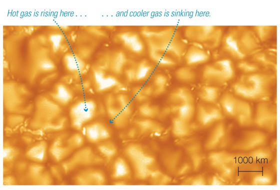


Energy gradually leaks out of the radiation zone in the form of randomly bouncing photons.



a This diagram shows convection beneath the Sun's surface: hot gas (yellow arrows) rises while cooler gas (black arrows) descends around it.

Convection (rising hot gas) takes energy to the surface.

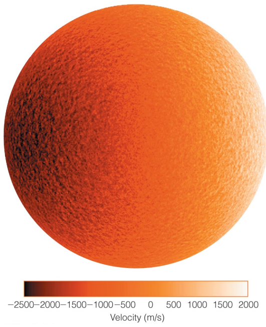


b This photograph shows the mottled appearance of the Sun's photosphere. The bright spots correspond to the rising plumes of hot gas in the diagram in part a.

Bright blobs on photosphere where hot gas reaches the surface

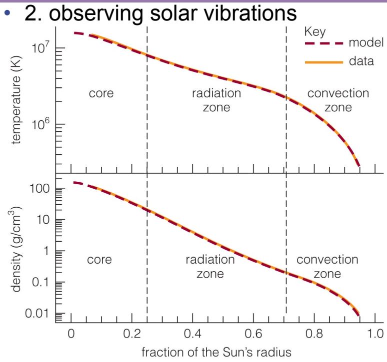
How do we know what is happening inside the Sun?

- 1. making mathematical models



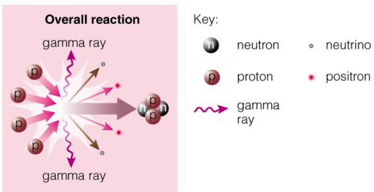
Patterns of vibration on the surface tell us about what the Sun is like inside.

- 2. observing solar vibrations



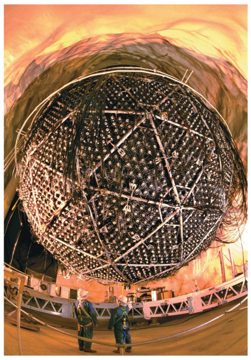
Data on solar vibrations agree with mathematical models of solar interior.

- 3. observing solar neutrinos



Neutrinos created during fusion fly directly through the Sun.

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



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.

What have we learned?

- How does nuclear fusion occur in the Sun?
  - The core's extreme temperature and density are just right for the nuclear fusion of hydrogen to helium through the proton–proton chain.
  - Gravitational equilibrium and energy balance together act as a thermostat to regulate the core temperature because the fusion rate is very sensitive to temperature.

What have we learned?

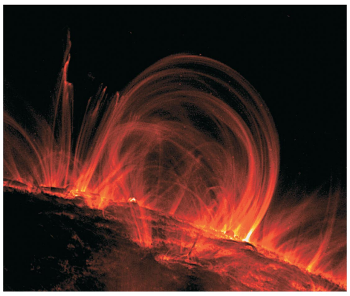
- How does the energy from fusion get out of the Sun?
  - Randomly bouncing photons carry it through the radiation zone.
  - The rising of hot plasma carries energy through the convection zone to the photosphere.
- How do we know what is happening inside the Sun?
  - Mathematical models agree with observations of solar vibrations and solar neutrinos.

11.3 The Sun–Earth Connection

Our goals for learning:

- What causes solar activity?
- How does solar activity vary with time?

What causes solar activity?

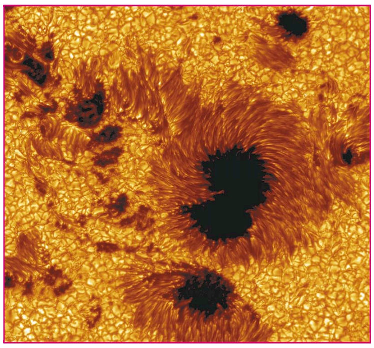


b This X-ray photo (from NASA's *TRACE* mission) shows hot gas trapped within looped magnetic field lines.

Solar activity is like "weather" on Earth.

- Sunspots
- Solar flares
- Solar prominences

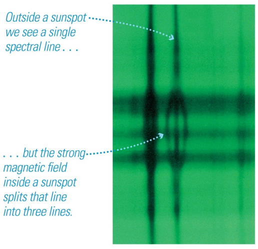
All these phenomena are related to magnetic fields.



Sunspots…

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

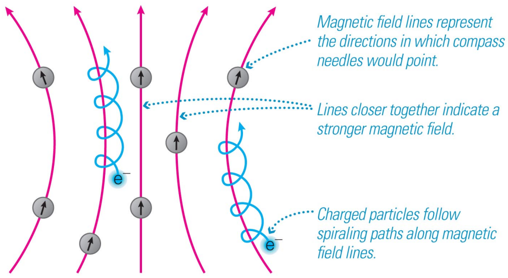
Are regions with strong magnetic fields.



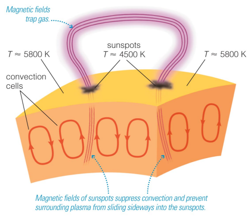
b Very strong magnetic fields split the absorption lines in spectra of sunspot regions. The dark vertical bands are absorption lines in a spectrum of the Sun. Notice that these lines split where they cross the dark horizontal bands corresponding to sunspots.

Zeeman Effect

We can measure magnetic fields in sunspots by observing the splitting of spectral lines.

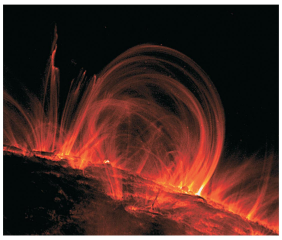


Charged particles spiral along magnetic field lines.

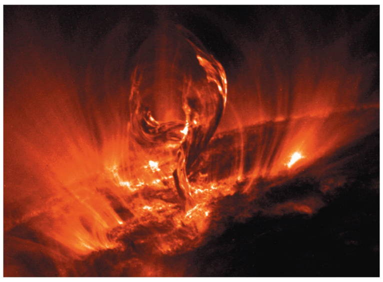


a Pairs of sunspots are connected by tightly wound magnetic field lines.

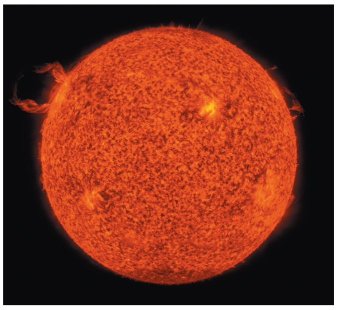
Loops of bright gas often connect sunspot pairs.



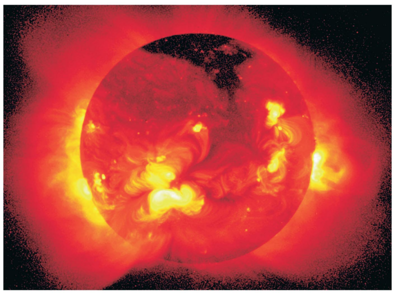
b This X-ray photo (from NASA's *TRACE* mission) shows hot gas trapped within looped magnetic field lines.



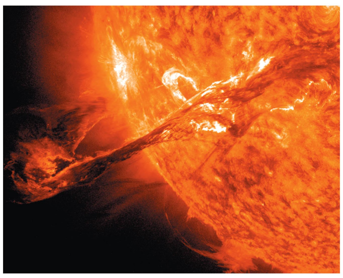
Magnetic activity causes ***solar flares*** that send bursts of X rays and charged particles into space.



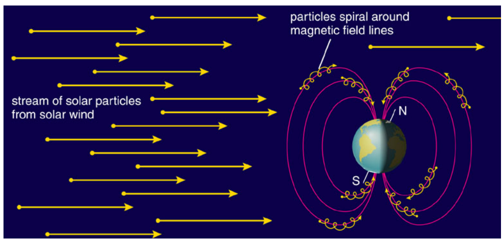
Magnetic activity also causes ***solar prominences*** that erupt high above the Sun's surface.



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

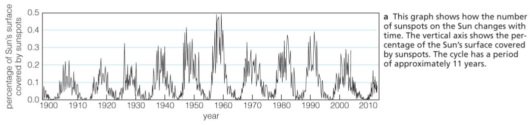


Coronal mass ejections send bursts of energetic charged particles out through the solar system.

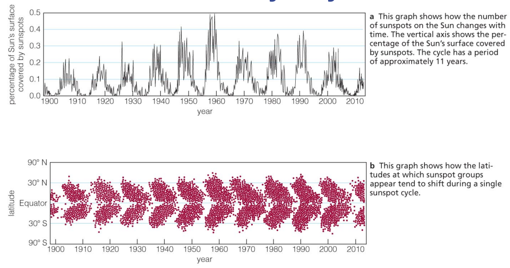


Charged particles streaming from the Sun can disrupt electrical power grids and disable communications satellites.

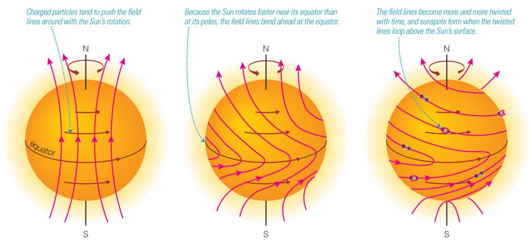
How does solar activity vary with time?



How does solar activity vary with time?



The number of sunspots rises and falls in 11-year cycles.



The sunspot cycle has something to do with the winding and twisting of the Sun's magnetic field.

What have we learned?

- What causes solar activity?
  - The stretching and twisting of magnetic field lines near the Sun's surface causes solar activity.
  - 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.