

Lecture Outline

**Chapter 11:
Our Star**

**The
Essential
Cosmic
Perspective**

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Seventh Edition

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11.1 A Closer Look at the Sun

Our goals for learning:

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

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Why does the Sun shine?

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Is it on FIRE?

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

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Is it CONTRACTING?

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

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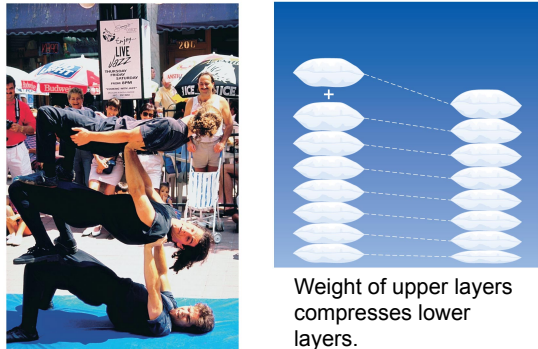
$$E = mc^2$$

 —Einstein, 1905

It is powered by NUCLEAR ENERGY!

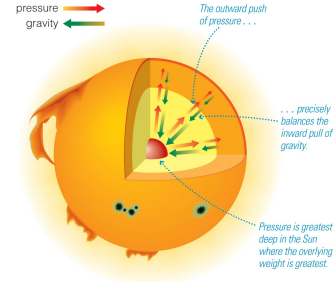
$$\frac{\text{Nuclear Potential Energy (core)}}{\text{Luminosity}} \sim 10 \text{ billion years}$$

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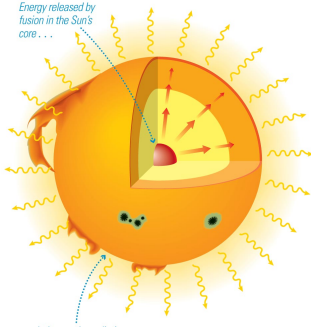
Weight of upper layers compresses lower layers.

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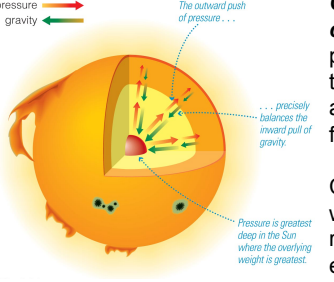
Gravitational equilibrium: Gravity pulling in balances pressure pushing out.

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

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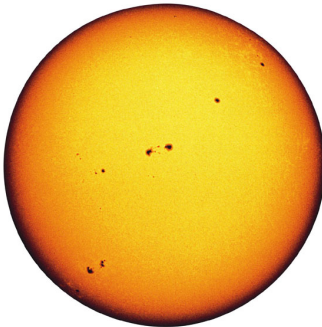


Gravitational contraction... provided energy that heated the core as the Sun was forming.

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

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What is the Sun's structure?

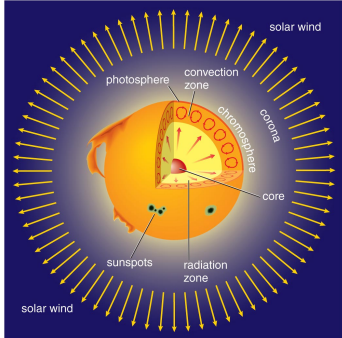


Radius:
 6.9×10^8 m
 (109 times Earth)

Mass:
 2×10^{30} kg
 (300,000 Earths)

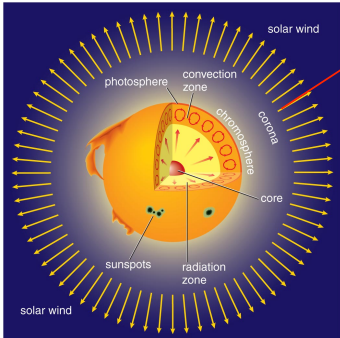
Luminosity:
 3.8×10^{26} watts

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

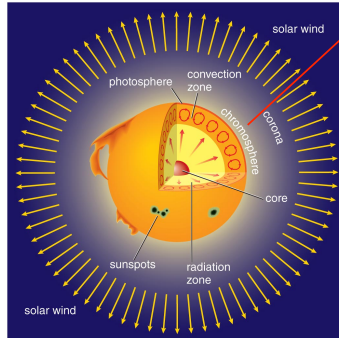
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Corona:
Outermost layer of solar atmosphere
~ 1 million K

The diagram shows a cross-section of the Sun with labels for the core, radiation zone, convection zone, photosphere, chromosphere, and corona. Sunspots are shown on the photosphere. Yellow arrows represent solar wind emanating from the corona. A red arrow points from the text to the corona layer.

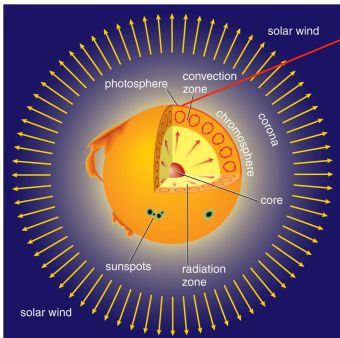
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Chromosphere:
Middle layer of solar atmosphere
~ 10^4 – 10^5 K

The diagram shows a cross-section of the Sun with labels for the core, radiation zone, convection zone, photosphere, chromosphere, and corona. Sunspots are shown on the photosphere. Yellow arrows represent solar wind emanating from the corona. A red arrow points from the text to the chromosphere layer.

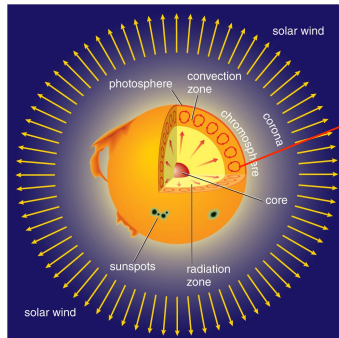
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Photosphere:
Visible surface of the Sun
~ 6000 K

The diagram shows a cross-section of the Sun with labels for the core, radiation zone, convection zone, photosphere, chromosphere, and corona. Sunspots are shown on the photosphere. Yellow arrows represent solar wind emanating from the corona. A red arrow points from the text to the photosphere layer.

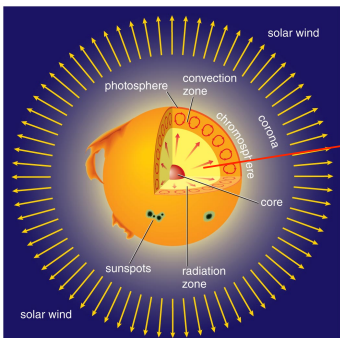
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Convection zone:
Energy transported upward by rising hot gas

The diagram shows a cross-section of the Sun with labels for the core, radiation zone, convection zone, photosphere, chromosphere, and corona. Sunspots are shown on the photosphere. Yellow arrows represent solar wind emanating from the corona. A red arrow points from the text to the convection zone layer.

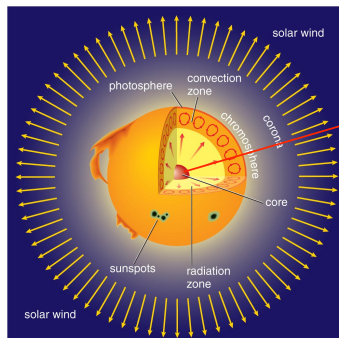
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Radiation zone:
Energy transported upward by photons

The diagram shows a cross-section of the Sun with labels for the core, radiation zone, convection zone, photosphere, chromosphere, and corona. Sunspots are shown on the photosphere. Yellow arrows represent solar wind emanating from the corona. A red arrow points from the text to the radiation zone layer.

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Core:
Energy generated by nuclear fusion
~ 15 million K

The diagram shows a cross-section of the Sun with labels for the core, radiation zone, convection zone, photosphere, chromosphere, and corona. Sunspots are shown on the photosphere. Yellow arrows represent solar wind emanating from the corona. A red arrow points from the text to the core layer.

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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.

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What have we learned?

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

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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?

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How does nuclear fusion occur in the Sun?

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<p>Fission</p> <p>Big nucleus splits into smaller pieces.</p> <p>(Nuclear power plants)</p>	<p>Fusion</p> <p>Small nuclei stick together to make a bigger one.</p> <p>(Sun, stars)</p>
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High temperatures enable nuclear fusion to happen in the core.

At low speeds, electromagnetic repulsion prevents the collision of nuclei.

At high speeds, nuclei come close enough for the strong force to bind them together.

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

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

Hydrogen Fusion by the Proton-Proton Chain

Step 1
Two protons fuse to make a deuterium nucleus (1 proton and 1 neutron). This step occurs twice in the overall reaction.

Step 2
The deuterium nucleus and a proton fuse to make a nucleus of helium-3 (2 protons, 1 neutron). This step also occurs twice in the overall reaction.

Step 3
Two helium-3 nuclei fuse to form helium-4 (2 protons, 2 neutrons), releasing two excess protons in the process.

Overall reaction
4 protons → ⁴He nucleus + 2 gamma rays + 2 positrons + 2 neutrinos

Total mass is 0.7% lower.

Key:
● neutron
● proton
● gamma ray

MA Interactive figure

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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.

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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.

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


Bright spots on photosphere where hot gas reaches the surface

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How do we know what is happening inside the Sun?

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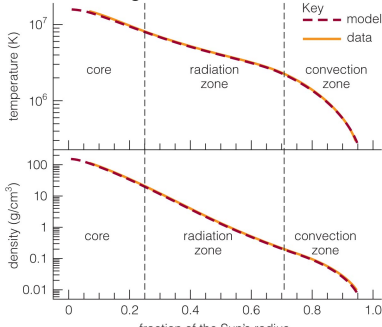
• 1. making mathematical models



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

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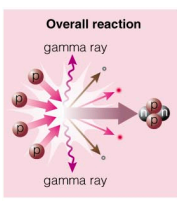
• 2. observing solar vibrations



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

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• 3. observing solar neutrinos



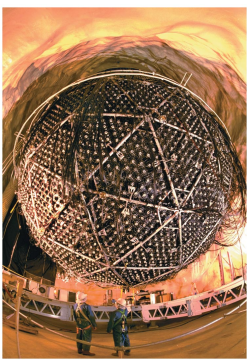
Key:

- neutron
- proton
- neutrino
- positron
- gamma ray

Neutrinos created during fusion fly directly through the Sun.

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

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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.

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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.

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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.

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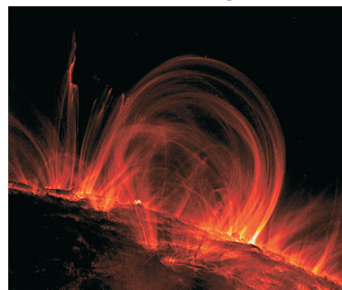
11.3 The Sun–Earth Connection

Our goals for learning:

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

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What causes solar activity?



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

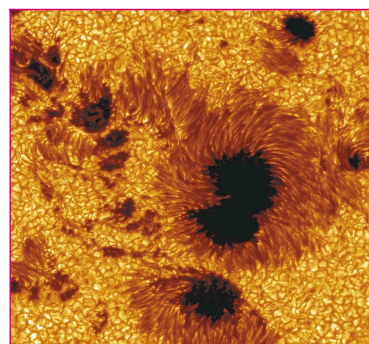
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Solar activity is like "weather" on Earth.

- Sunspots
- Solar flares
- Solar prominences

All these phenomena are related to magnetic fields.

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Sunspots...

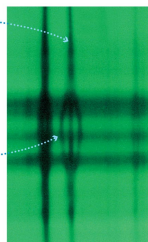
Are cooler than other parts of the Sun's surface (4000 K).

Are regions with strong magnetic fields.

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

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

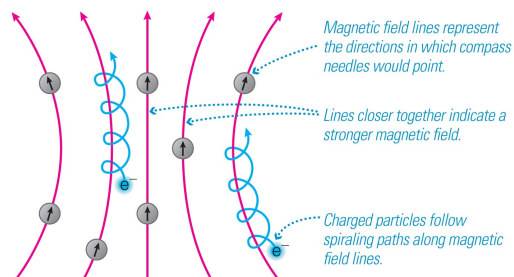


Zeeman Effect

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

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.

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Charged particles spiral along magnetic field lines.

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Magnetic field loops
 sunspots
 $T \approx 5800\text{ K}$
 $T \approx 4500\text{ K}$
 $T \approx 5800\text{ K}$
 convection cells

Magnetic fields of sunspots suppress convection and prevent surrounding plasma from sliding sideways into the sunspots.

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.

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

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

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

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

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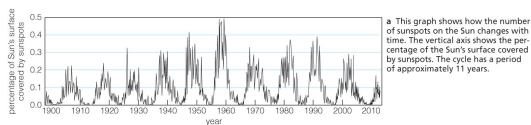
stream of solar particles from solar wind

particles spiral around magnetic field lines

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

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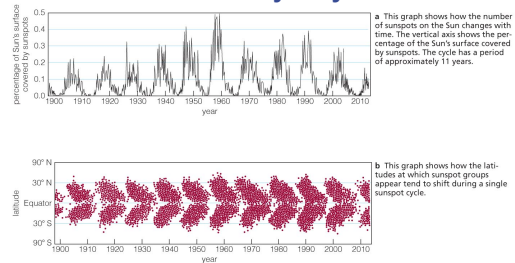
How does solar activity vary with time?



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.

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How does solar activity vary with time?

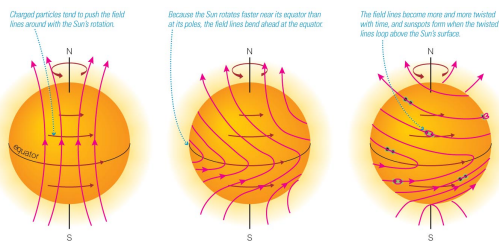


a This graph shows how the number of sunspots on the Sun changes with time. The vertical axis shows the percentage of the Sun's surface covered by sunspots. The cycle has a period of approximately 11 years.

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

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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.

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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.

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