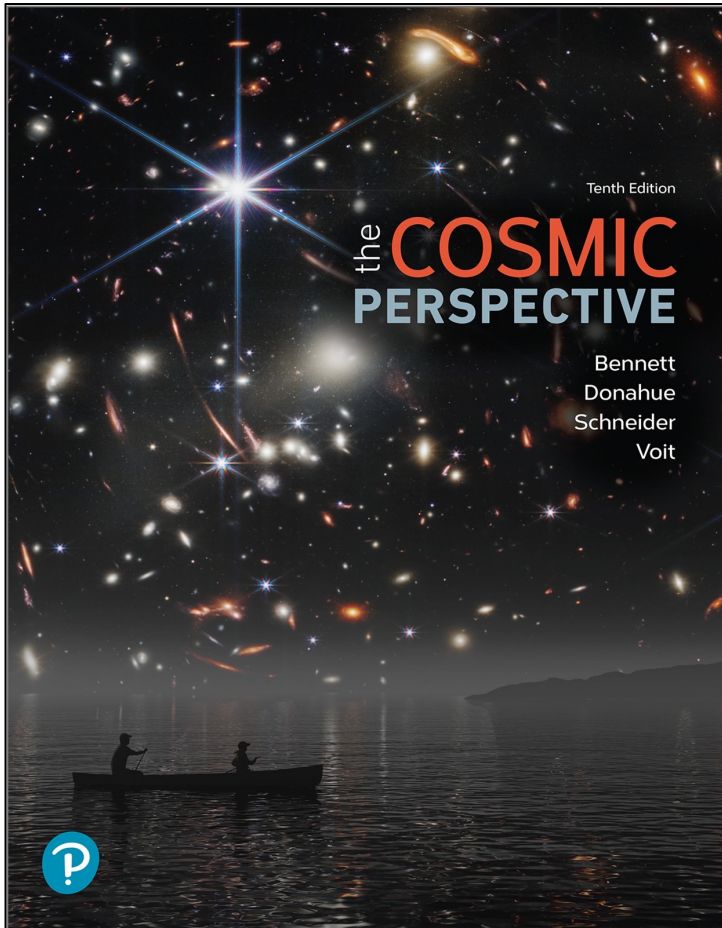


The Cosmic Perspective

Tenth Edition



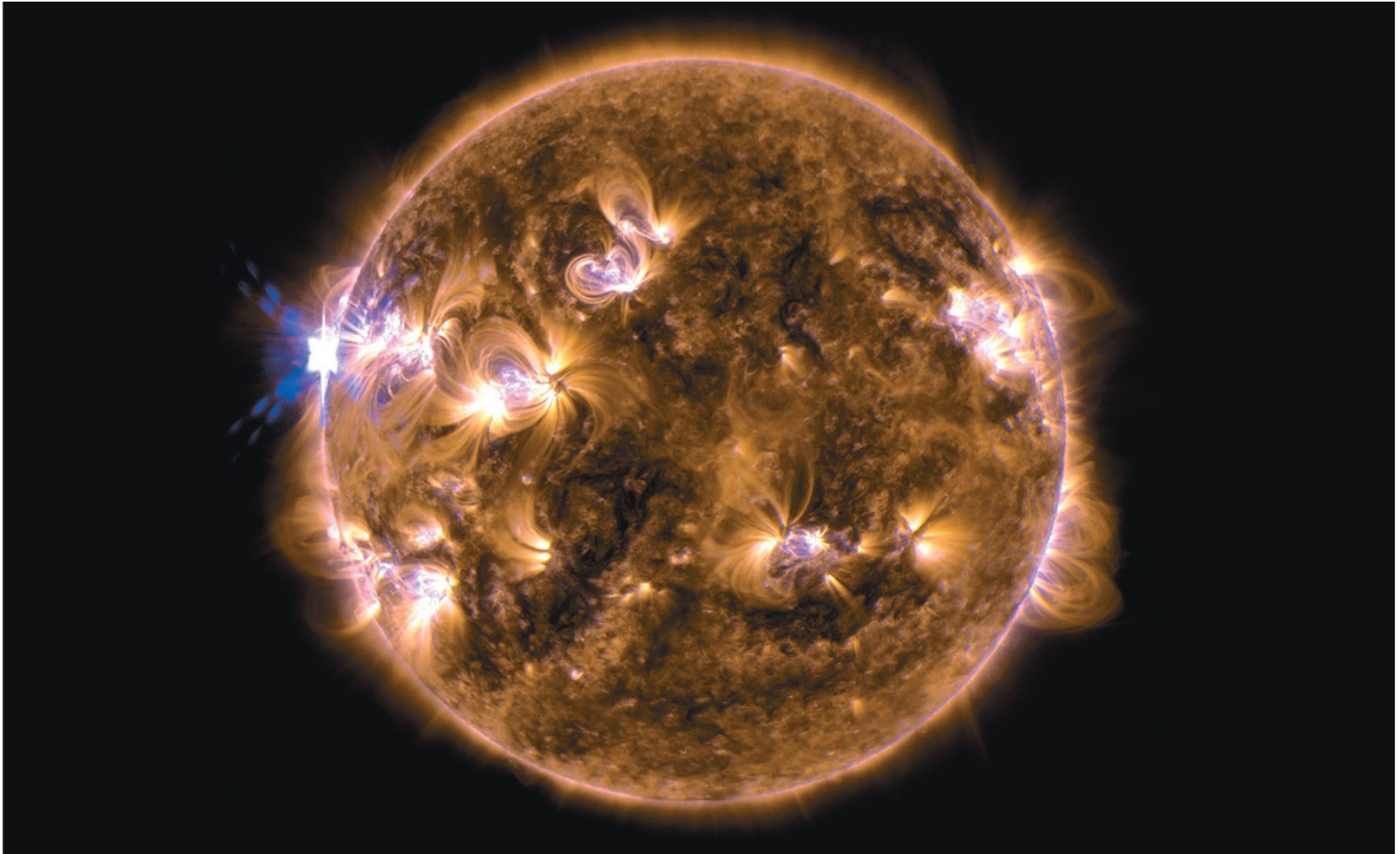
Chapter 14 Lecture

Our Star

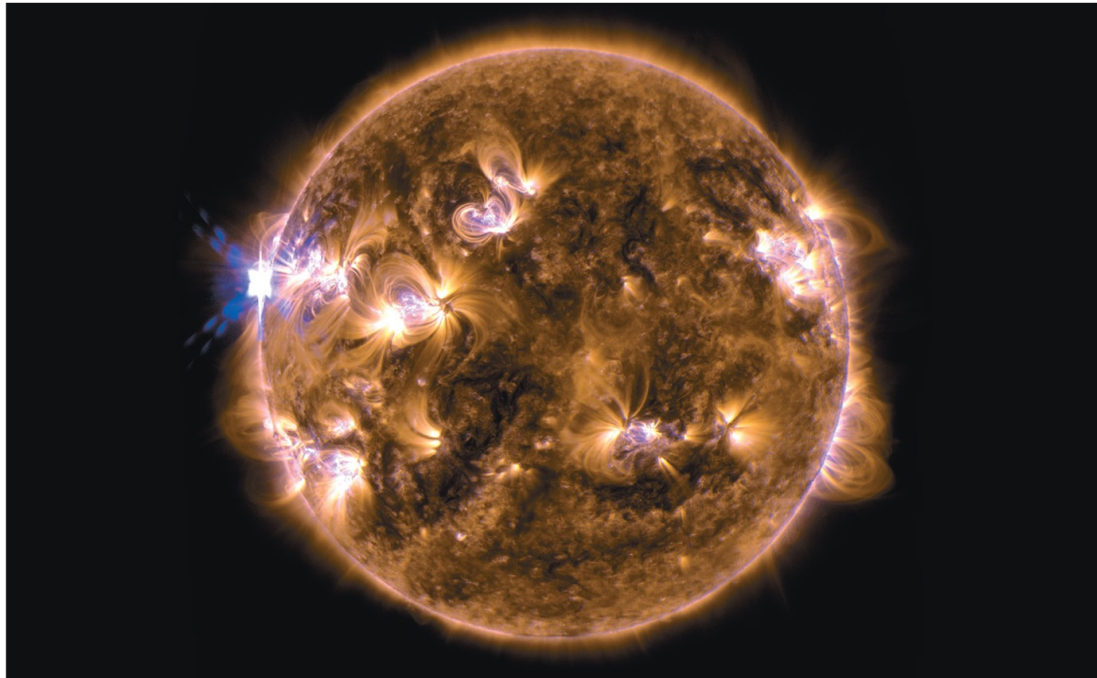
14.1 A Closer Look at the Sun

- Our goals for learning:
 - **Why does the Sun shine?**
 - **What is the Sun's structure?**

Why Does the Sun Shine?



A Closer Look at the Sun (7 of 7)



- It can be powered by Nuclear energy! ($E = mc^2$)

$$\frac{\text{Nuclear potential energy (core)}}{\text{Luminosity}} \sim 10 \text{ billion years}$$

The Stable Sun (1 of 4)

- The Sun is in **gravitational equilibrium** (also called **hydrostatic equilibrium**).
- Weight of upper layers compresses lower layers.

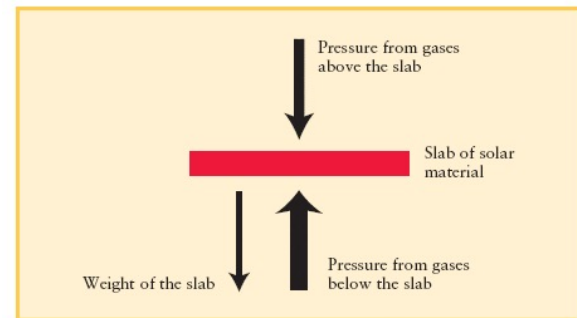
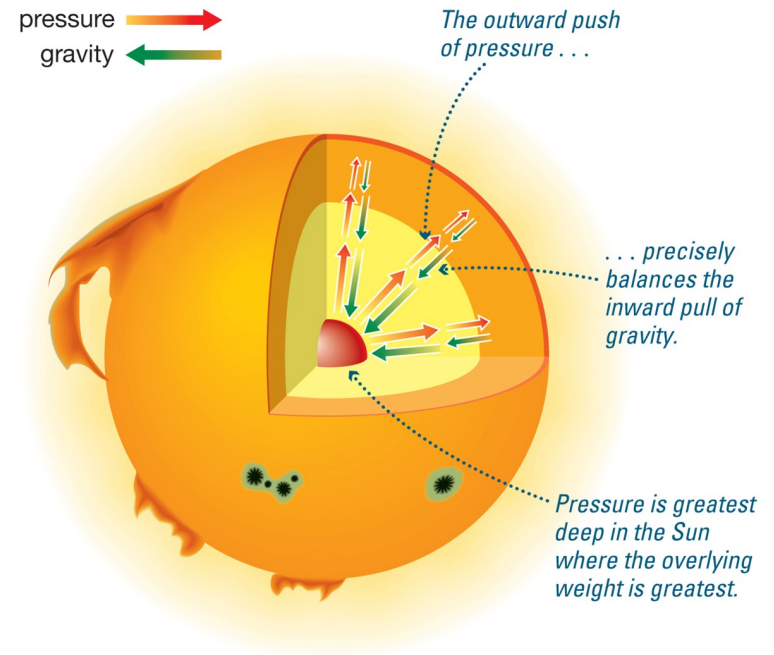


The Stable Sun (2 of 4)

Gravitational equilibrium:

- Energy supplied by fusion maintains the pressure that balances the inward crush of gravity.

($F_p = P/A$, where P is pressure, A is area and F_p is the force from this pressure)

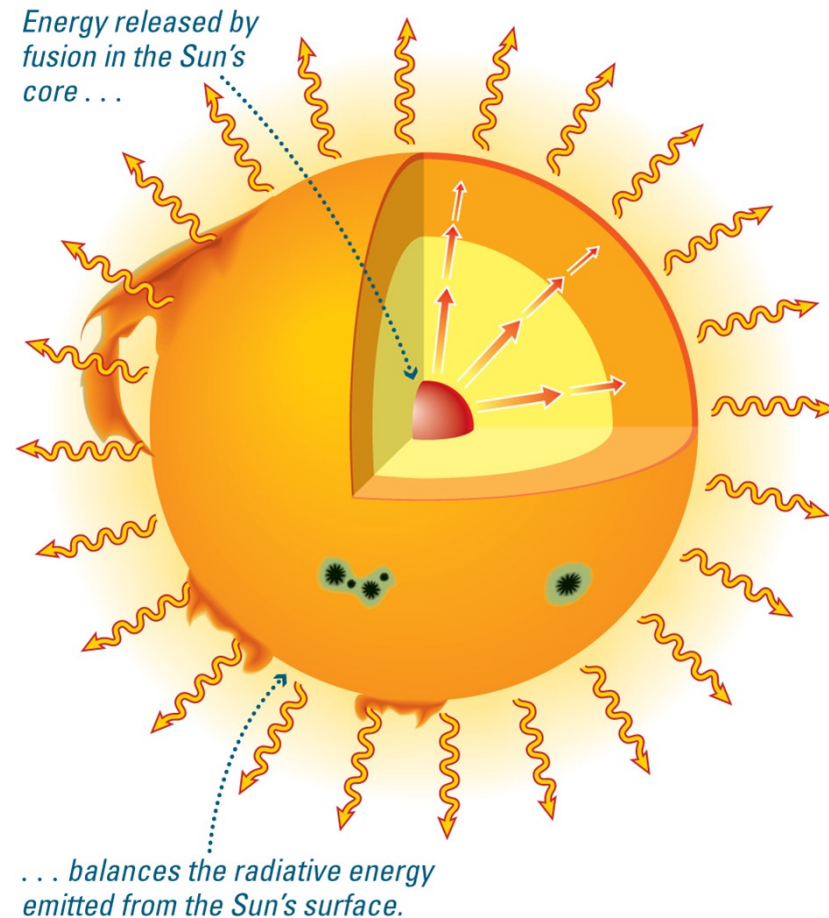


(a) Material inside the sun is in hydrostatic equilibrium, so forces balance

The Stable Sun (3 of 4)

Energy Balance:

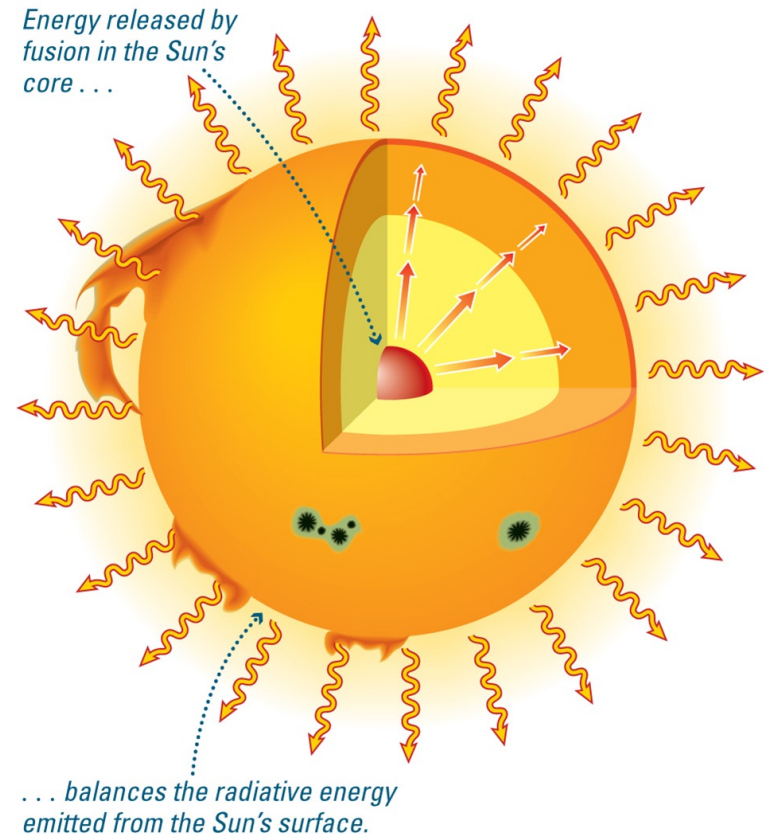
- The rate at which energy radiates from the surface of the Sun must be the same as the rate at which it is released by fusion in the core.



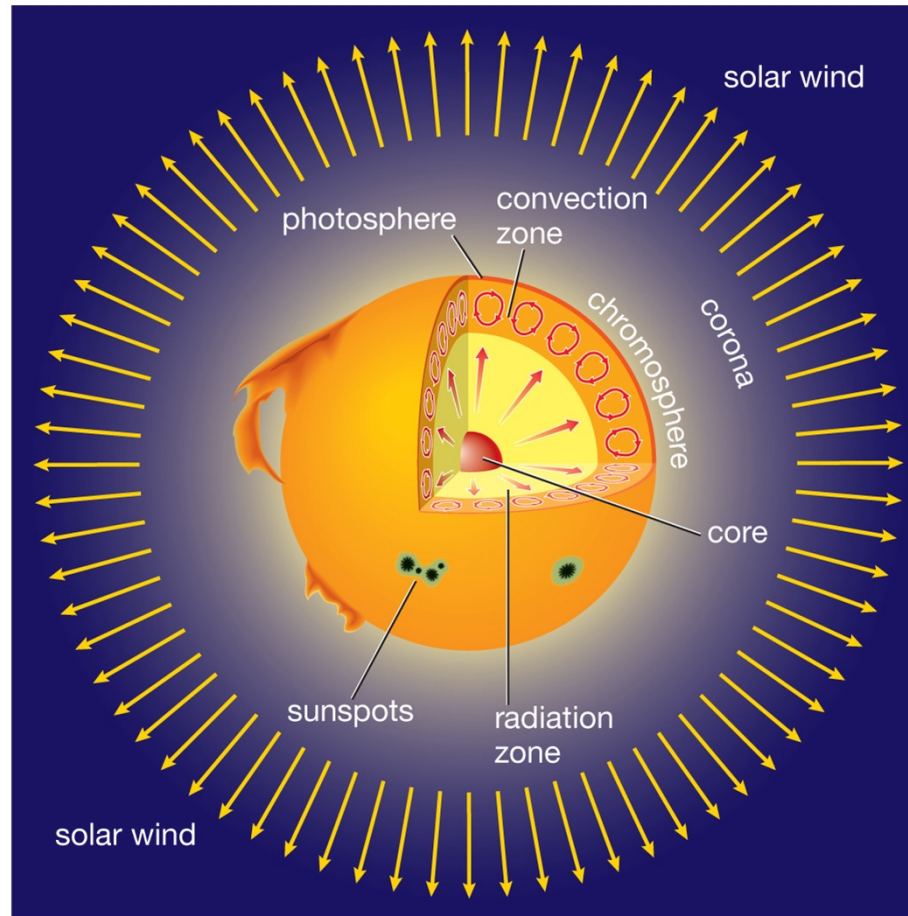
The Stable Sun (4 of 4)

Gravitational contraction:

- Provided the energy that heated the core as Sun was forming.
- Contraction stopped when fusion began.



What Is the Sun's Structure?



Basic Properties of the Sun

Radius:

6.9×10^8 m (109 times Earth)

Mass:

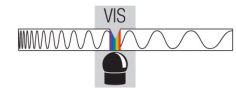
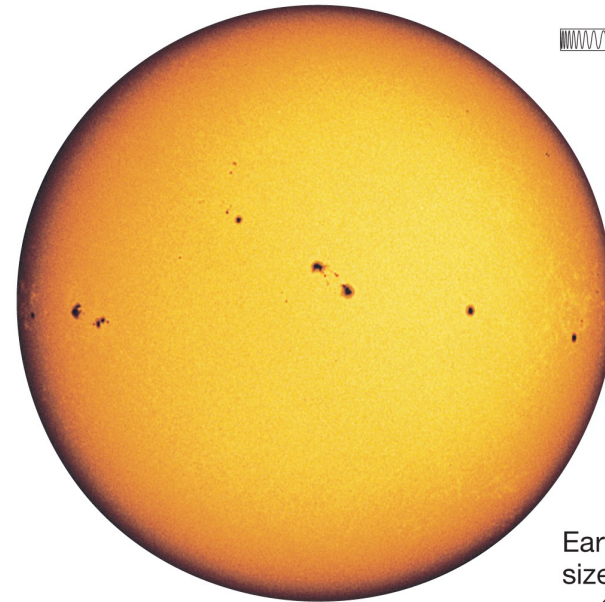
2×10^{30} kg (300,000 Earths)

Luminosity:

3.8×10^{26} watts

Rotation:

25 days at the equator to 30 days at the poles



Earth shown for size comparison

Thought Question 1 (1 of 2)

What two properties of Earth are necessary to use Newton's version of Kepler's third law to determine the mass of the Sun?

- A. Earth's radius and mass
- B. Earth's orbital radius and mass
- C. Earth's orbital radius and orbital period
- D. Earth's radius and orbital period

Thought Question 1 (2 of 2)

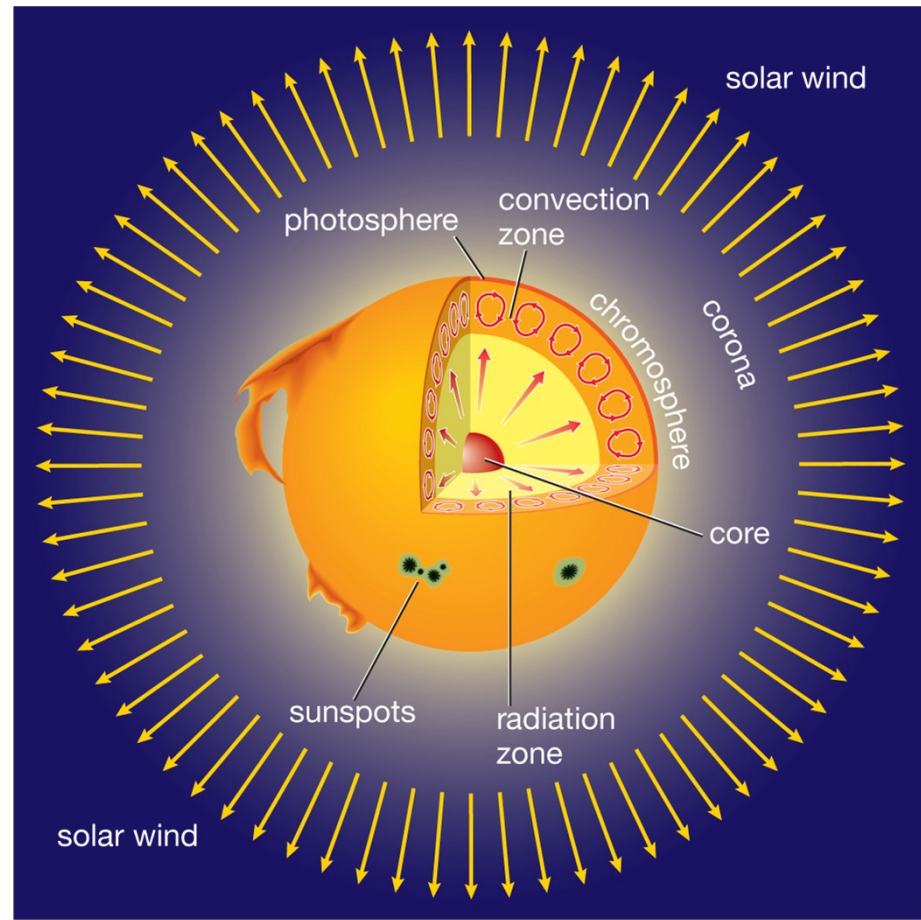
What two properties of Earth are necessary to use Newton's version of Kepler's third law to determine the mass of the Sun?

- A. Earth's radius and mass
- B. Earth's orbital radius and mass
- C. Earth's orbital radius and orbital period**
- D. Earth's radius and orbital period

The Sun's Structure (1 of 7)

Solar wind:

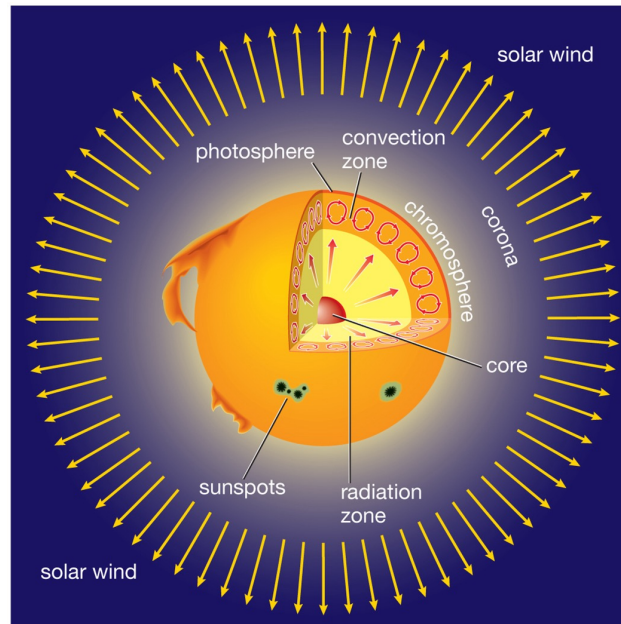
- A flow of charged particles from the surface of the Sun
- The solar wind speed can range between $\sim 300 - 1000$ km/s



The Sun's Structure (2 of 7)

Corona:

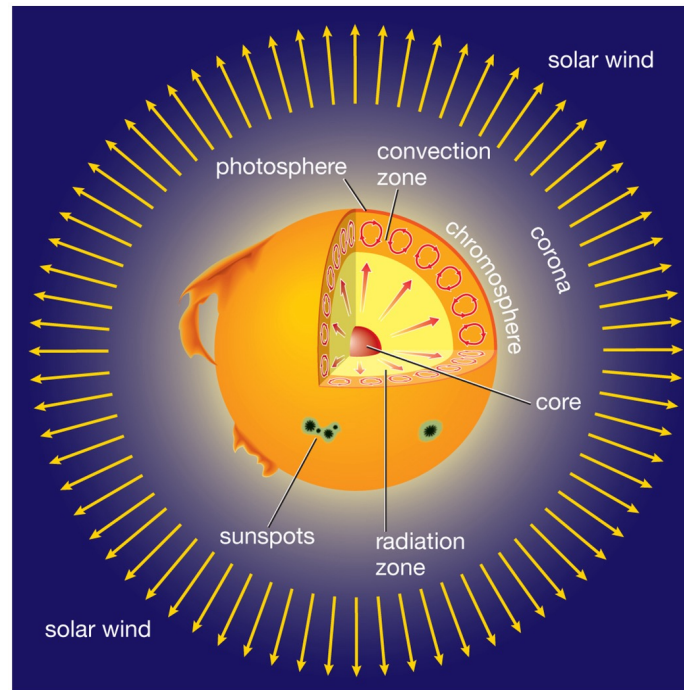
- Very thin (low density) material
- Outermost layer of solar atmosphere ~ 1-2 million K



The Sun's Structure (3 of 7)

Chromosphere:

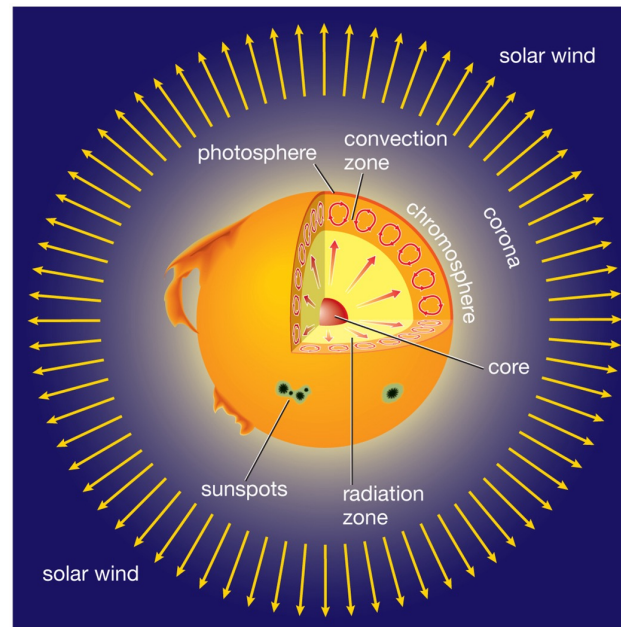
- Middle layer of solar atmosphere ~ 10,000 – 100,000 K



The Sun's Structure (4 of 7)

Photosphere:

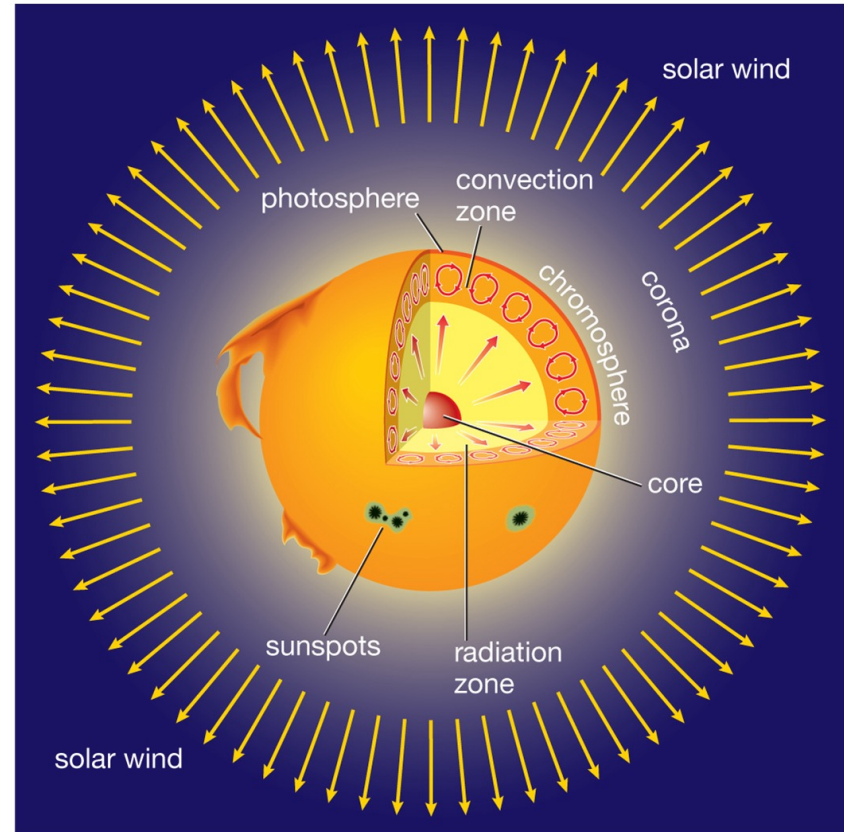
- Where the plasma becomes transparent
- Visible surface of Sun ~ 5800 K



The Sun's Structure (5 of 7)

Convection Zone:

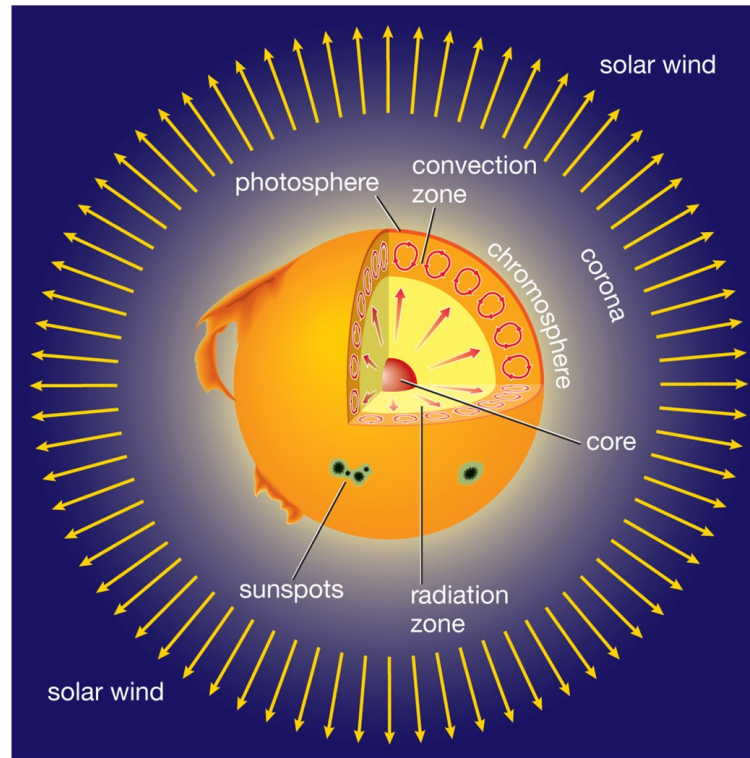
- Energy transported upward by rising hot gas



The Sun's Structure (6 of 7)

Radiation Zone:

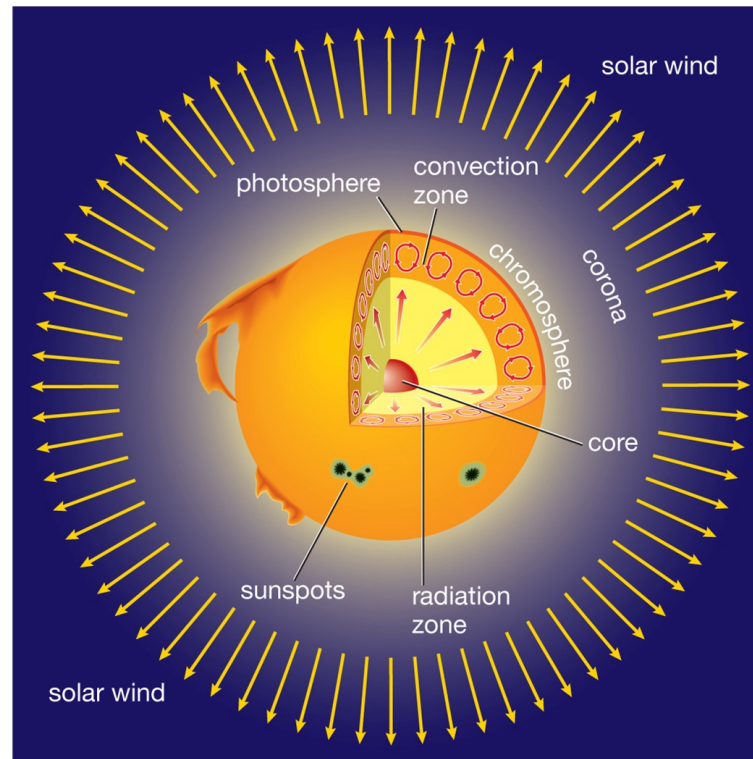
- Energy transported upward by photons



The Sun's Structure (7 of 7)

Core:

- Energy generated by nuclear fusion at ~ 15 million K



What Have We Learned? (1 of 5)

- **Why does the Sun shine?**
 - Chemical and gravitational energy sources could not explain how the Sun could sustain its luminosity for more than about 25 million years.
 - The Sun shines because **gravitational equilibrium** keeps **its core hot and dense enough to release energy through nuclear fusion.**

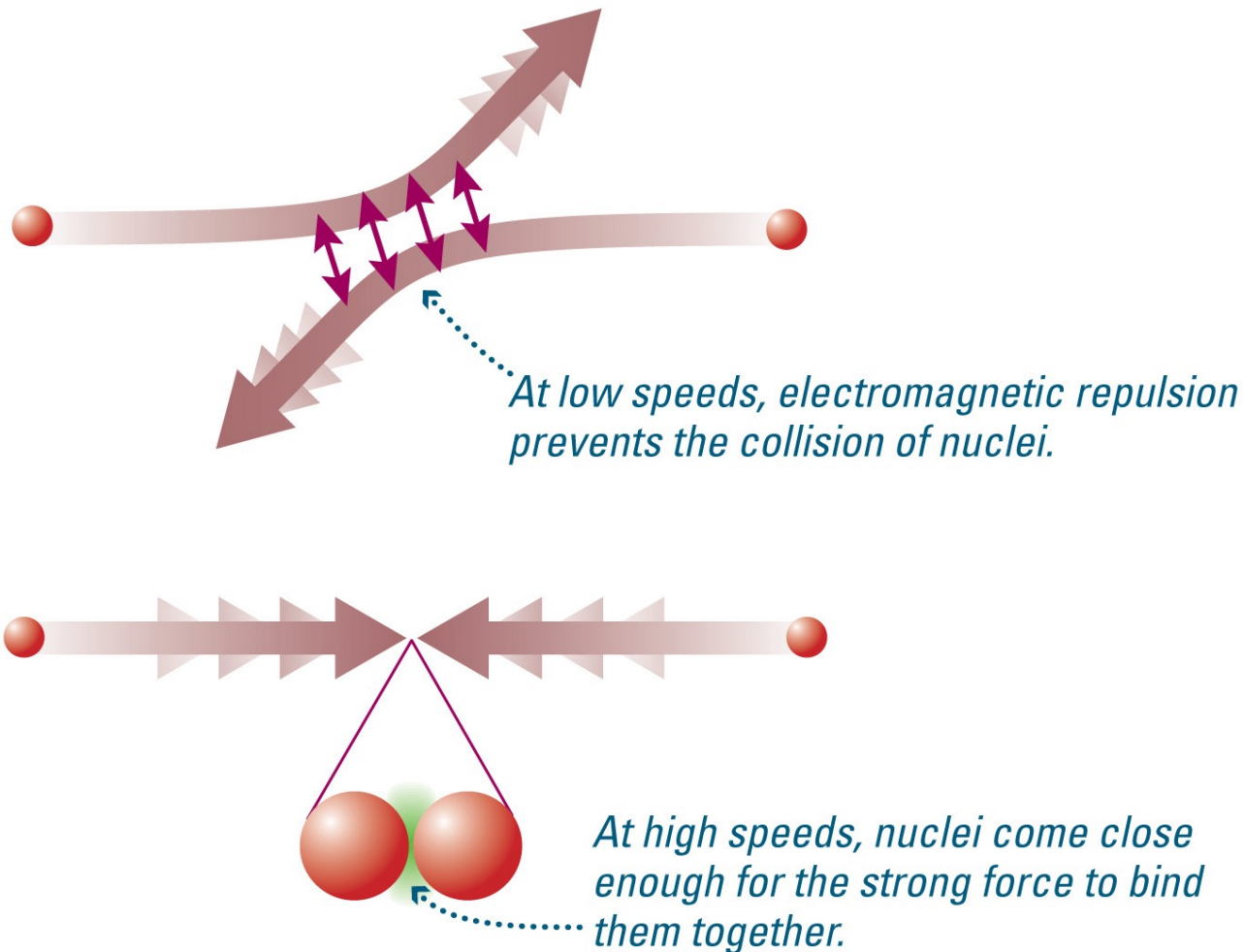
What Have We Learned? (2 of 5)

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

14.2 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?**

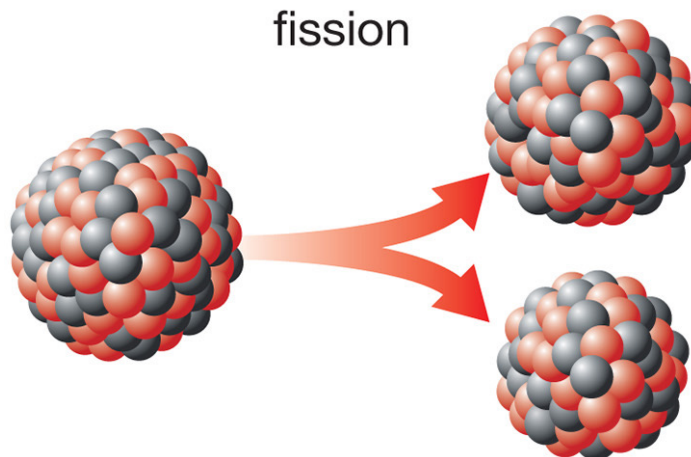
How Does Nuclear Fusion Occur in the Sun?



Nuclear Fusion in the Sun (1 of 5)

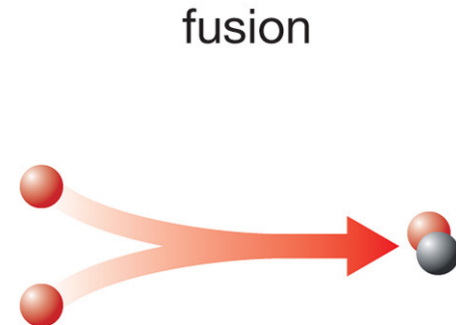
Fission

- Big nucleus splits into smaller pieces.
- (Example: nuclear power plants)



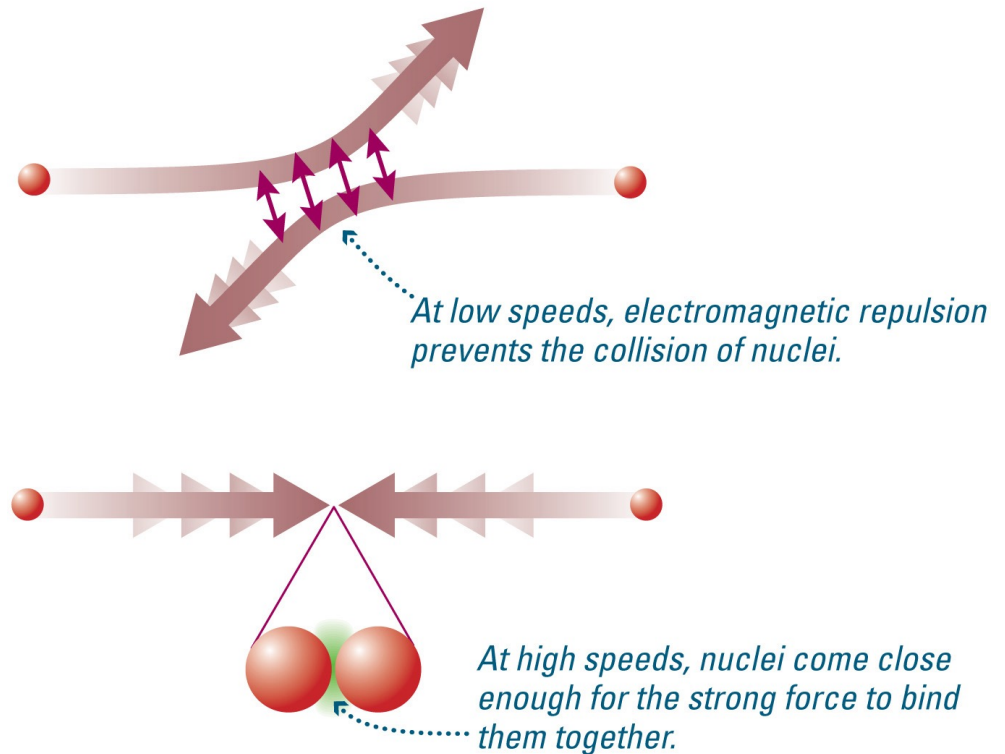
Fusion

- Small nuclei stick together to make a bigger one.
- (Example: the Sun, stars)

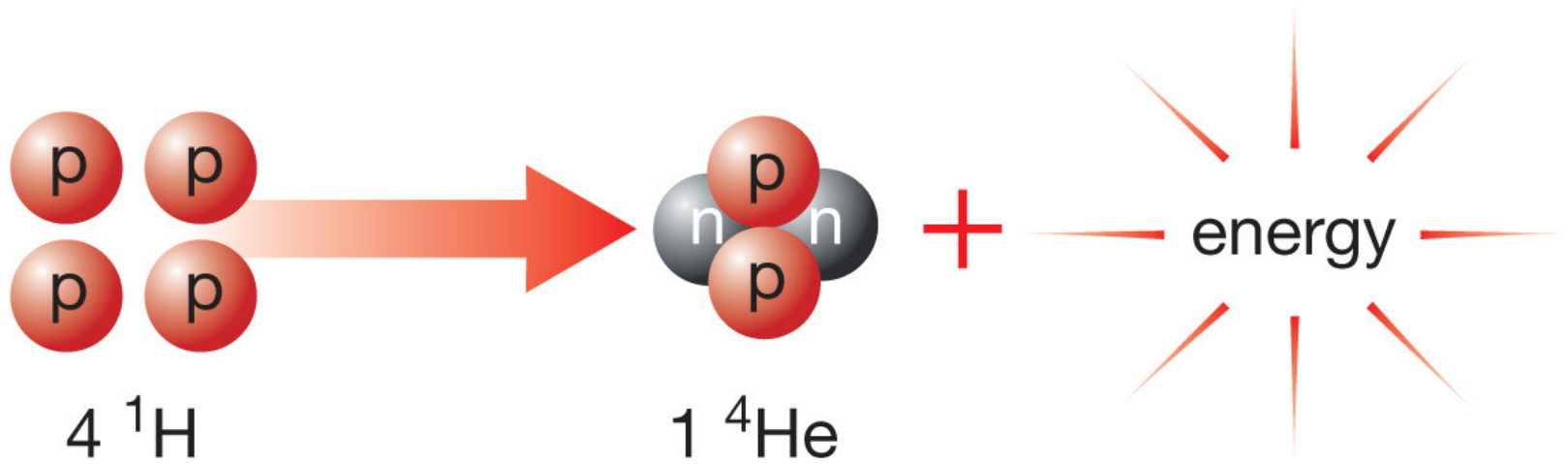


Nuclear Fusion in the Sun (2 of 5)

- High temperatures enable nuclear fusion to happen in the core.



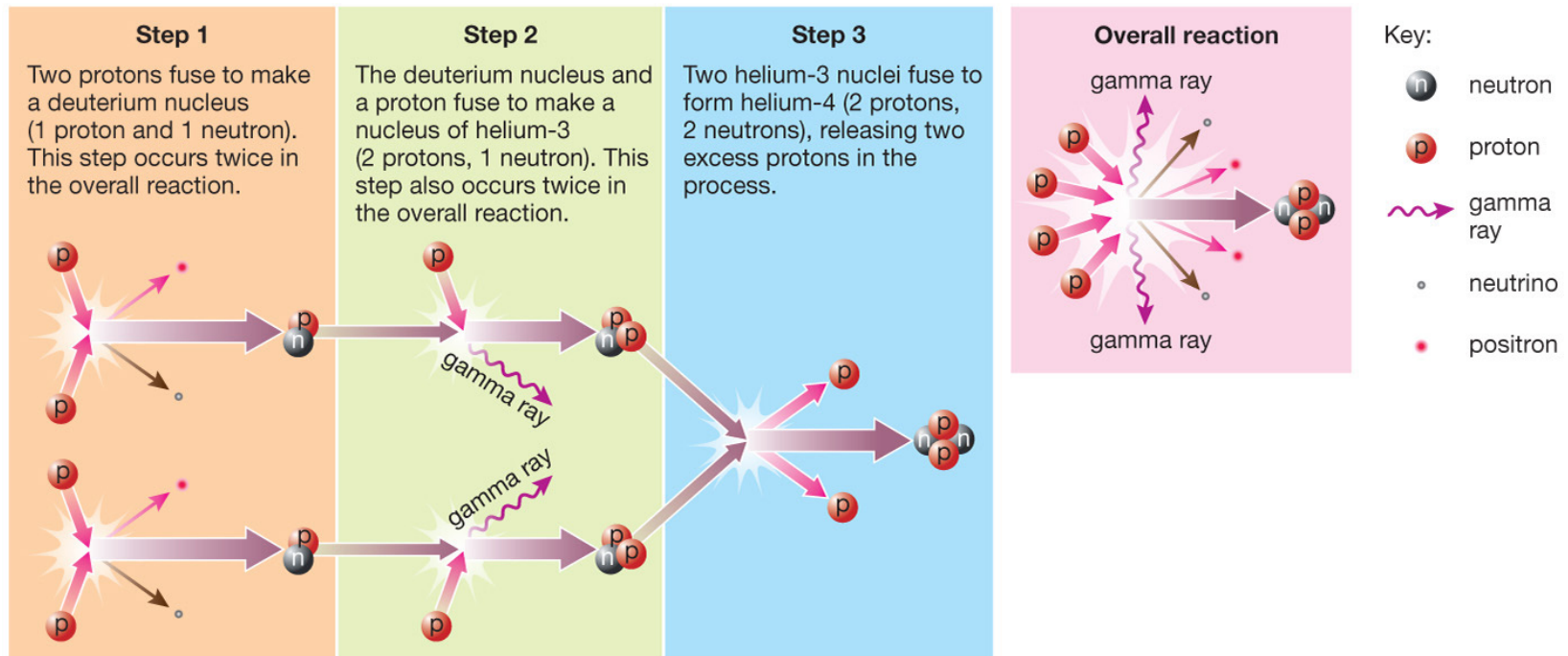
Nuclear Fusion in the Sun (3 of 5)



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

Nuclear Fusion in the Sun (4 of 5)

Hydrogen Fusion by the Proton-Proton Chain



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

Nuclear Fusion in the Sun (5 of 5)

In

4 protons

Out

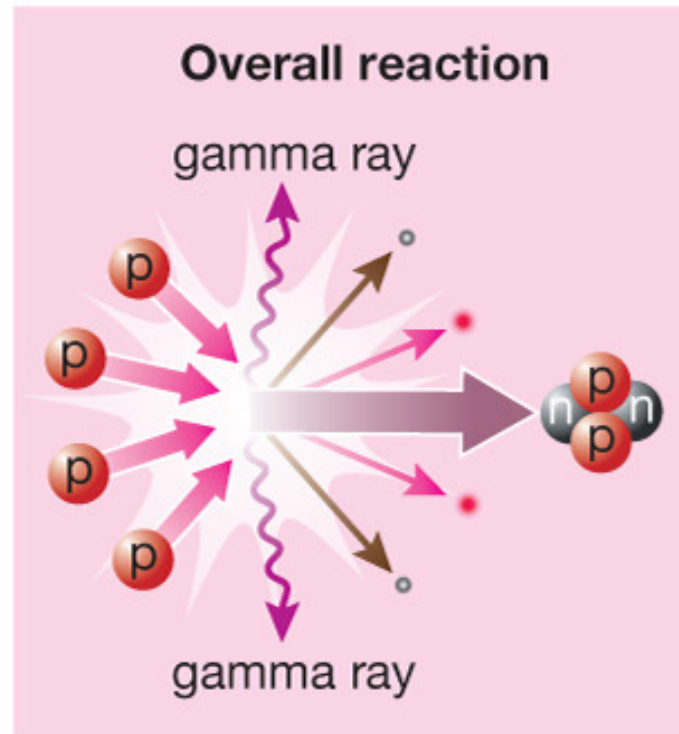
^4He nucleus

2 gamma rays

2 positrons

2 neutrinos

**Total mass is
0.7% lower.**



Key:

 neutron

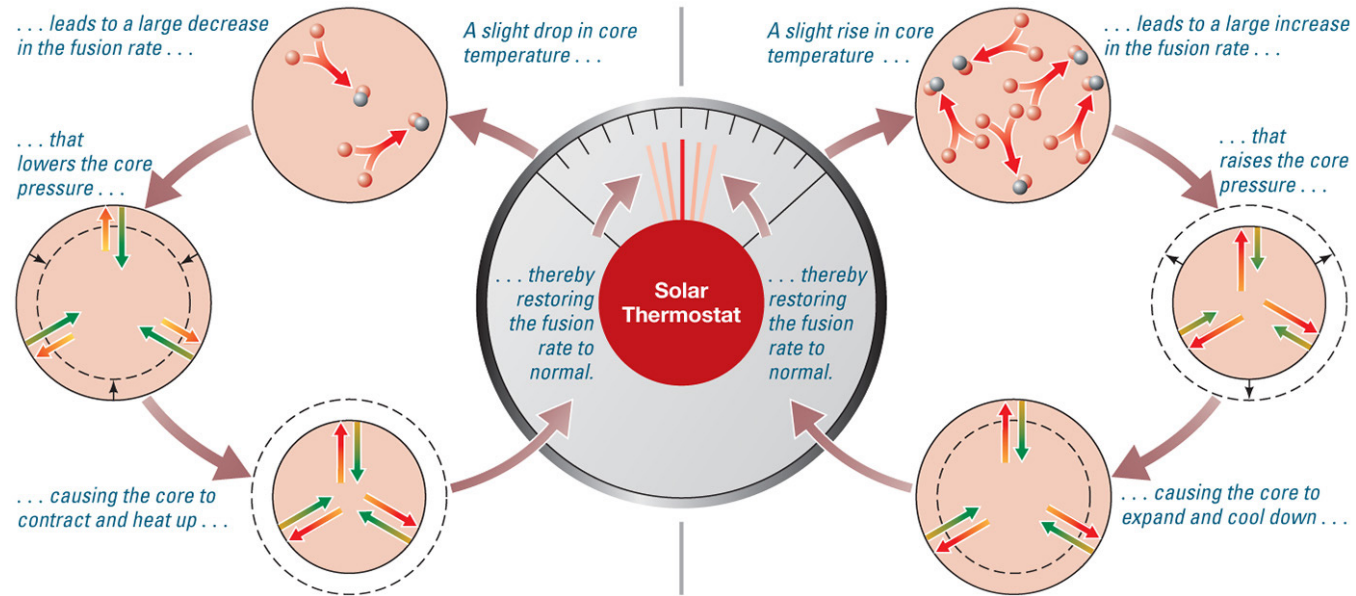
 proton

 gamma ray

 neutrino

 positron

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.

Thought Question 2 (1 of 2)

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

Thought Question 2 (2 of 2)

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

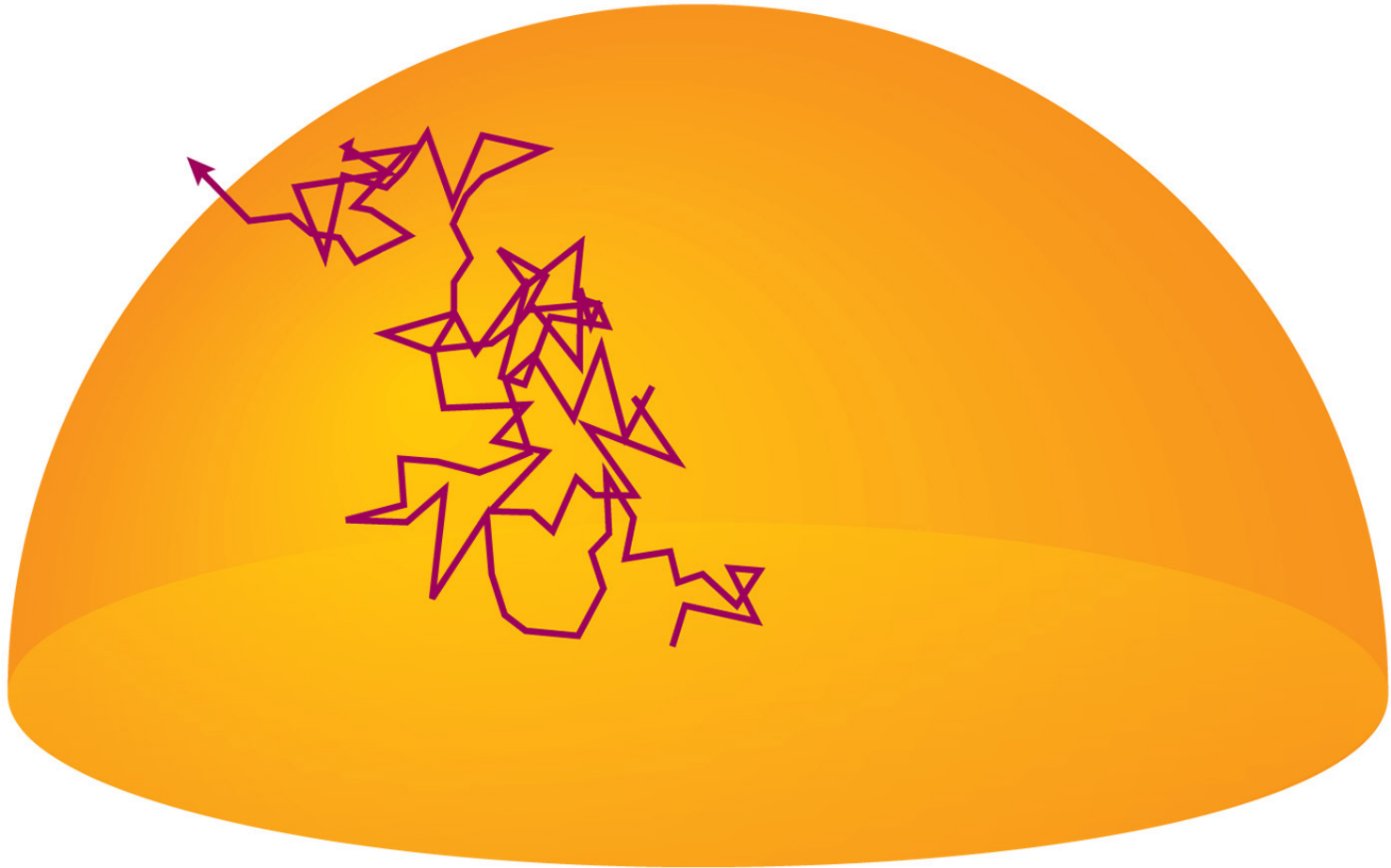
A. The core would expand and heat up.

B. The core would expand and cool.

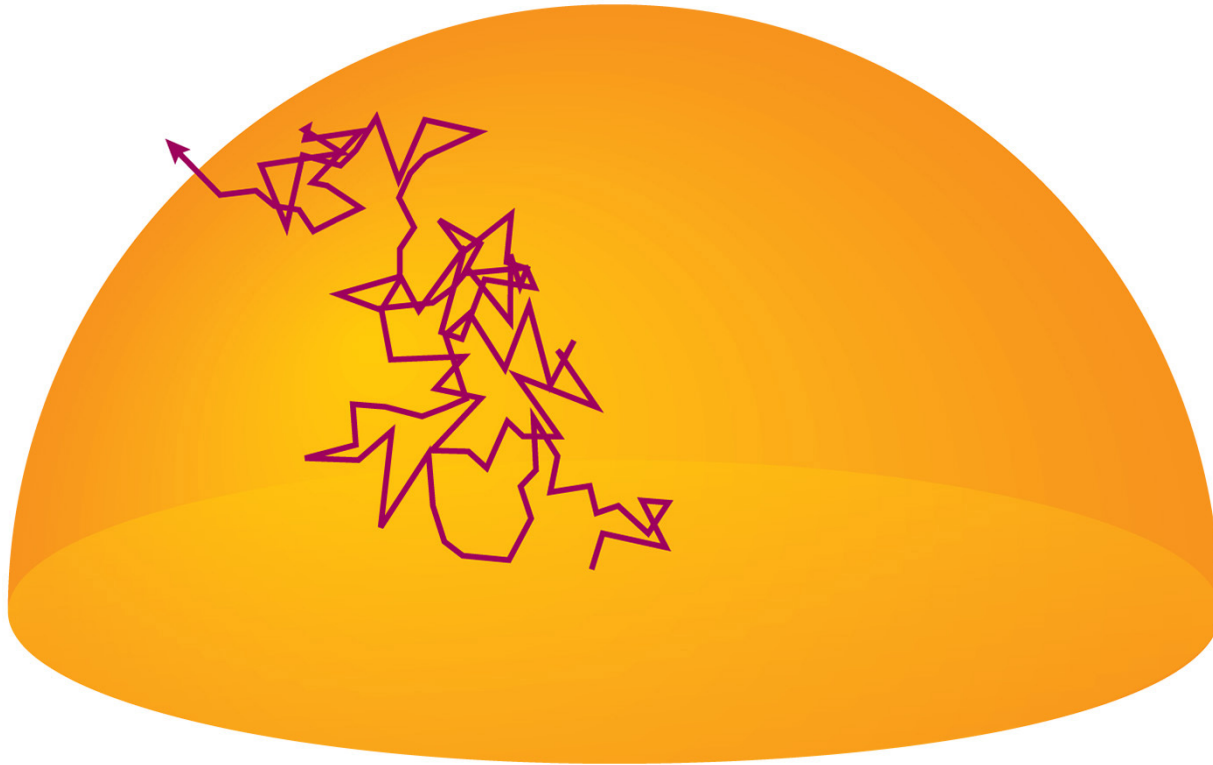
C. The Sun would blow up like a hydrogen bomb.

The solar thermostat keeps burning rate steady.

Energy Escape from the Sun (1 of 4)



Energy Escape from the Sun (2 of 4)

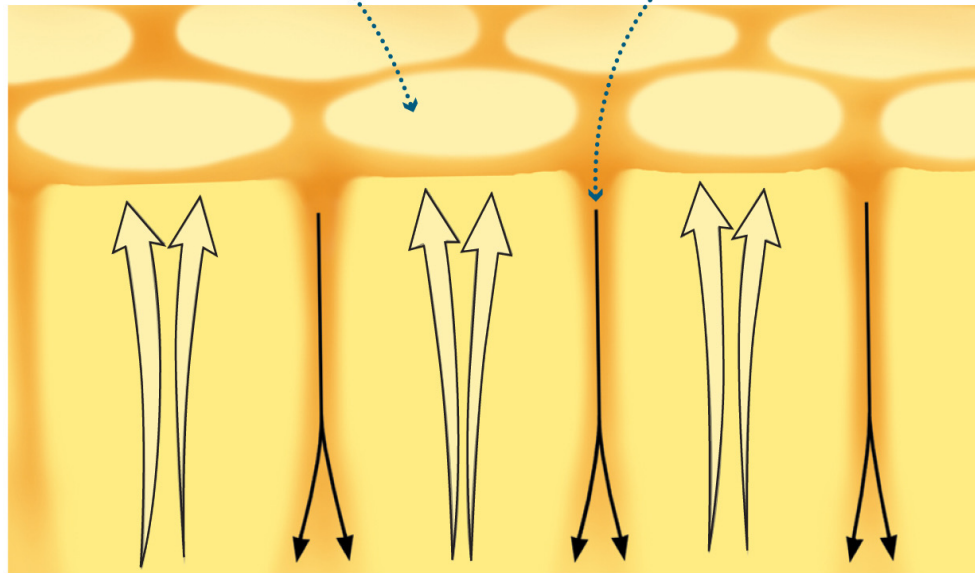


- Energy gradually leaks out of the radiation zone in the form of randomly bouncing photons.

Energy Escape from the Sun (3 of 4)

Bright spots appear on Sun's surface where hot gas is rising . . .

. . . then the gas sinks after it has cooled off.

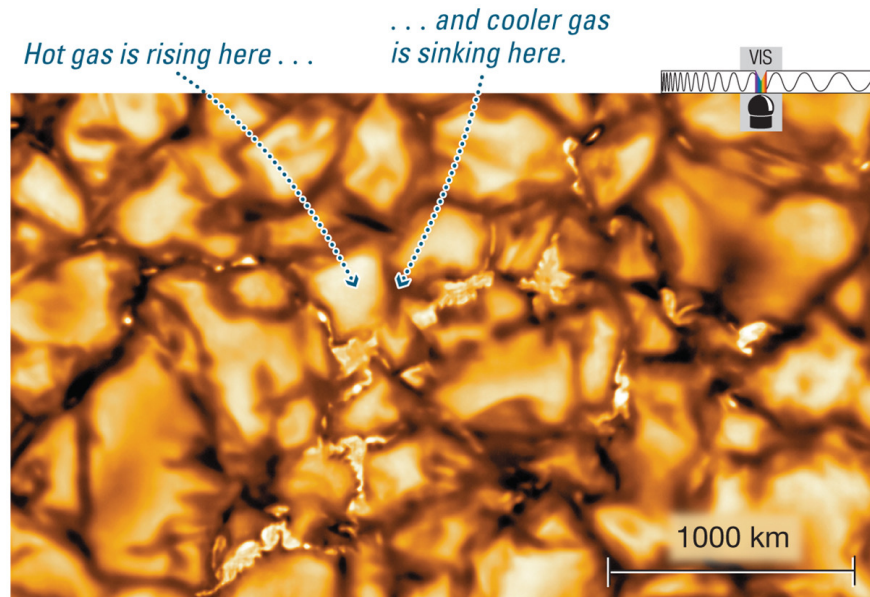


a This diagram shows convection beneath the Sun's surface: Hot gas (yellow arrows) rises while cooler gas (black arrows) descends around it.

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

Energy Escape from the Sun (4 of 4)

- Bright blobs on photosphere show where hot gas is reaching the surface.



b This image from the Daniel K Inouye Solar Telescope in Hawai'i shows the mottled appearance of the Sun's photosphere. The bright spots, each about the size of Texas, correspond to the rising plumes of hot gas in the diagram in part a.

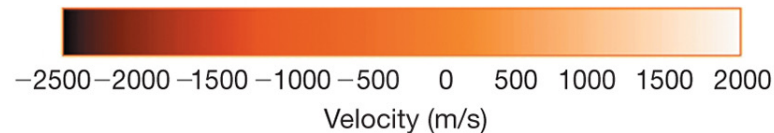
Photon transport from the Sun's Core

Energy radiated by photons from the surface of the sun originates from the sun's core. To get to the surface, however, energy is transported via various mechanisms, thus making it difficult to tell how it was actually produced in the core.

Photon transport from the core to the surface:

1. Photons created in the Sun's core from hydrogen fusion diffuse towards the Sun's surface (~ 170,000 years to get out).
2. Beyond the radiative zone, energy is transported to the surface through **convection (bulk transfer of plasma)**.
3. At the surface, photons are mostly radiated out by blackbody radiation.

How We Know What Is Happening Inside the Sun?



We Learn About the Inside of the Sun by ...

- making mathematical models
- observing solar vibrations
- observing solar neutrinos

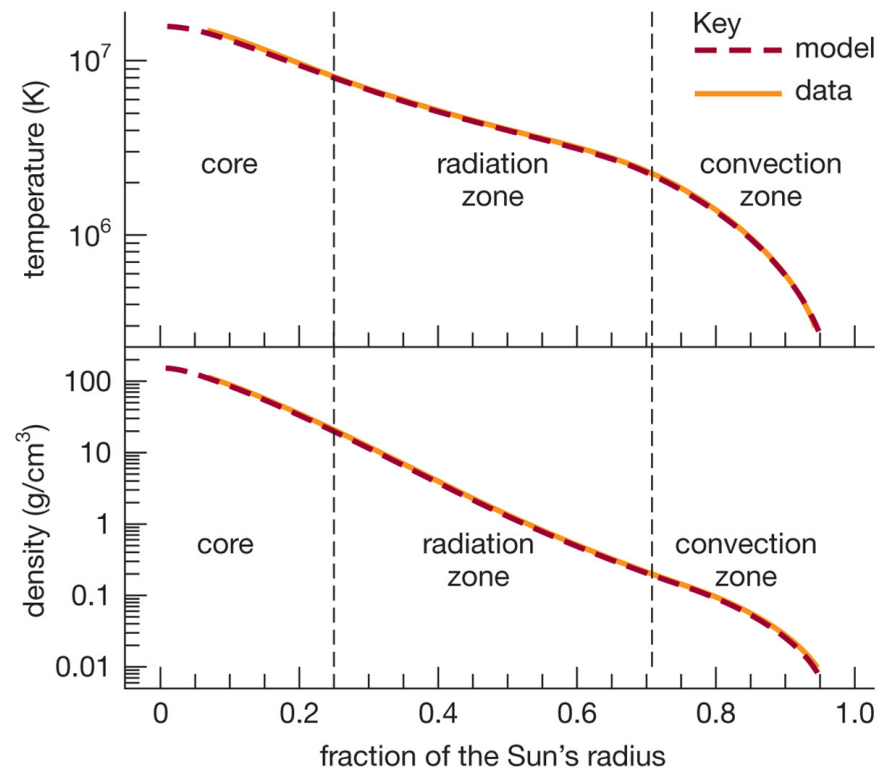
Solar Vibrations

- Patterns of vibration on the surface tell us about what the Sun is like inside.
- Here, vibrations revealed by Doppler shifts are shown.



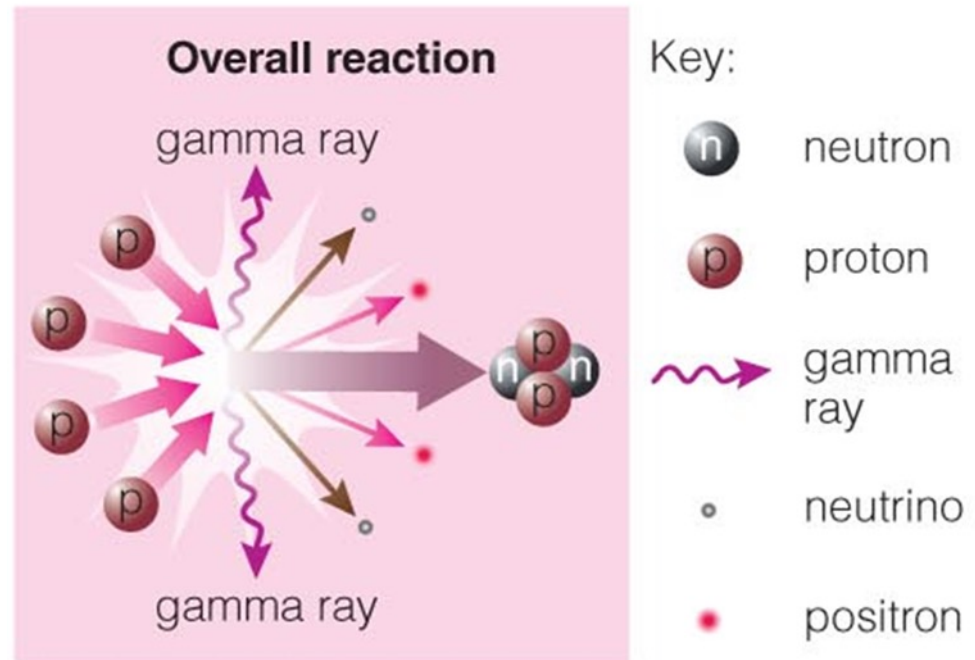
Solar Models

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



Solar Neutrinos (1 of 2)

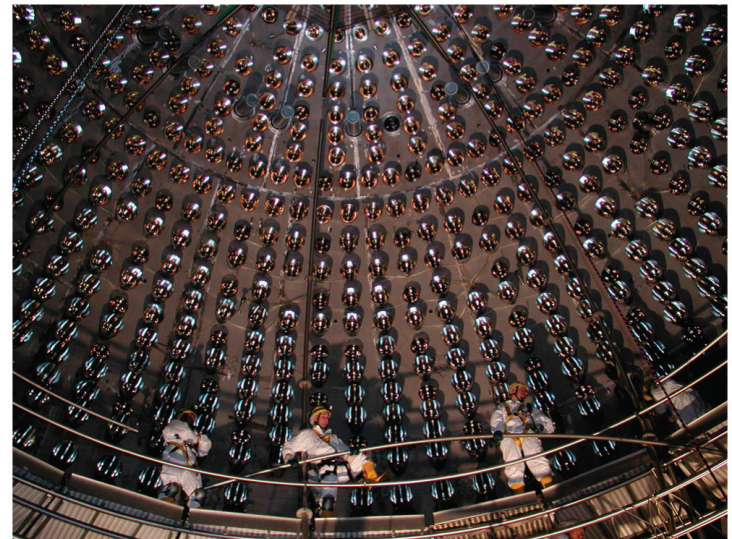
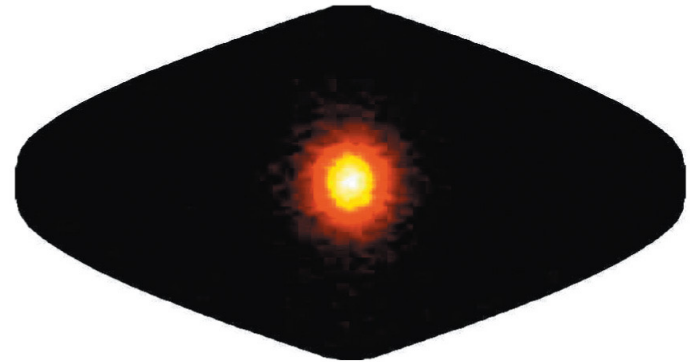
- Neutrinos created during fusion fly directly through the Sun.
- Observations of these solar neutrinos can tell us what's happening in the core.



Solar Neutrinos (2 of 2)

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.
- $4\ ^1\text{H} \rightarrow\ ^4\text{He} + 2\nu + 2\gamma + 2e^+$



What Have We Learned? (3 of 5)

- **How does nuclear fusion occur in the Sun?**
 - The core's extreme temperature and density are just right for 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.

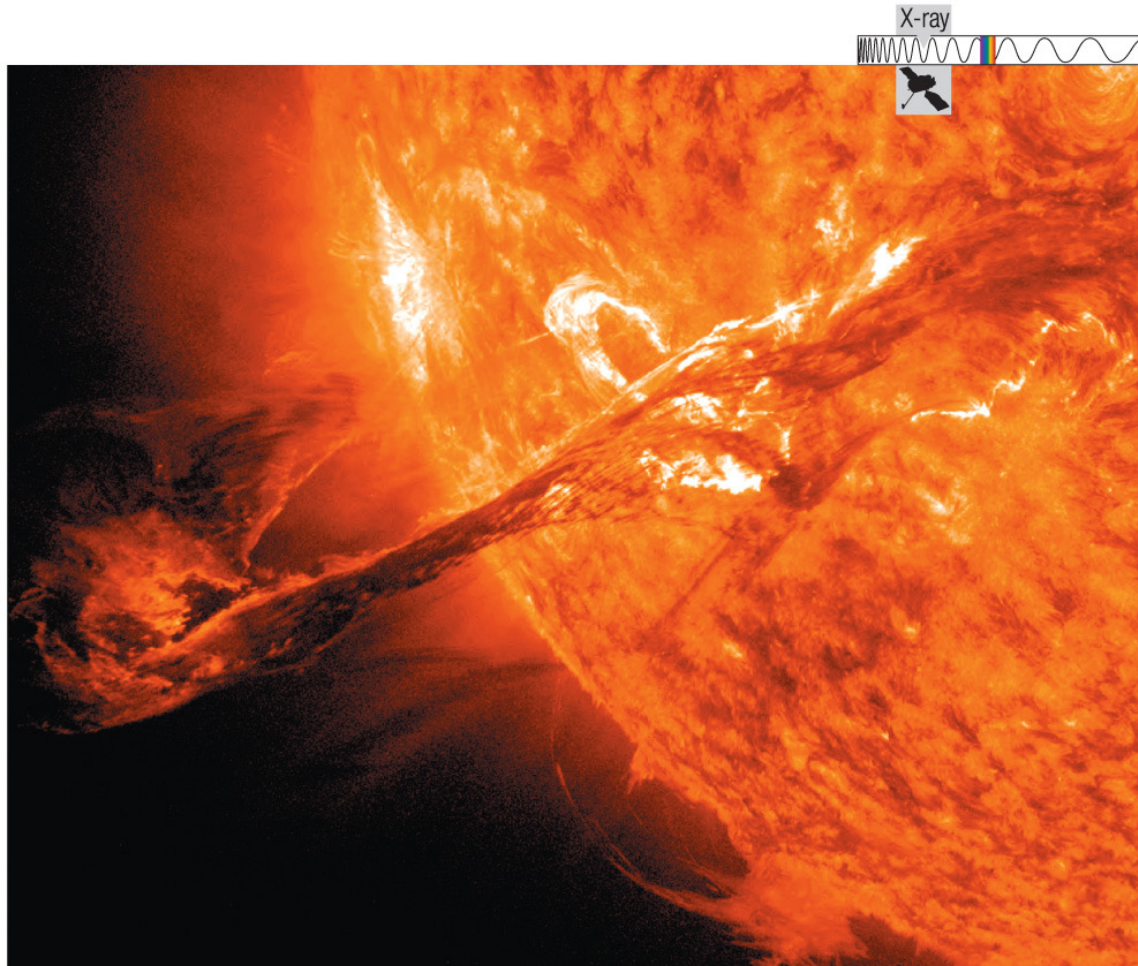
What Have We Learned? (4 of 5)

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

14.3 The Sun–Earth Connection

- Our goals for learning:
 - **What causes solar activity?**
 - **How does solar activity vary with time?**

What Causes Solar Activity? (1 of 2)



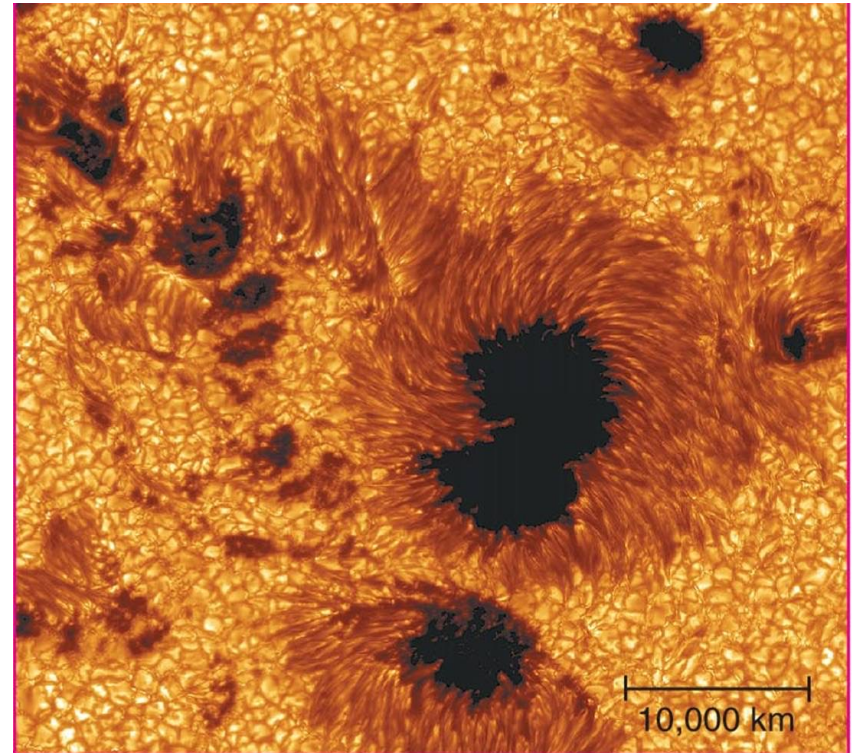
Solar Activity Is Like “Weather”

- Sunspots
- Solar flares
- Solar prominences
- All these phenomena are related to magnetic fields.

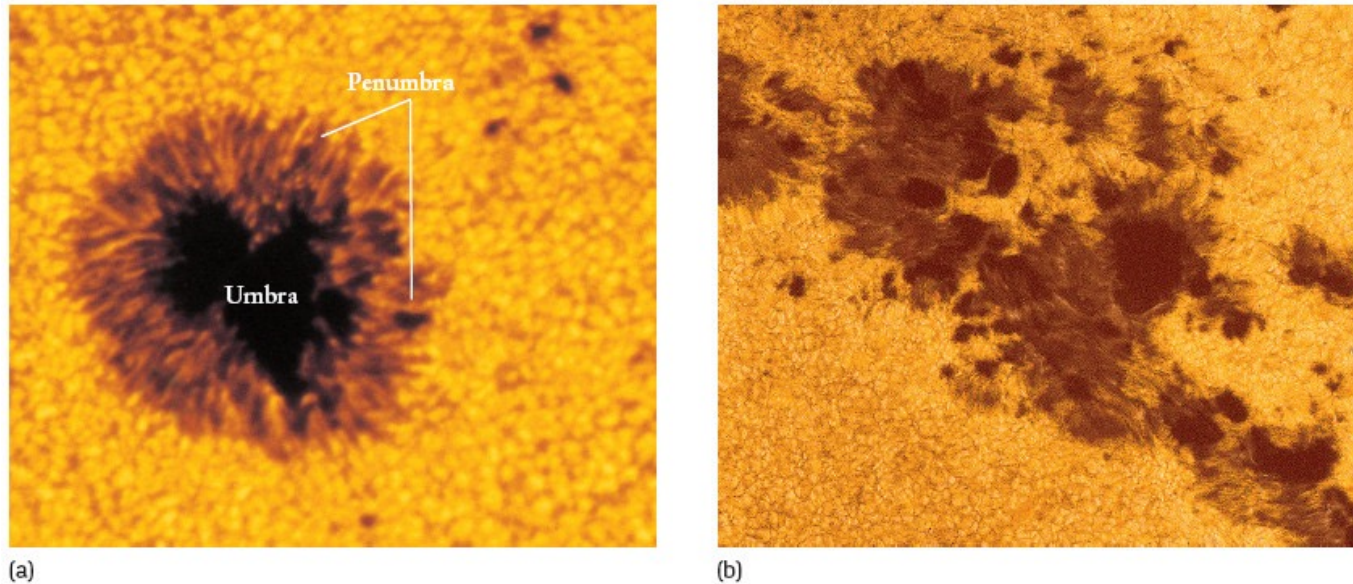
Solar Activity (1a of 10)

Sunspots

- Are cooler than other parts of the Sun's surface (4000 Kelvin)
- Are regions with strong magnetic fields
- Convection inhibited by twisted magnetic field lines makes these spots cooler.



Solar Activity (1b of 10)



(a) An isolated sunspot, (b) a group of sunspots

Sunspots are temporary cool regions in the solar photosphere. Because of their relatively low temperature they appear dark. They have typical sizes of $\sim 10,000$ km across and have a lifetime of hours to years. $T_{\text{Umbra}} \sim 4,300$ K and $T_{\text{Penumbra}} \sim 5,000$ K.

Solar Activity (1c of 10)

The **sun's rotation** can be tracked by observing the rotation of sunspots.

Observations show that a sunspot near the equator takes ~ **25 days to go around** once whereas sunspots at larger latitudes take longer.

The sun does not rotate as a rigid body. Different parts of the sun rotate at different velocities. This is referred to as differential rotation.



November 9



November 12



November 14



November 15



November 17



November 19

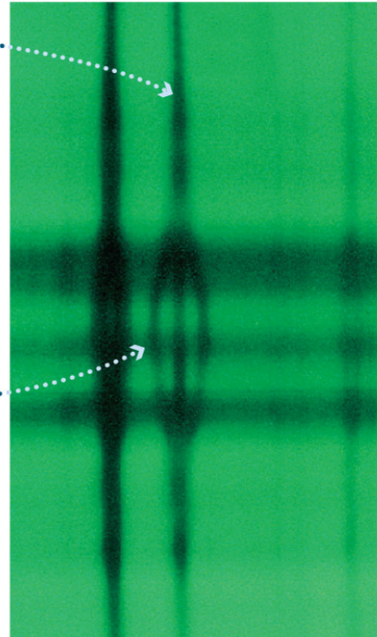
Solar Activity (2 of 10)

Zeeman Effect

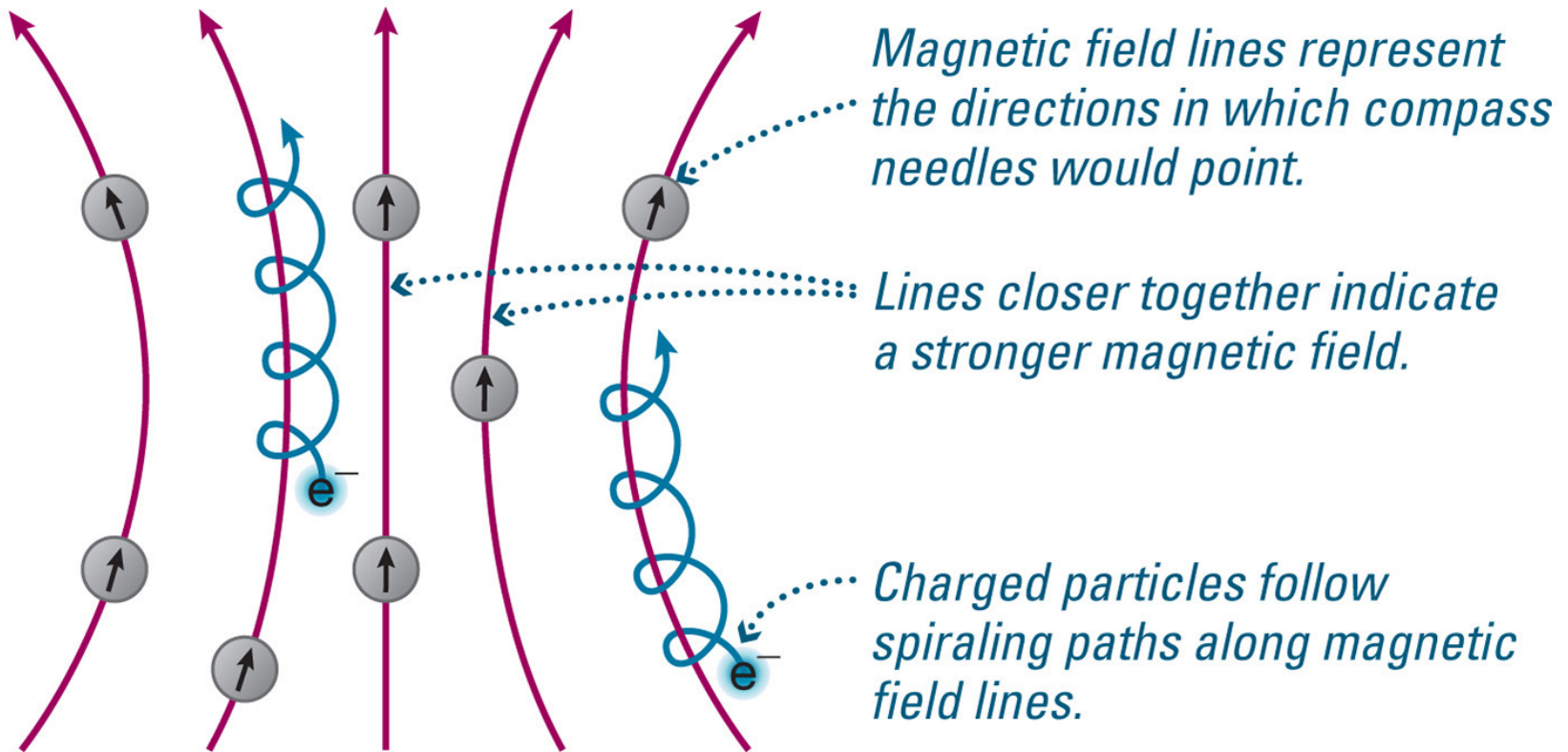
- We can measure magnetic fields in sunspots by observing the splitting of spectral lines.

Outside a sunspot we see a single spectral line . . .

. . . but the strong magnetic field inside a sunspot splits that line into three lines.

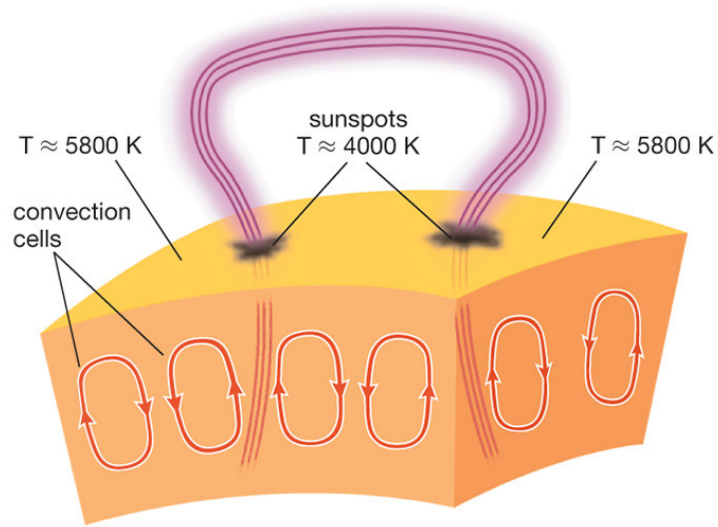


Solar Activity (3 of 10)

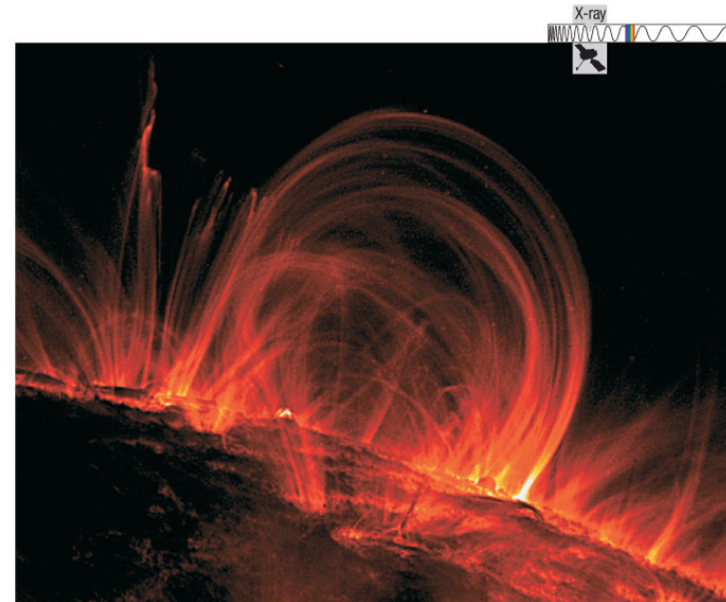


- Charged particles spiral along magnetic field lines.

Solar Activity (4 of 10)



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

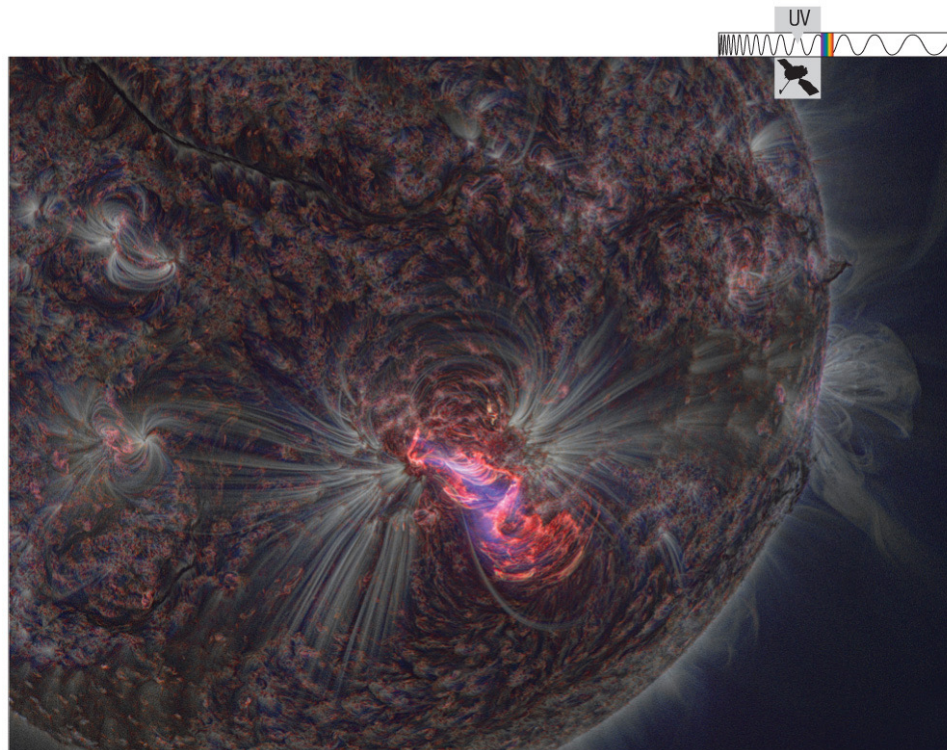


b This x-ray photo (from NASA's *TRACE* mission) shows hot gas trapped within looped magnetic field lines.

- Loops of bright gas often connect sunspot pairs of opposite polarity.

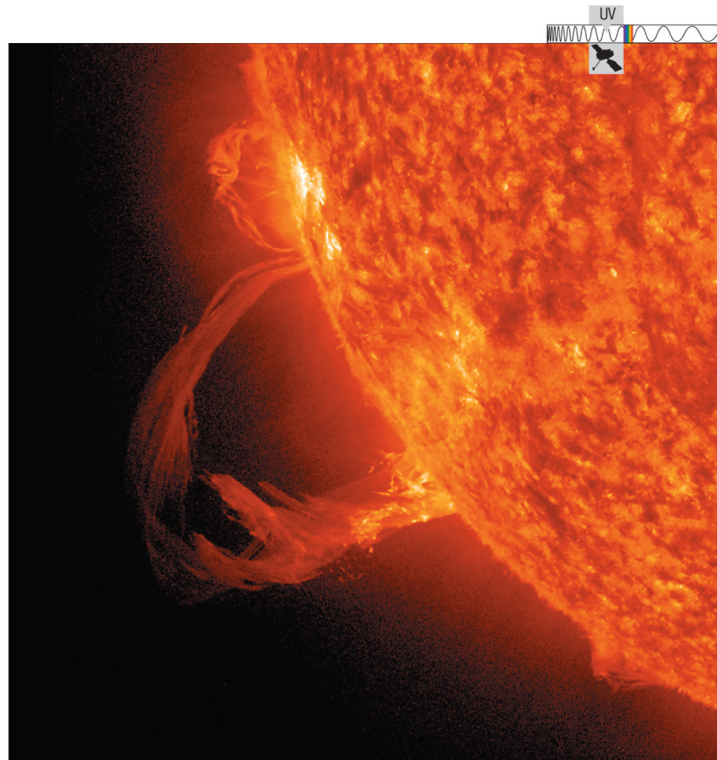
Solar Activity (5 of 10)

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

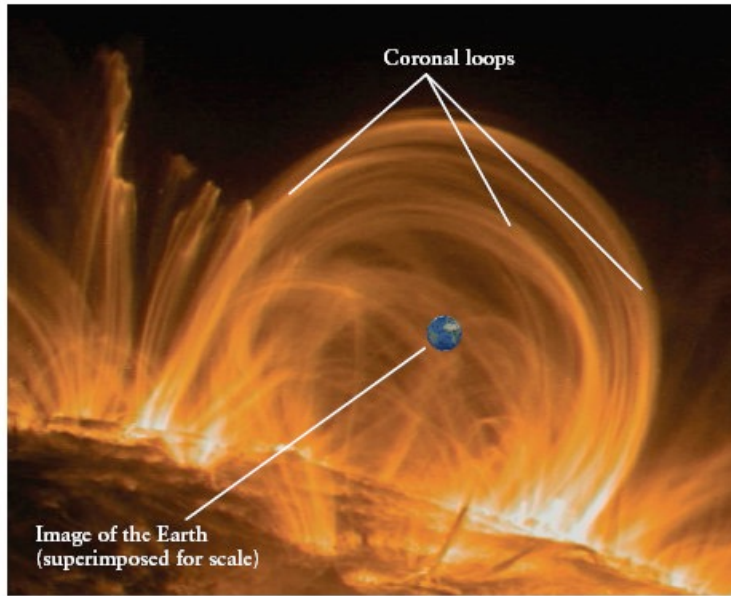


Solar Activity (6a of 10)

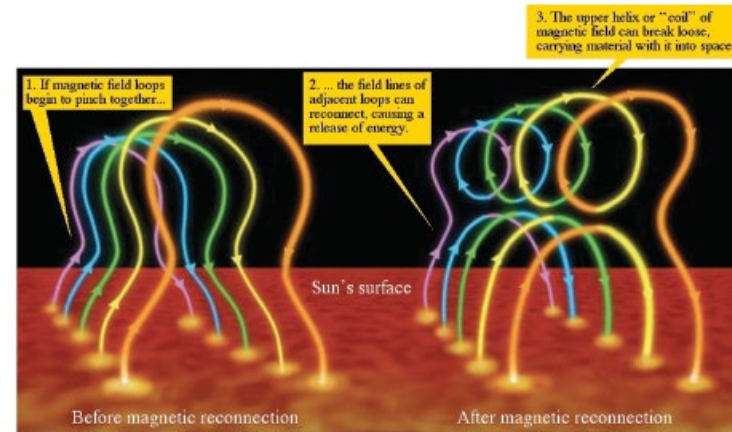
- Magnetic activity also causes **solar prominences** that erupt high above the Sun's surface.



Solar Activity (6b of 10)



(a)

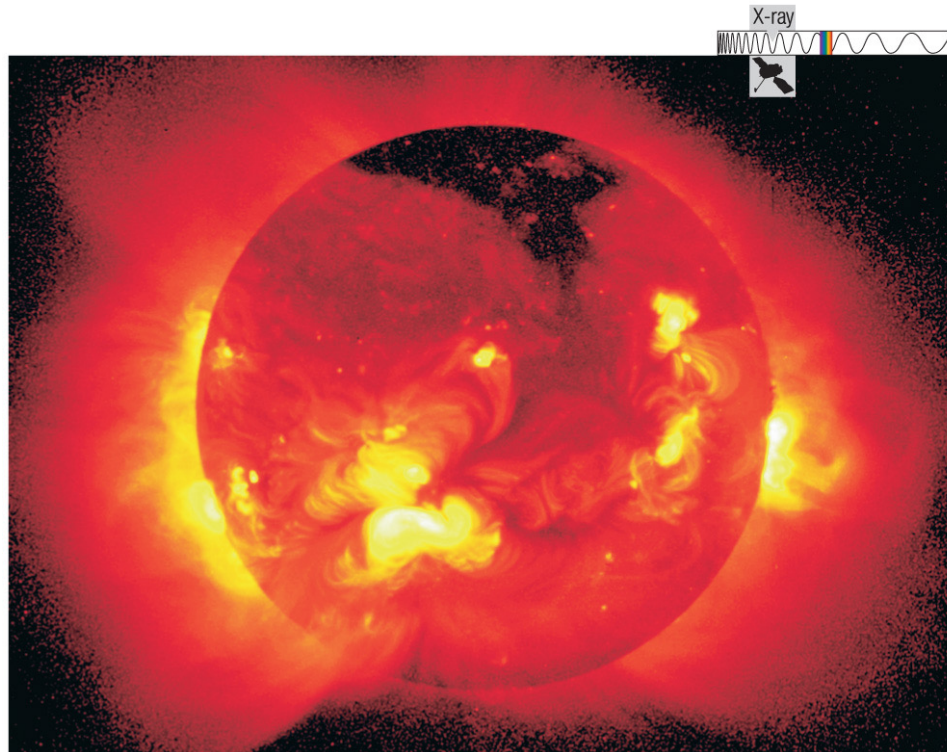


(b)

Plasma can easily flow along magnetic field lines but takes more time to diffuse across field lines. Occasionally the magnetic field lines protrude through the sun's surface (near the edges of supergranules) forming giant **coronal loops**. Plasma flows along these loops.

Whenever magnetic field lines reconnect a large amount of energy is released that heats up the surrounding plasma to high temperatures.

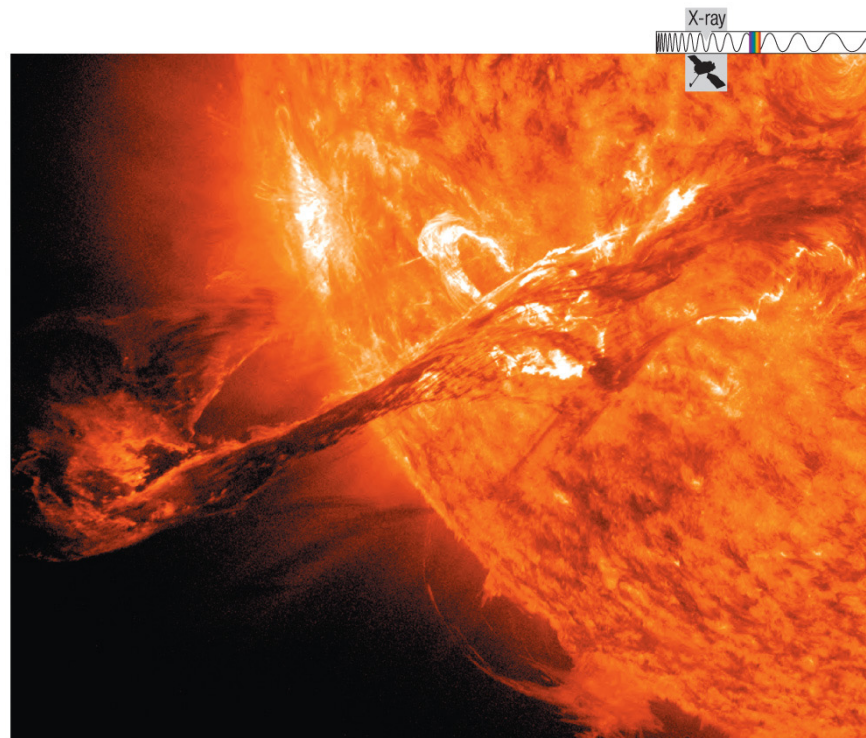
Solar Activity (7 of 10)



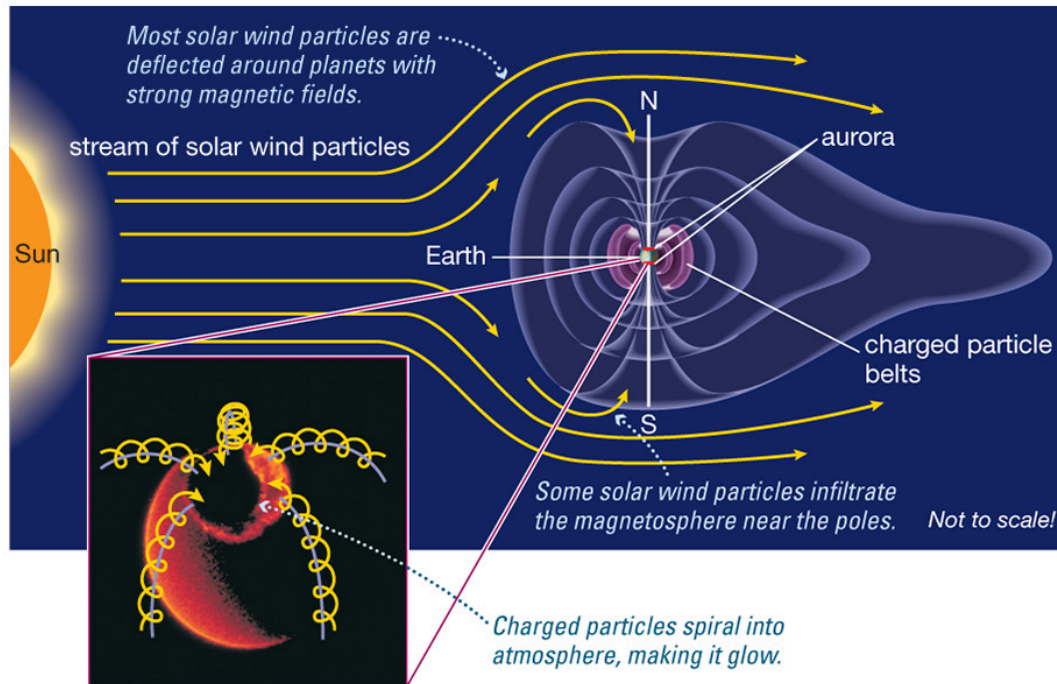
- The corona appears bright in x-ray photos in places where magnetic fields trap hot gas.

Solar Activity (8 of 10)

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



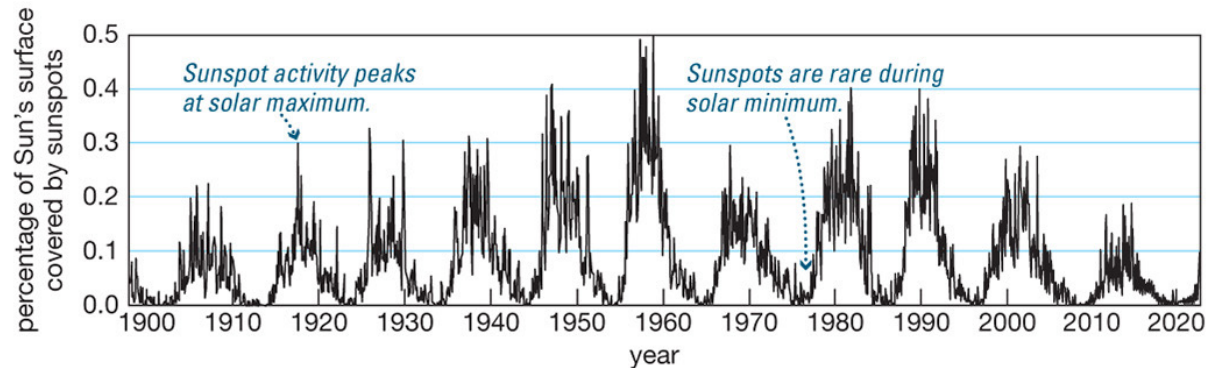
Effects of Solar Activity on Earth



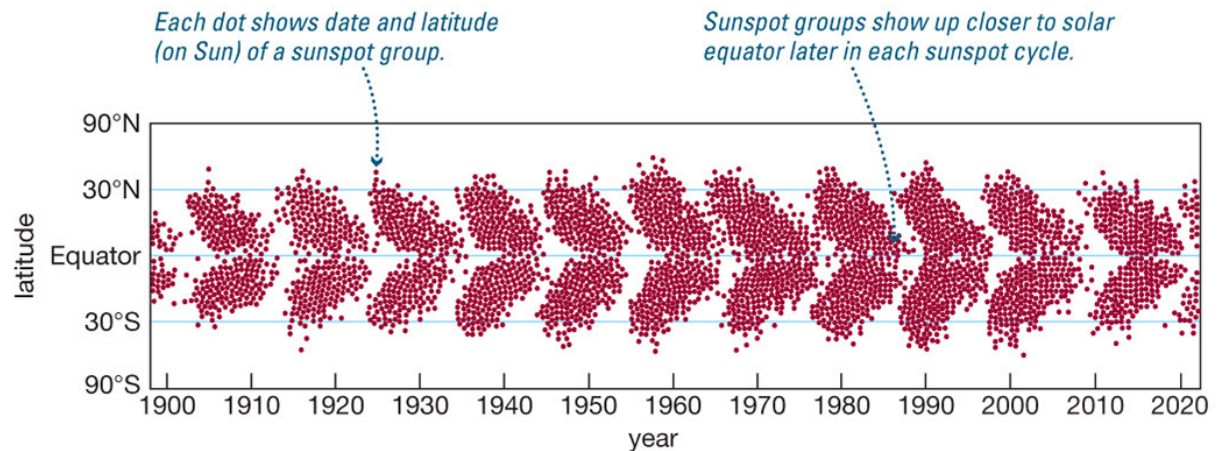
- Charged particles streaming from the Sun can disrupt electrical power grids and can disable communications satellites.

How Does Solar Activity Vary with Time?

a This graph shows how the number of sunspots on the Sun changes with time. The vertical axis shows the percentage of the Sun's surface covered by sunspots. The cycle has a period of approximately 11 years.

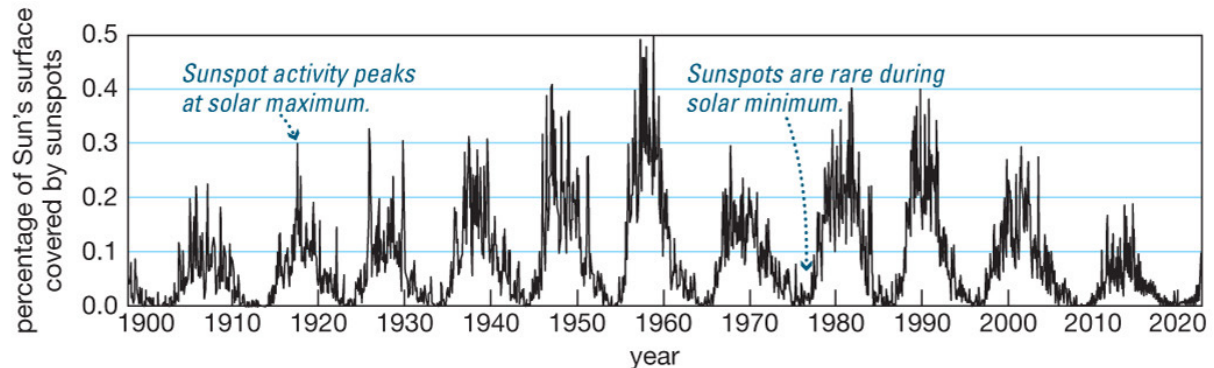


b This graph shows how the latitudes at which sunspot groups appear tend to shift during a single sunspot cycle.



Solar Activity (9 of 10)

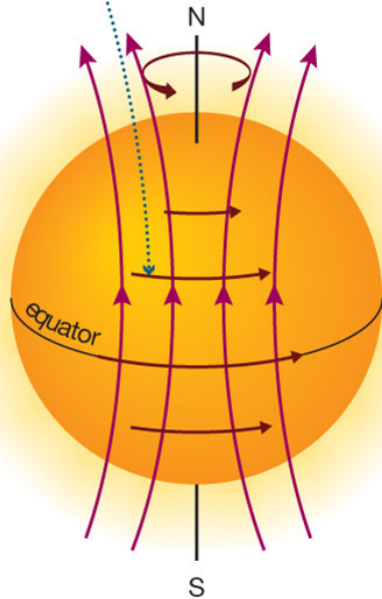
a This graph shows how the number of sunspots on the Sun changes with time. The vertical axis shows the percentage of the Sun's surface covered by sunspots. The cycle has a period of approximately 11 years.



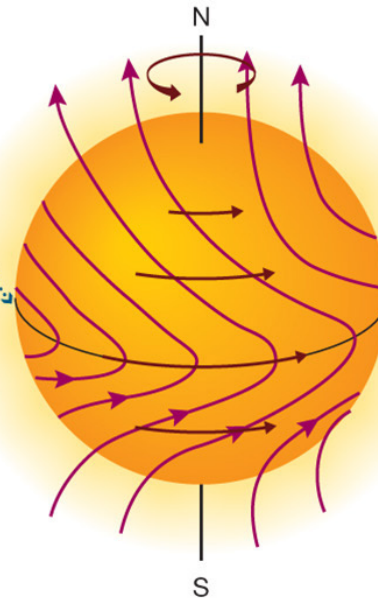
- There are additional variances over longer periods.

Solar Activity (10 of 10)

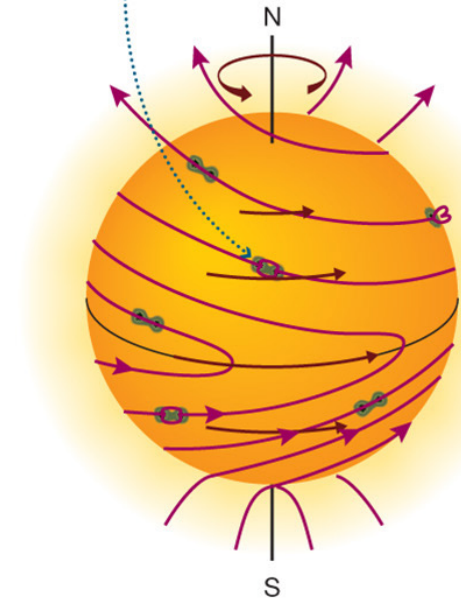
Charged particles tend to push the field lines around with the Sun's rotation.



Because the Sun rotates faster near its equator than at its poles, the field lines bend ahead at the equator.

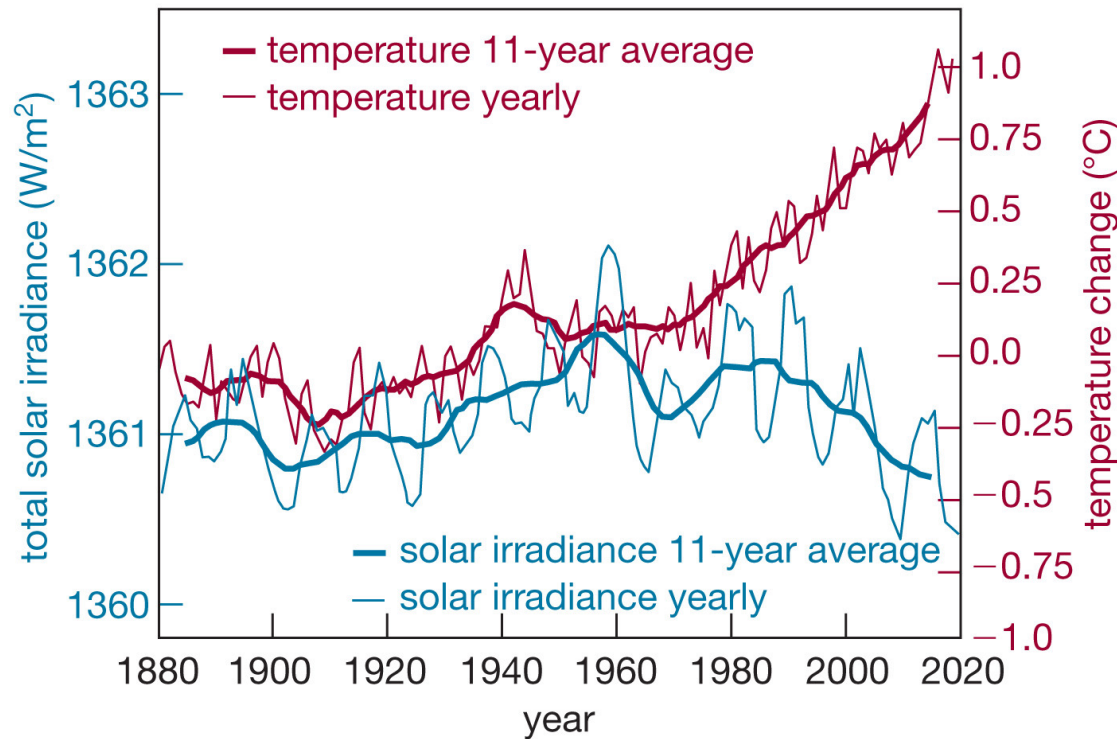


The field lines become more and more twisted with time, and sunspots form when the twisted lines loop above the Sun's surface.



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

The Sunspot Cycle and Earth's Climate

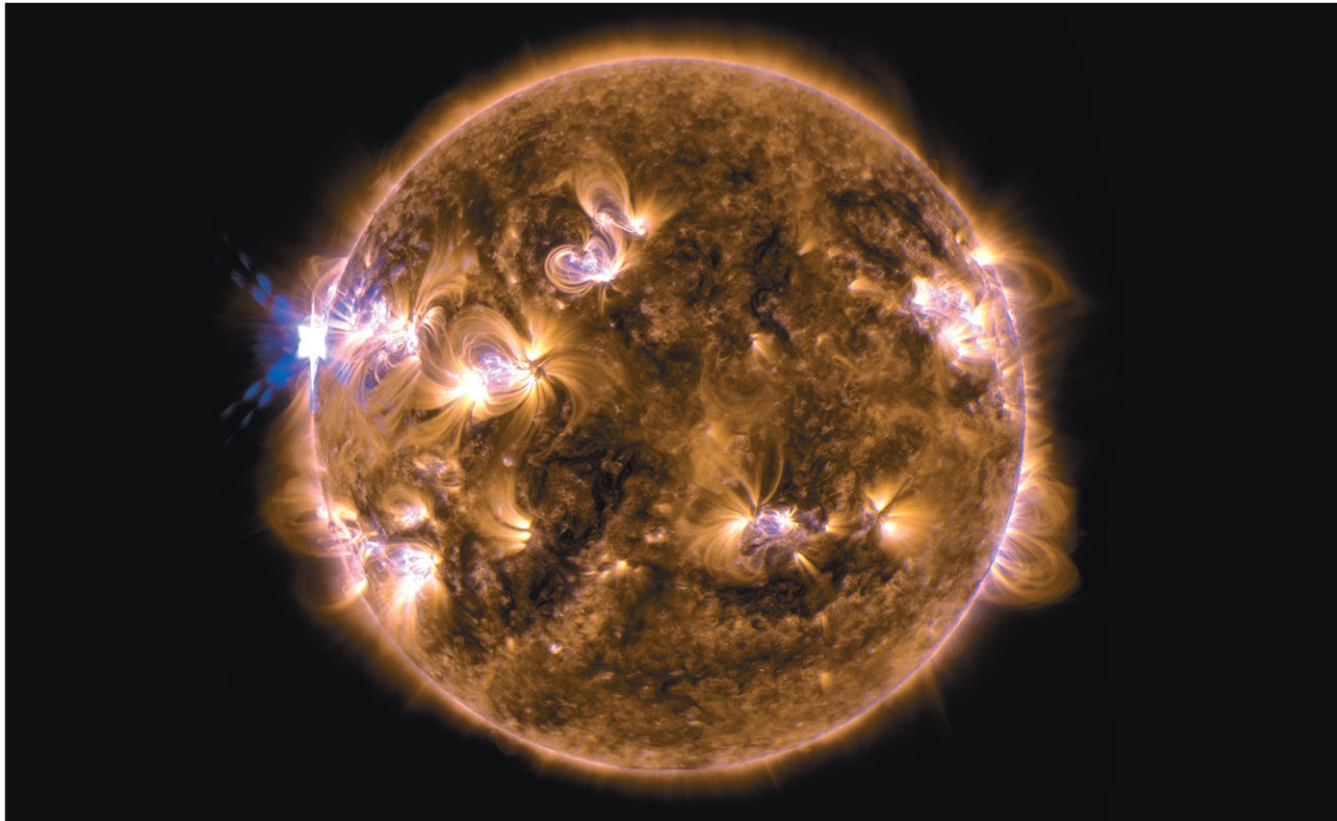


- Despite an 11-year cycle, the amount of sunlight has remained approximately constant while Earth has warmed.

What Have We Learned? (5 of 5)

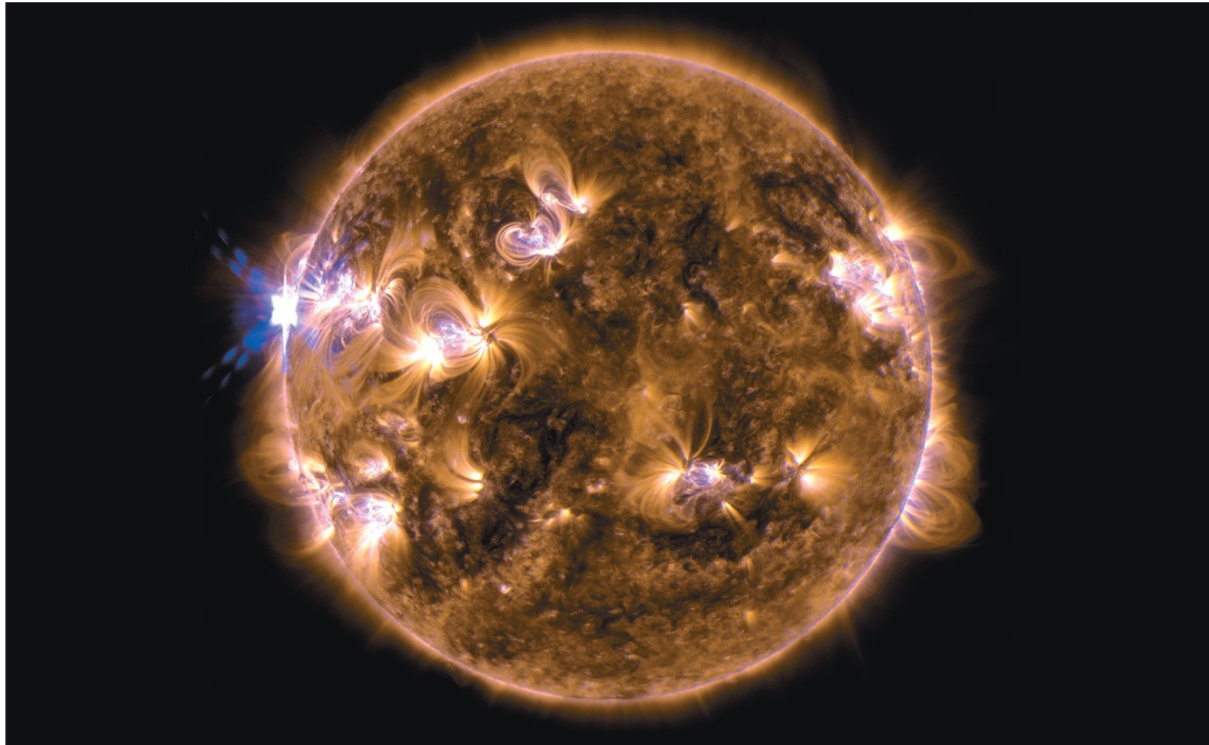
- **What causes solar activity?**
 - Stretching and twisting of magnetic field lines near the Sun's surface cause solar activity.
- **How does solar activity vary with time?**
 - Activity rises and falls with an 11-year period.

A Closer Look at the Sun (1 of 7)



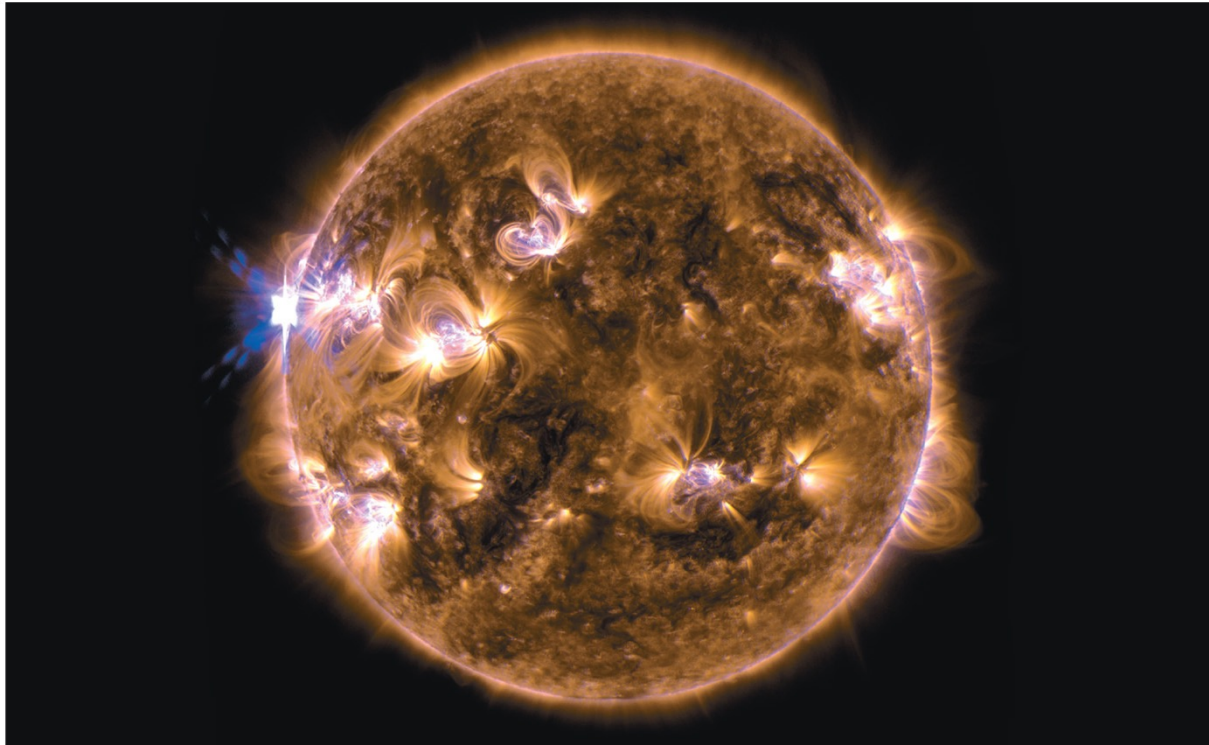
- **Is it on Fire?**

A Closer Look at the Sun (2 of 7)



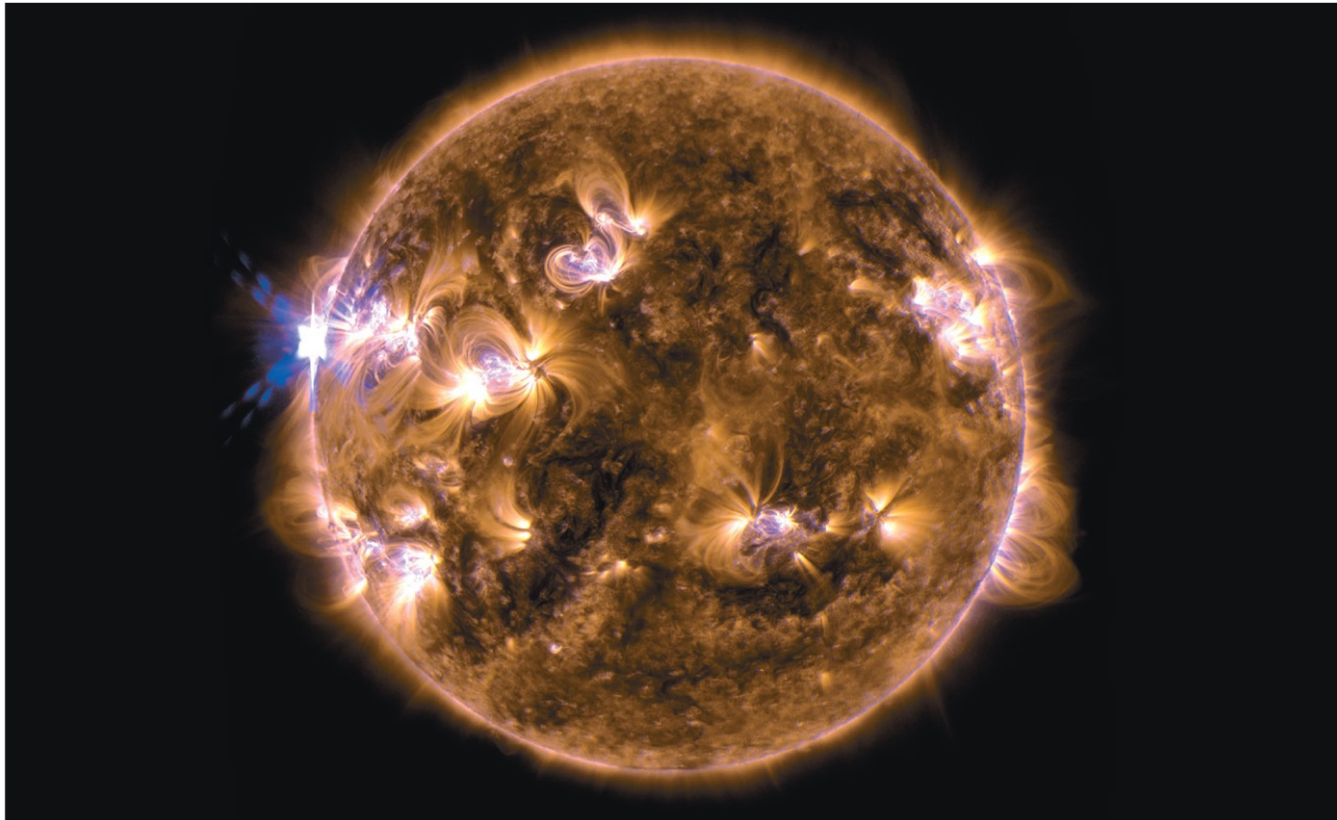
- **Is it on Fire?** $\frac{\text{Chemical energy content}}{\text{Luminosity}} \sim 10,000 \text{ years}$

A Closer Look at the Sun (3 of 7)



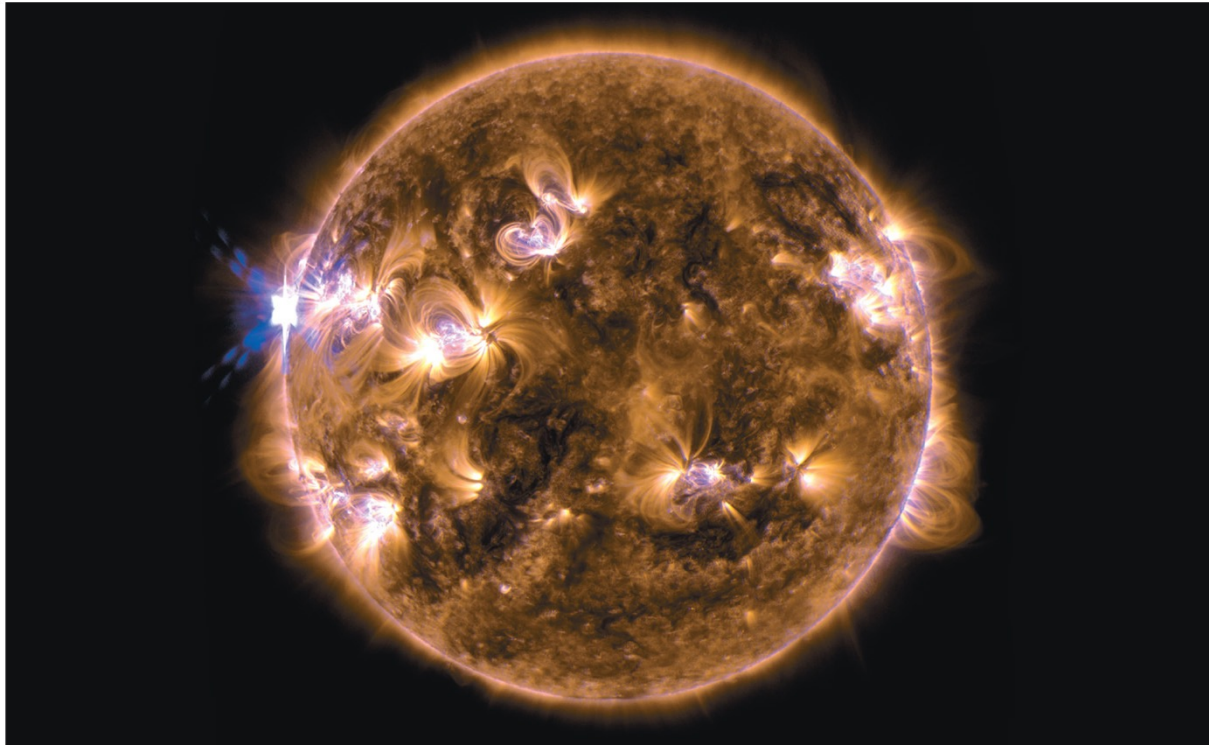
- **Is it on Fire? ... No!** $\frac{\text{Chemical energy content}}{\text{Luminosity}} \sim 10,000 \text{ years}$

A Closer Look at the Sun (4 of 7)



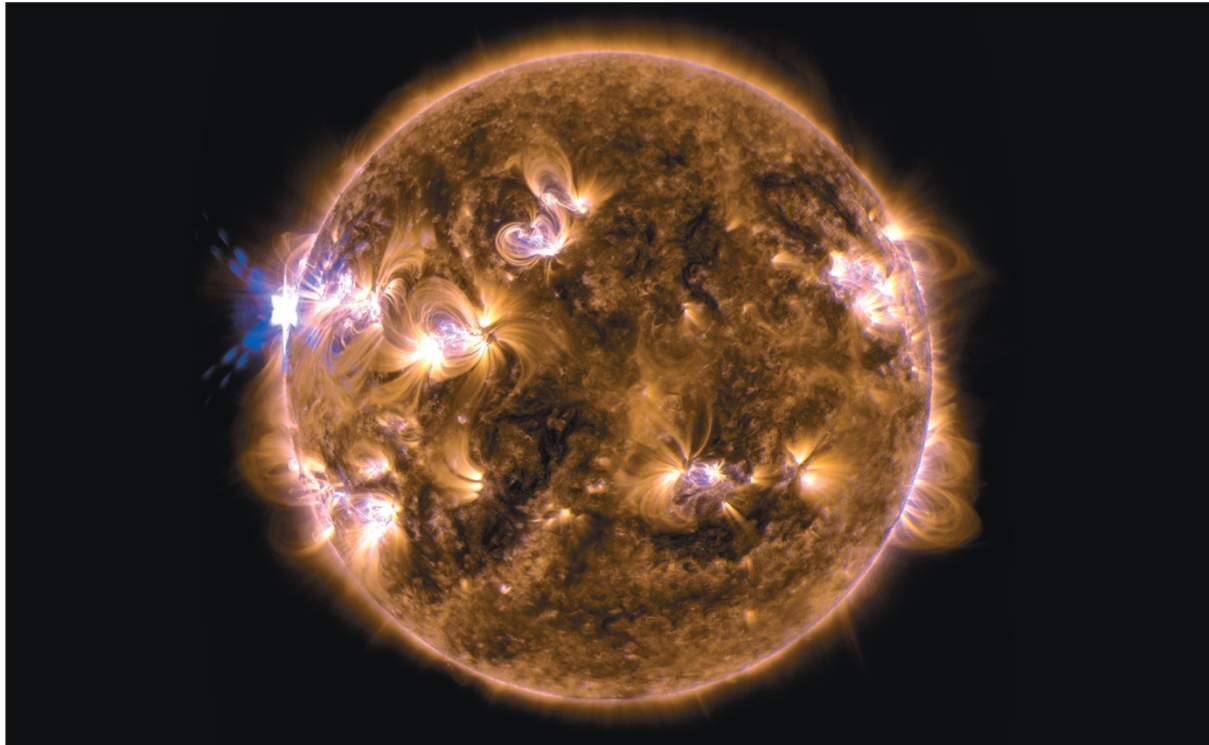
- **Is it Contracting?**

A Closer Look at the Sun (5 of 7)



- **Is it Contracting?** $\frac{\text{Gravitational potential}}{\text{Luminosity}} \sim 25 \text{ million years}$

A Closer Look at the Sun (6 of 7)



- **Is it Contracting? ... No!** $\frac{\text{Gravitational potential}}{\text{Luminosity}} \sim 25 \text{ million years}$

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