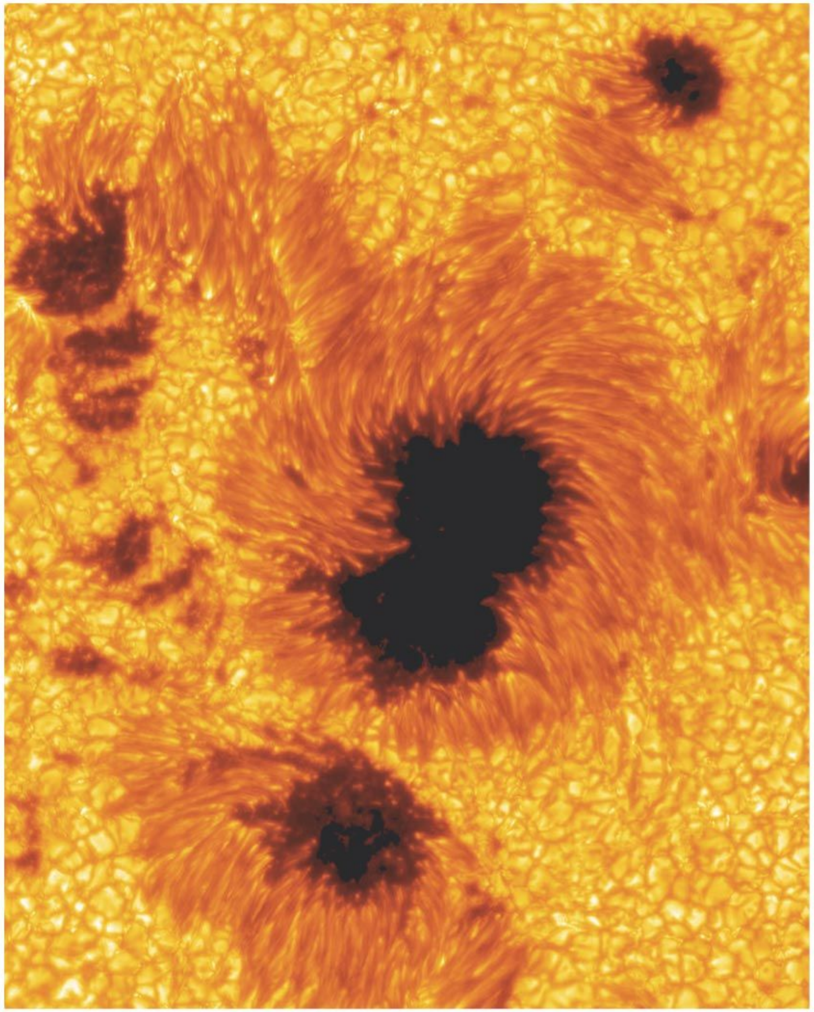
Chapter 16
The Sun



Units of Chapter 16

Units of Chapter 16 (cont.)

16.6 The Heart of the Sun

- Fundamental Forces
- Energy Generation in the Proton–Proton Chain

16.7 Observations of Solar Neutrinos

16.1 Physical Properties of the Sun

Radius: 700,000 km

Mass: 2.0×10^{30} kg

Density: 1400 kg/m^3

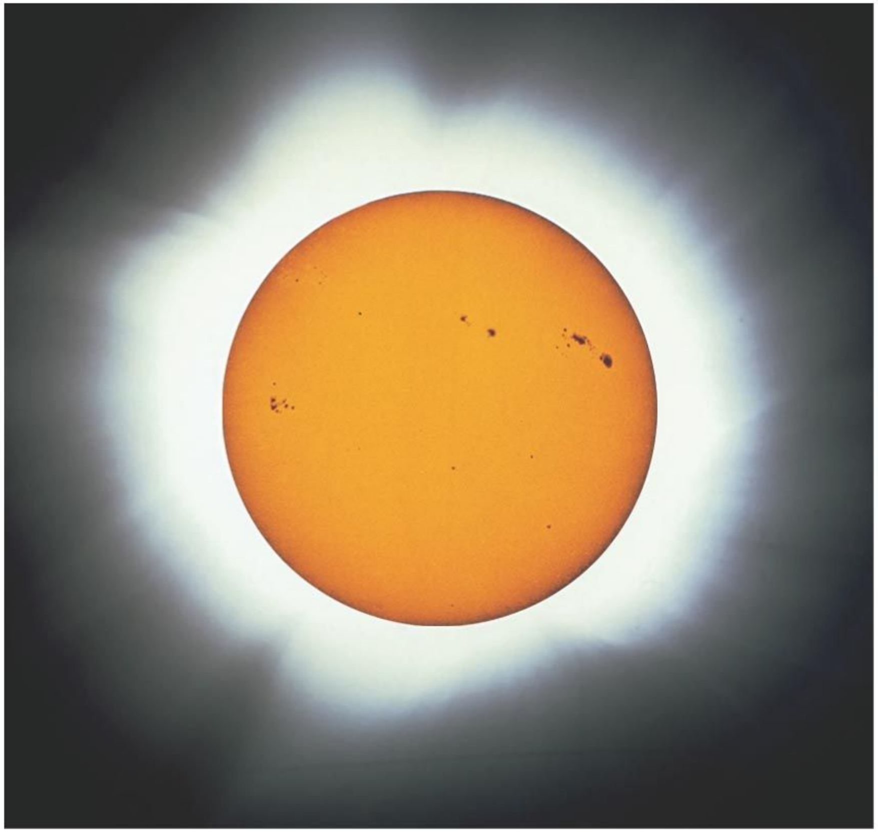
Rotation: Differential; period about a month

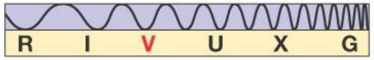
Surface temperature: 5800 K

Apparent surface of Sun is **photosphere**

16.1 Physical Properties of the Sun

This composite image shows both the filamentary corona and the sharp outline of the photosphere.





16.1 Physical Properties of the Sun

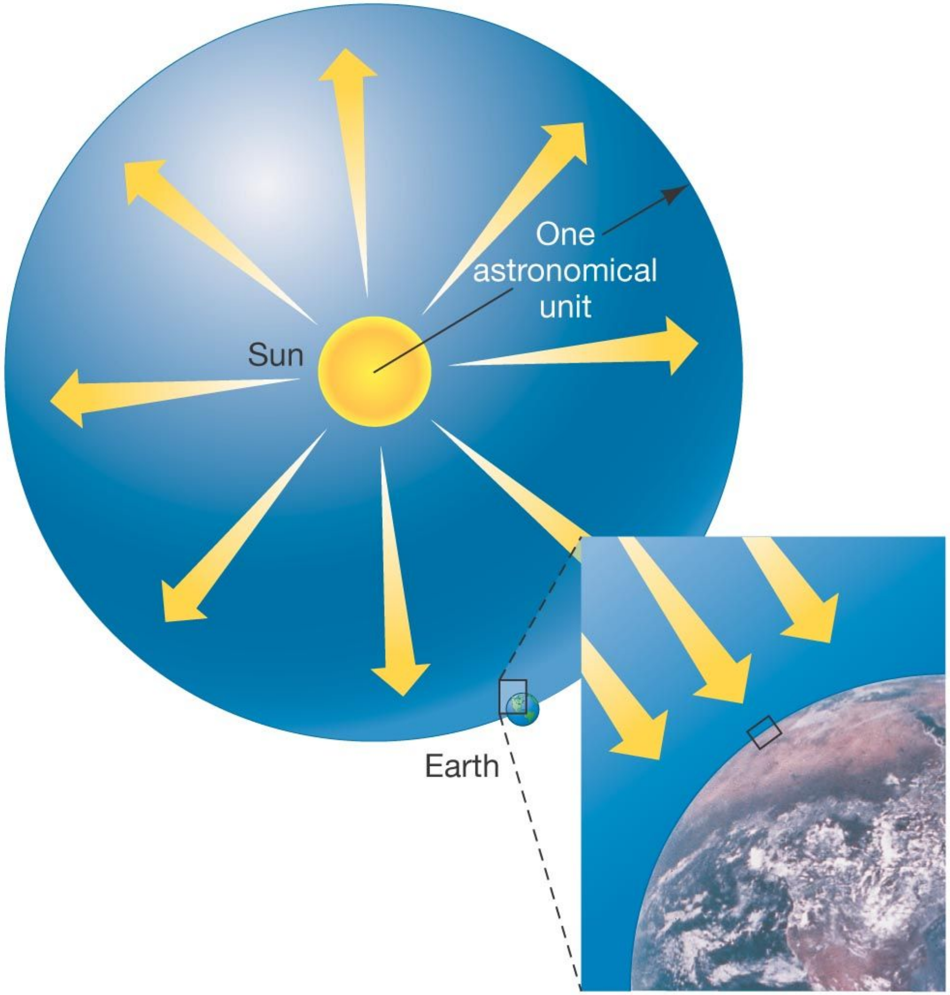
Luminosity—total energy radiated per second in all directions. (Can have L_V or L_B or L_{bol})

Solar constant—amount of Sun's energy passing through a square meter at 1 AU — **1400 W/m²**.

Total luminosity is about **4×10^{26} W**—the equivalent of 10 billion 1-megaton nuclear bombs per second.

16.1 Physical Properties of the Sun

how to extrapolate from the radiation hitting Earth to the entire output of the Sun ...

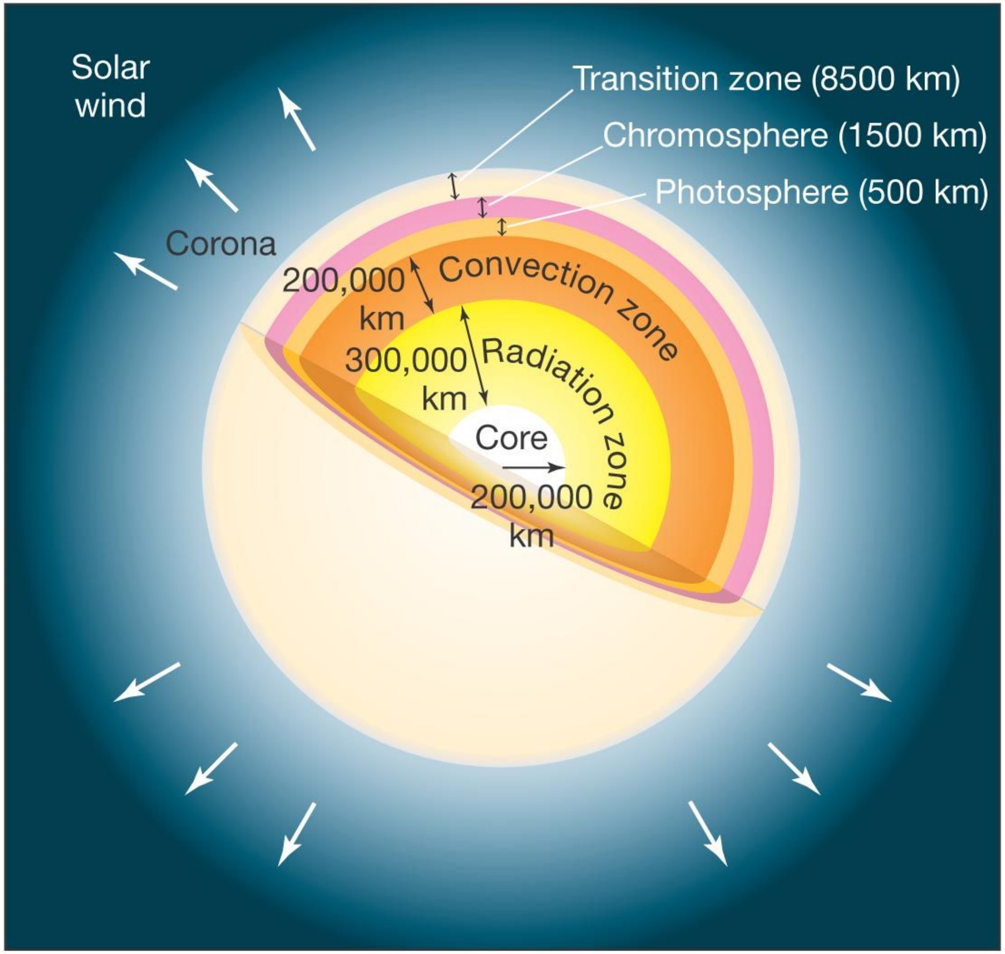


16.2 The Solar Interior

Interior structure of the Sun:
core: where energy is created (fusion)

Radiative Zone:
heat transferred outward by radiation

Convective Zone
heat transfer by radiation and convection

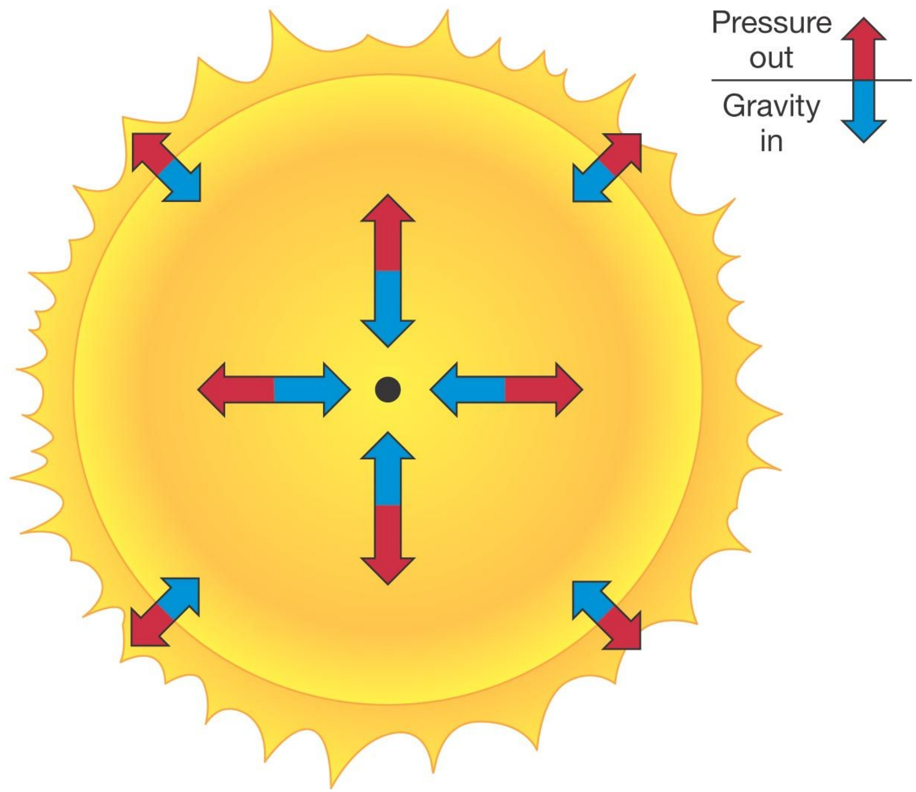


(Outer layers are not to scale.)

16.2 The Solar Interior

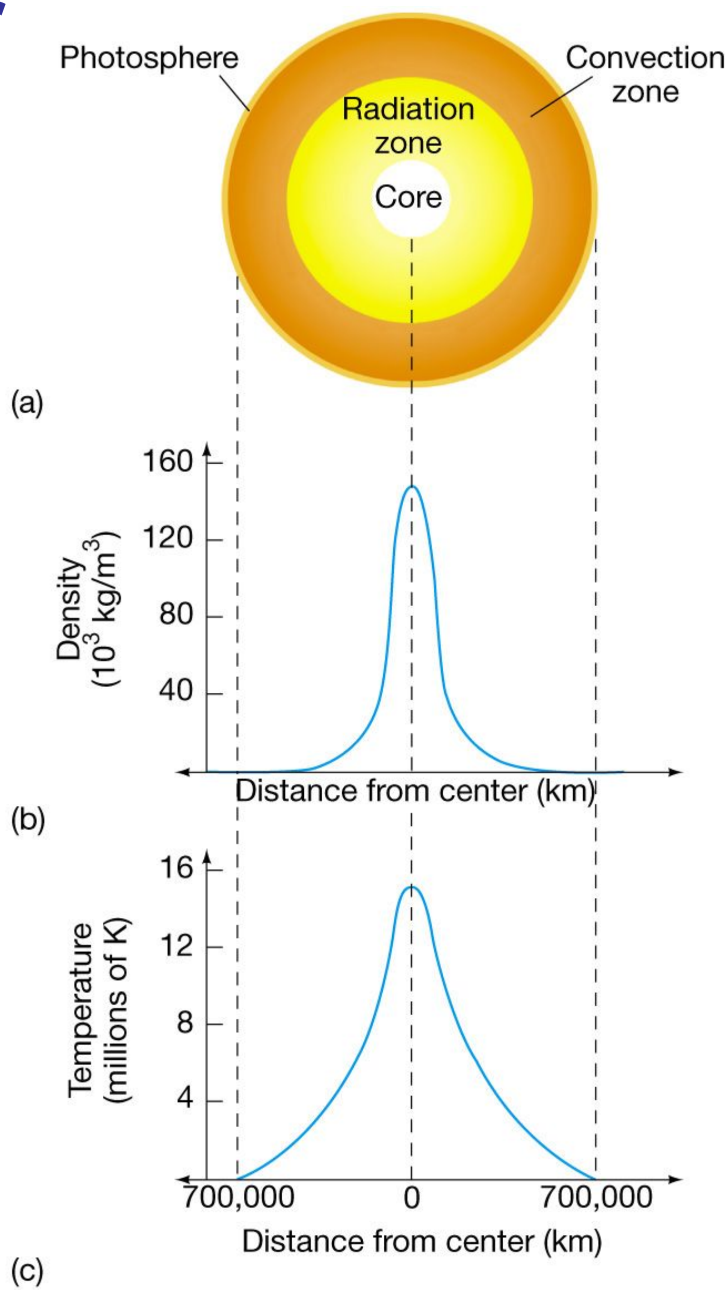
Astrophysics uses 4 "structural equations" which help us estimate temp, density, pressure, etc. in the Sun's interior.

One is called **hydrostatic equilibrium**: for a stable star, inward **gravitational force** must be balanced by outward **pressure**.



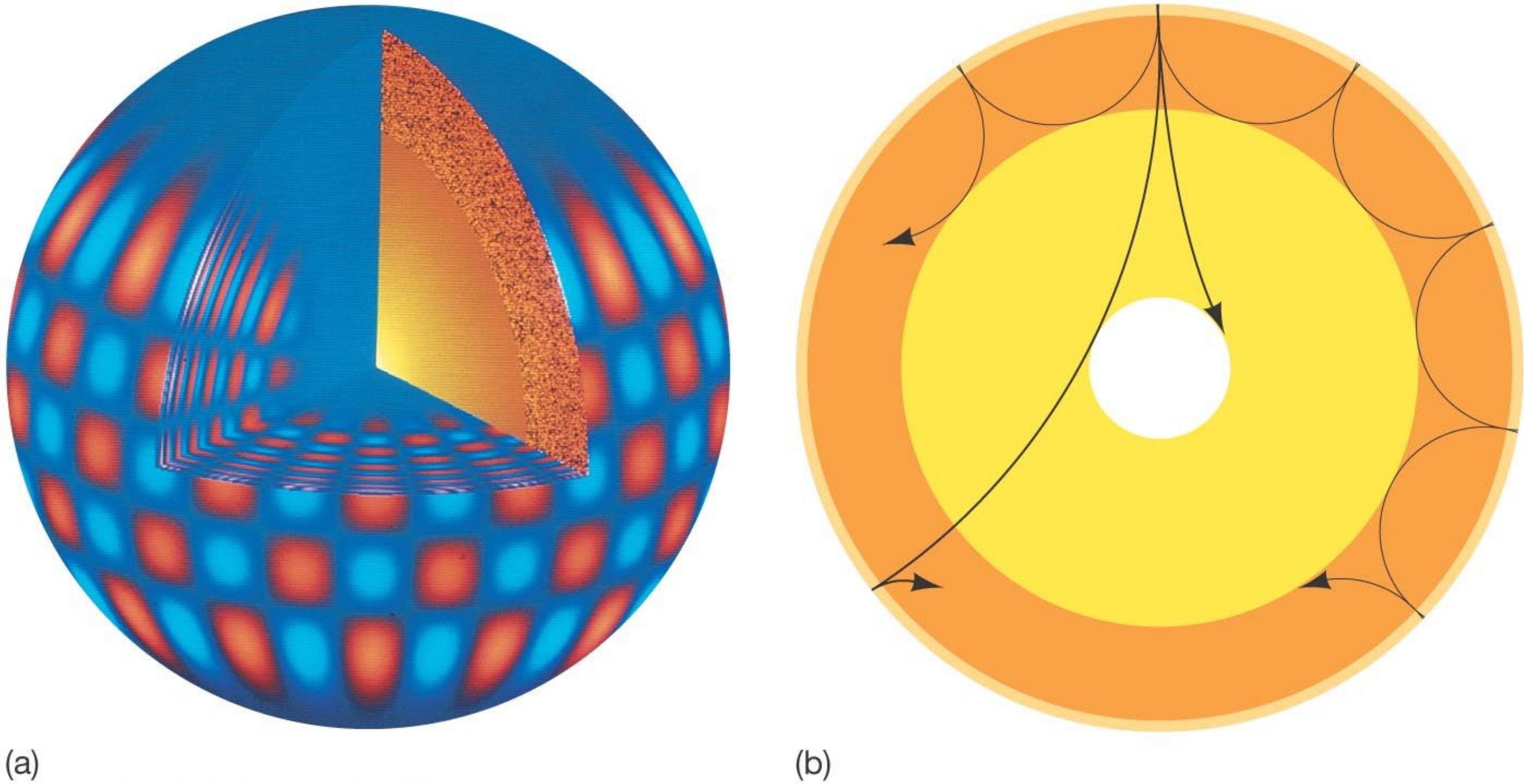
16.2 The Solar Interior

Solar **density** and **temperature**, according to the standard solar model:



16.2 The Solar Interior

Doppler shifts of solar spectral lines indicate a complex pattern of **vibrations**.

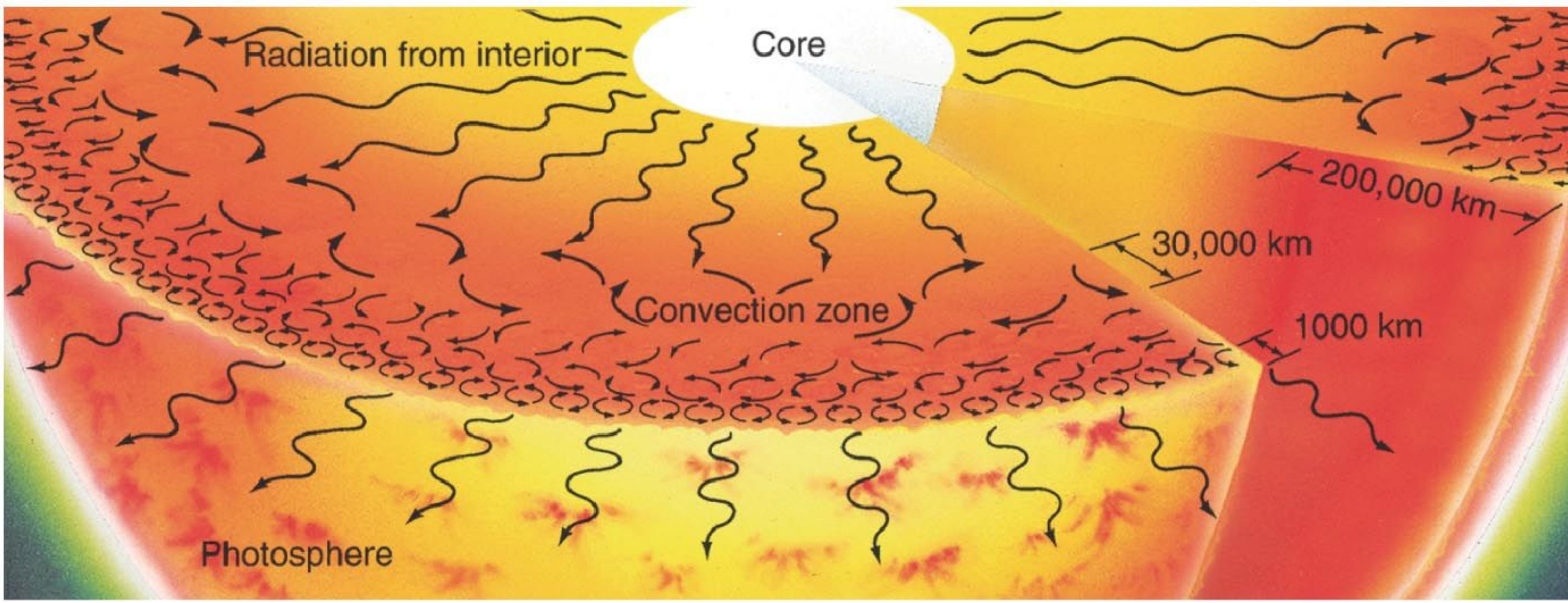


Helioseismology, the study of oscillation modes of the Sun, gives additional clues about the interior.

16.2 The Solar Interior

Energy transport:

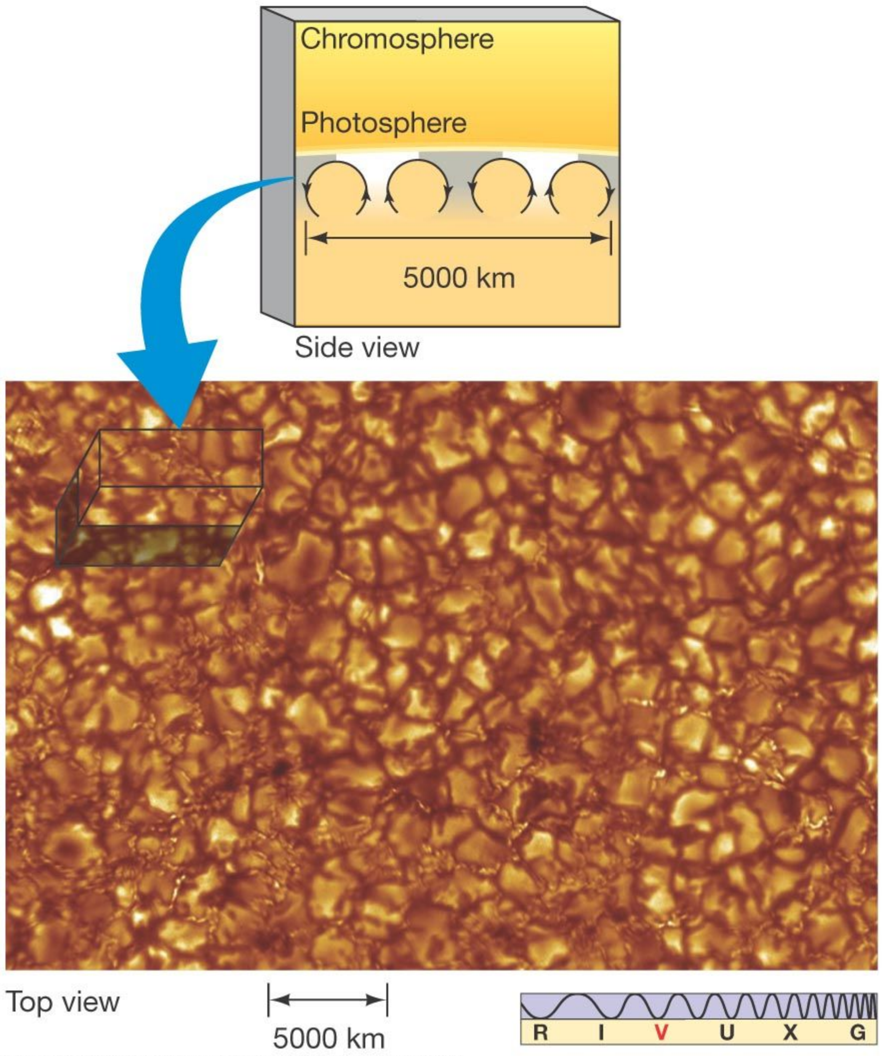
The **radiation zone** is relatively transparent; the cooler **convection zone** is opaque



16.2 The Solar Interior

Signs of convection: the photosphere appears **granulated**.

Upwelling gas - hot
sinking gas - cool

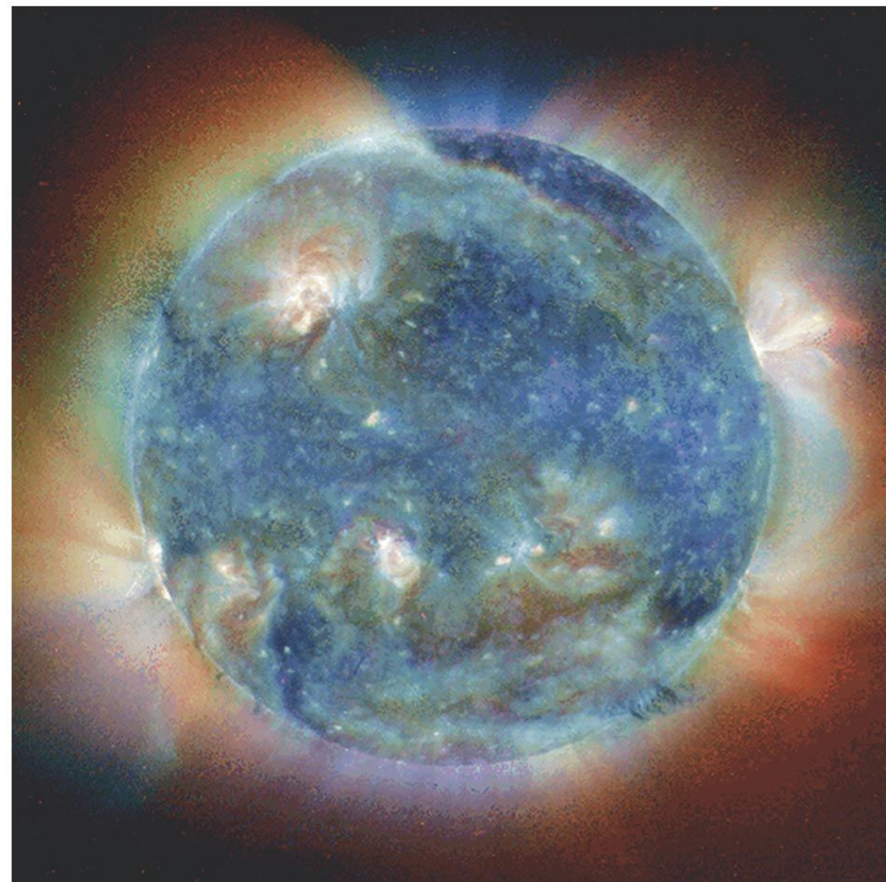


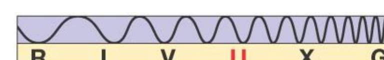
SOHO: Eavesdropping on the Sun

SOHO: Solar and Heliospheric Observatory

Measures magnetic field, corona, vibrations, and UV emissions

Finds comets!



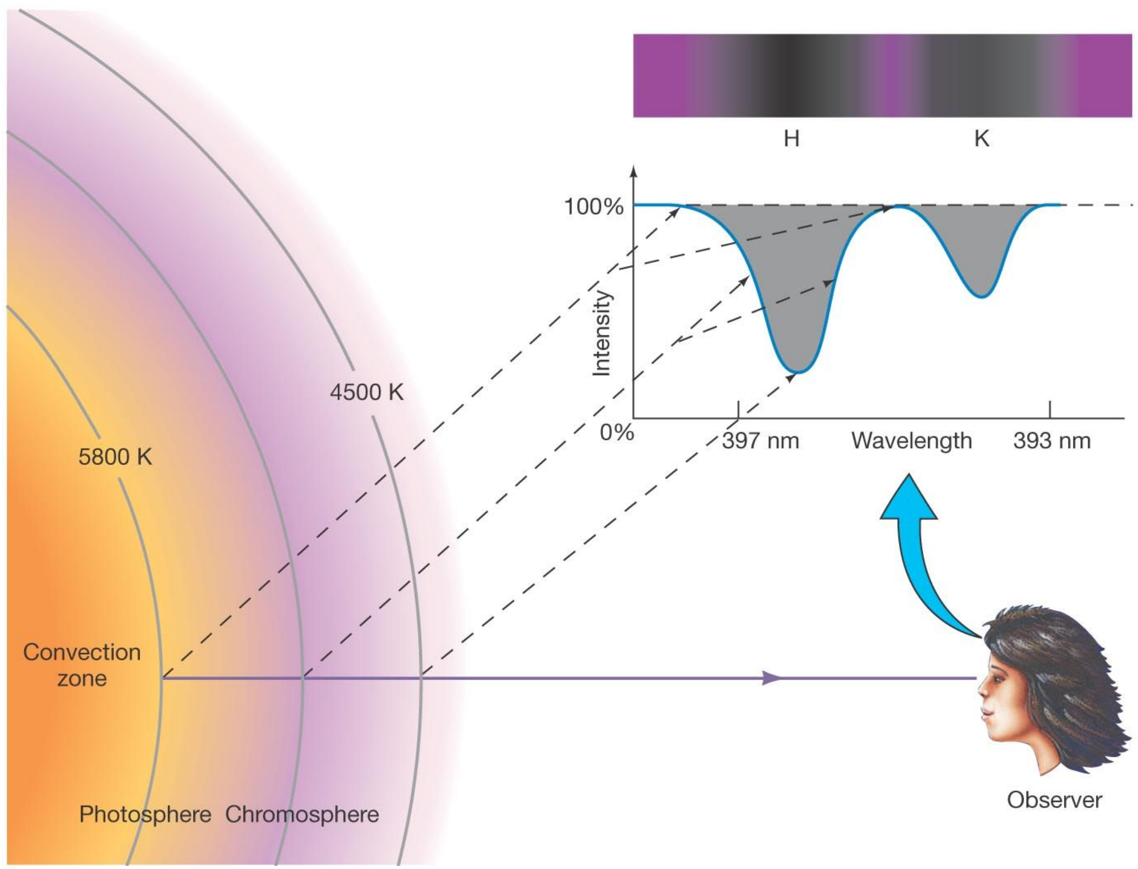


16.3 The Sun's Atmosphere

Spectral analysis can tell us what elements are present in the chromosphere and photosphere of the Sun. This spectrum has lines from 67 different elements:

16.3 The Sun’s Atmosphere

Spectral absorption lines. We can't see as deep into the Sun at the wavelengths being absorbed.



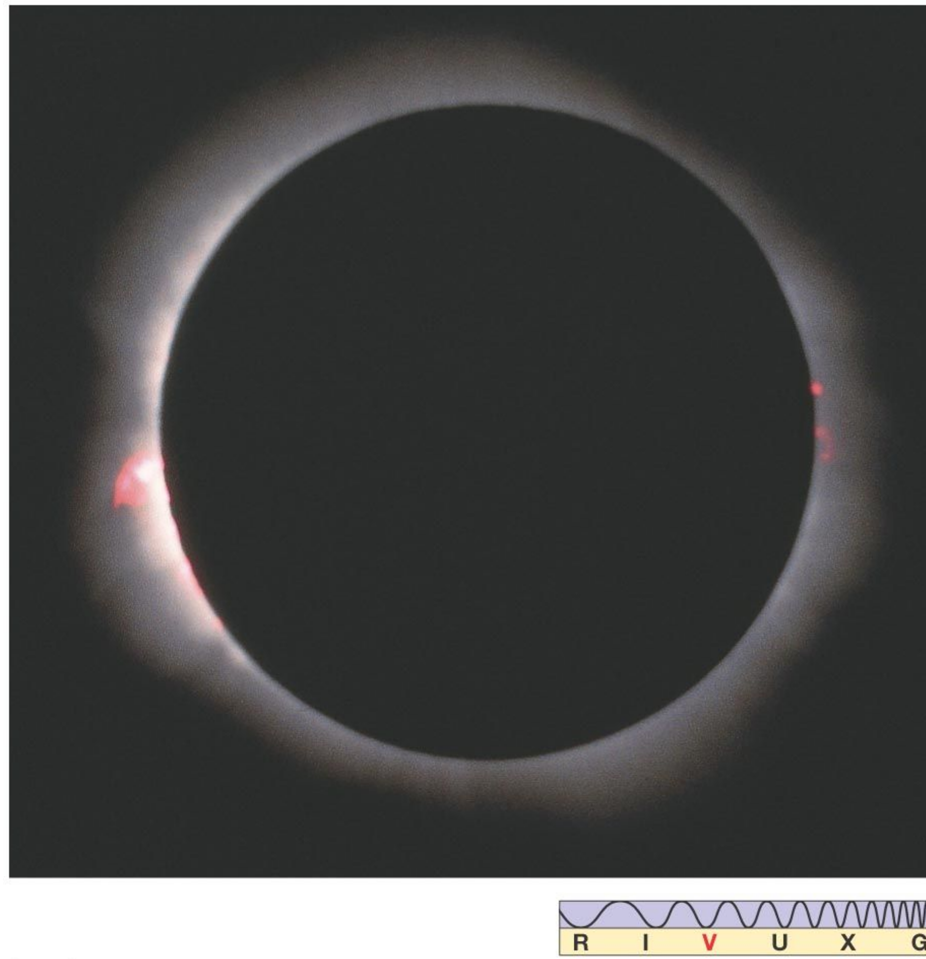
16.3 The Sun’s Atmosphere

The colorful chromosphere is above the photosphere.

The chromosphere is reddish-pink.

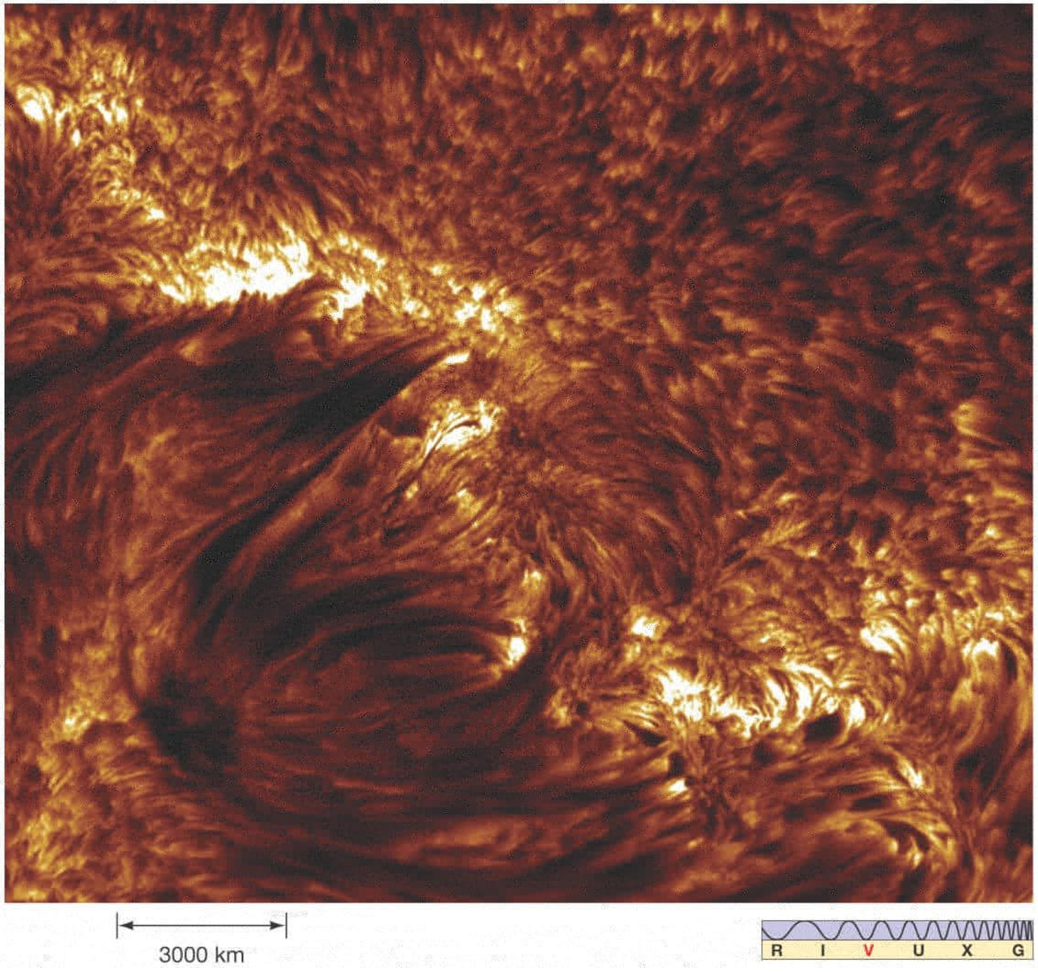
Lower density than photosphere.

Temp increases with height from 4400 K to 25,000 K in 2000 km.



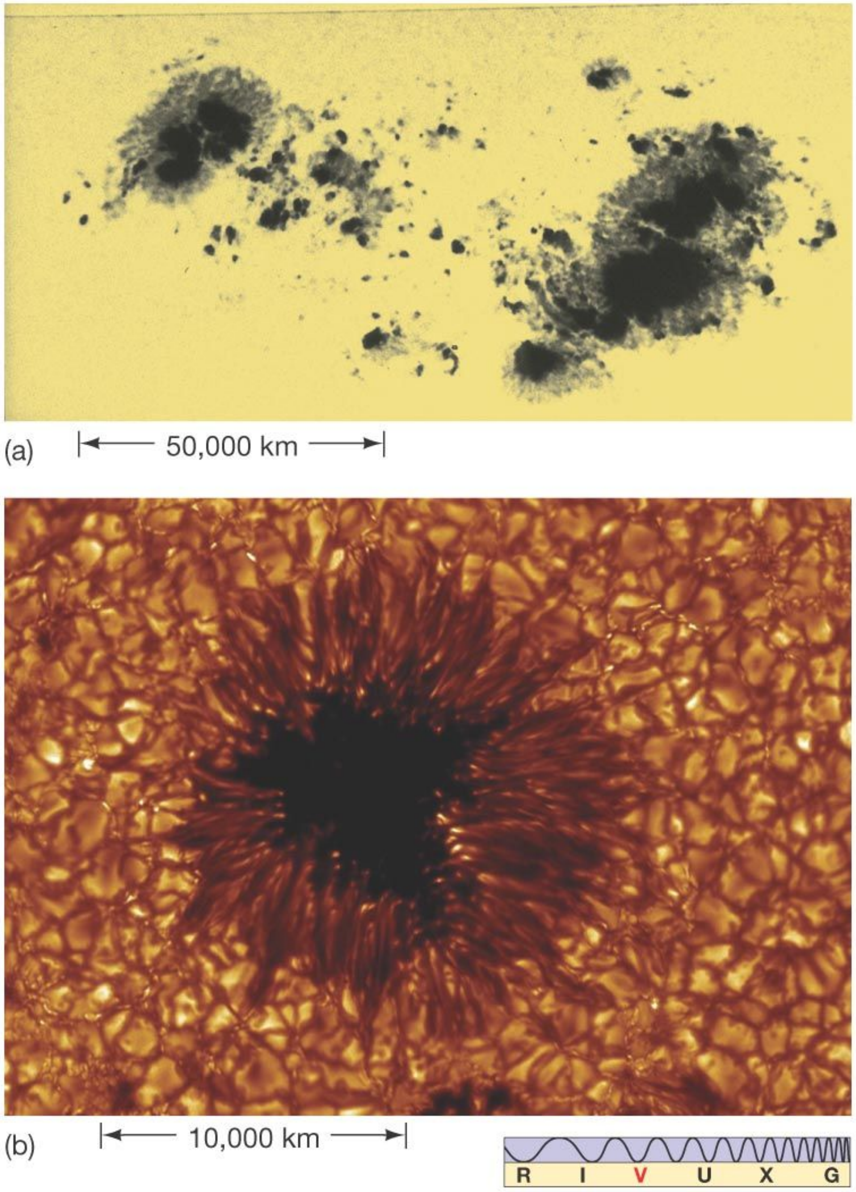
16.3 The Sun’s Atmosphere

Small solar storms in chromosphere emit **spicules**: tubes of magnetically channeled hot gas



16.4 Solar Magnetism

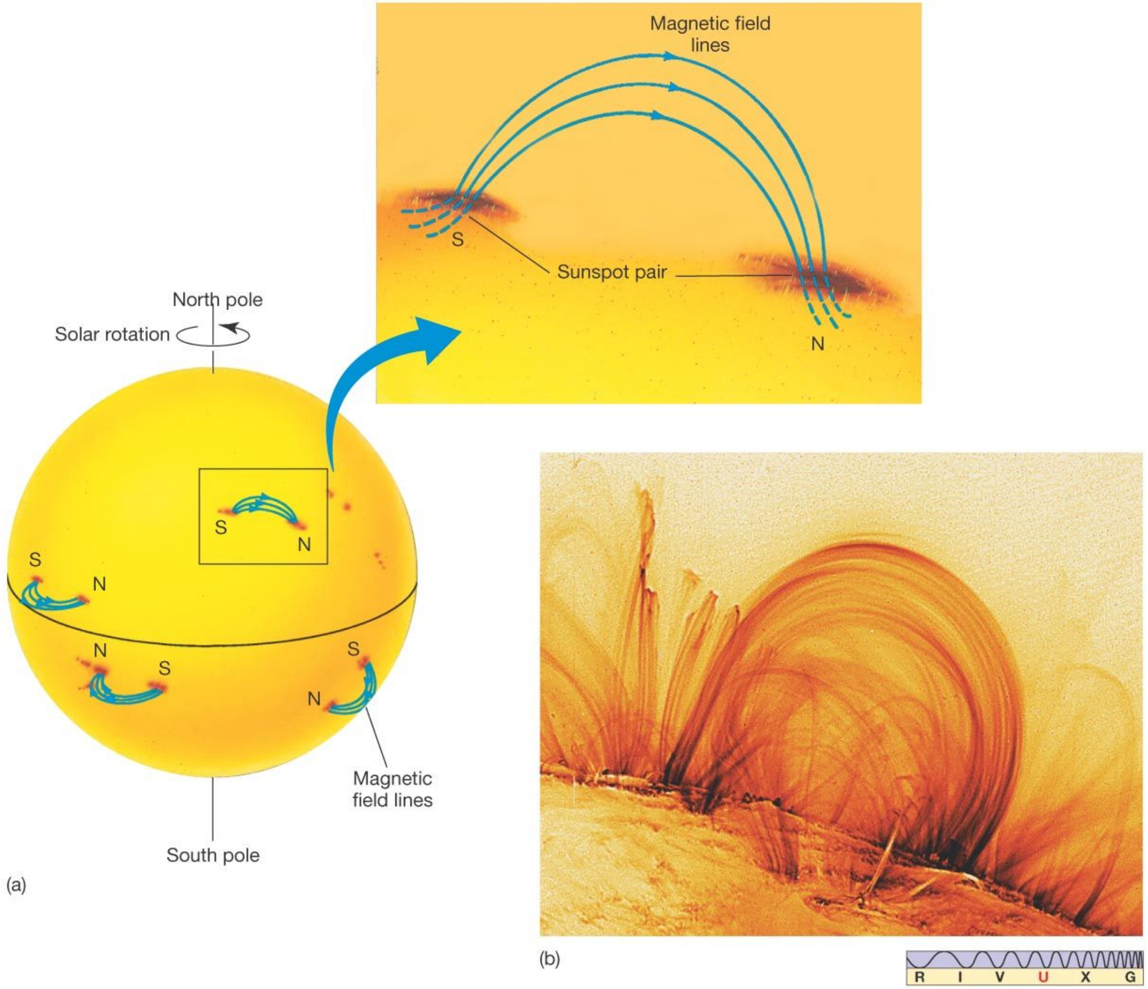
Sunspots: Appear dark because slightly cooler than surroundings



16.4 Solar Magnetism

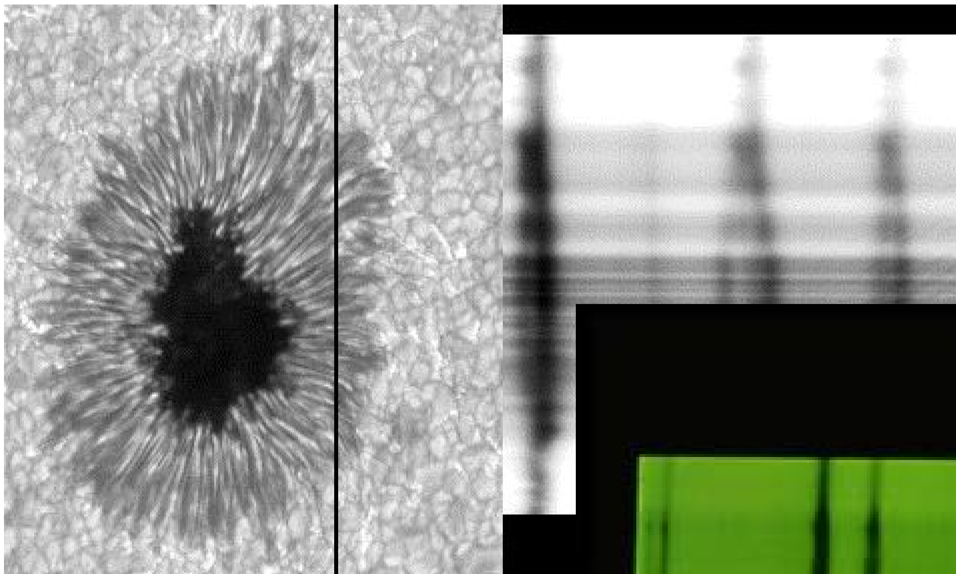
Sunspots come and go, typically in a few days.

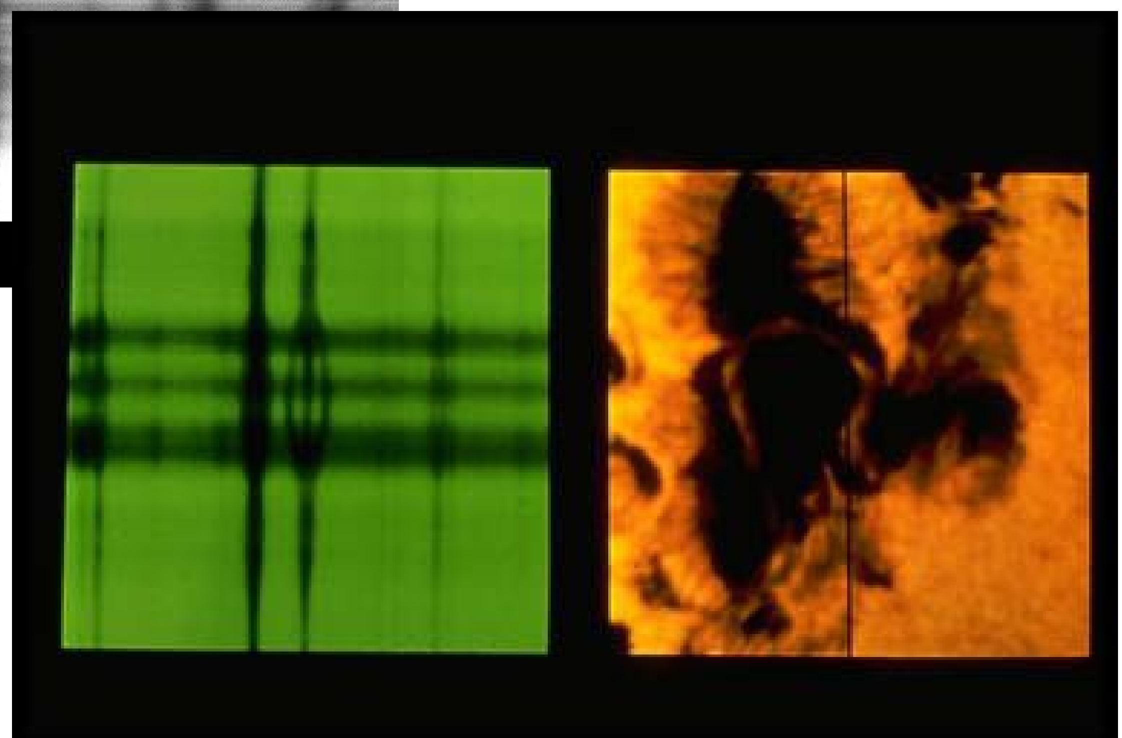
Pairs of sunspots are linked by **magnetic field lines**:



16.4 Solar Magnetism

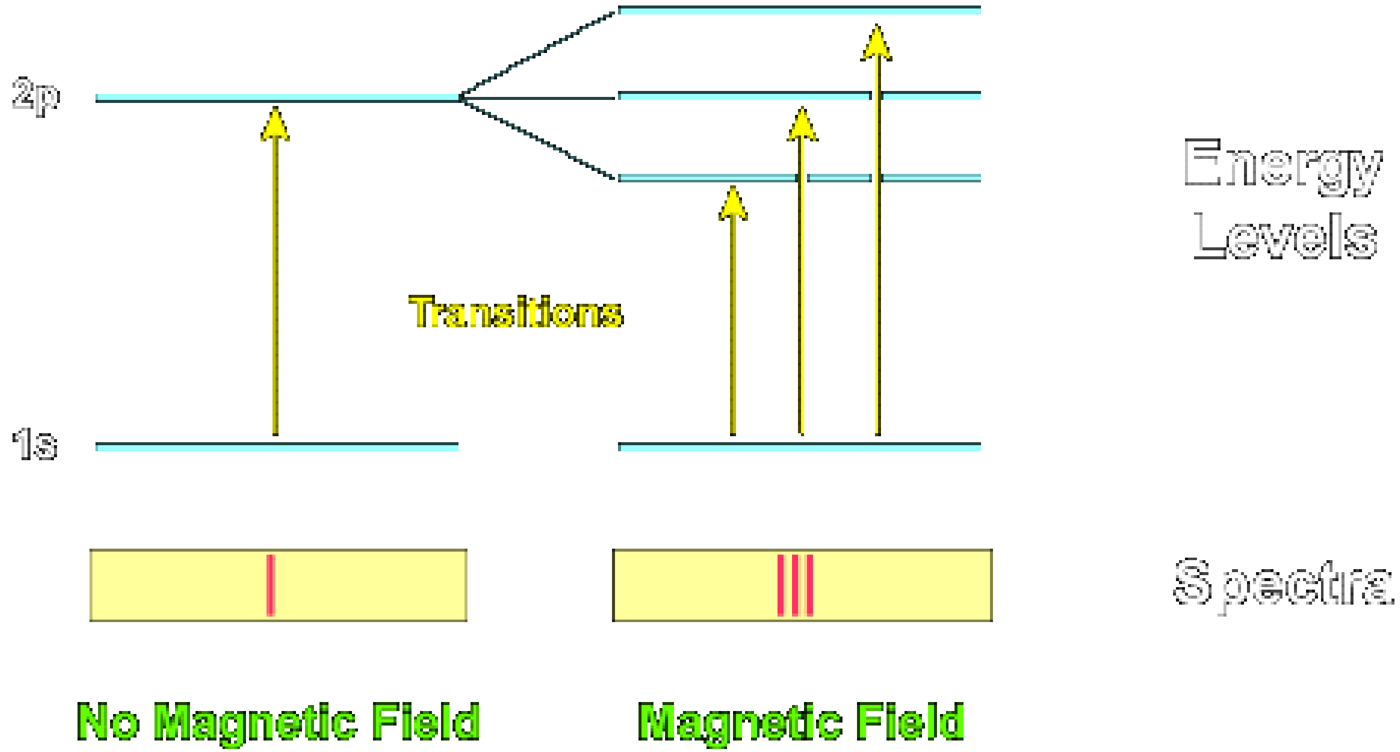
Confirmation of strong magnetic fields in sunspots ...
the Zeeman Effect!





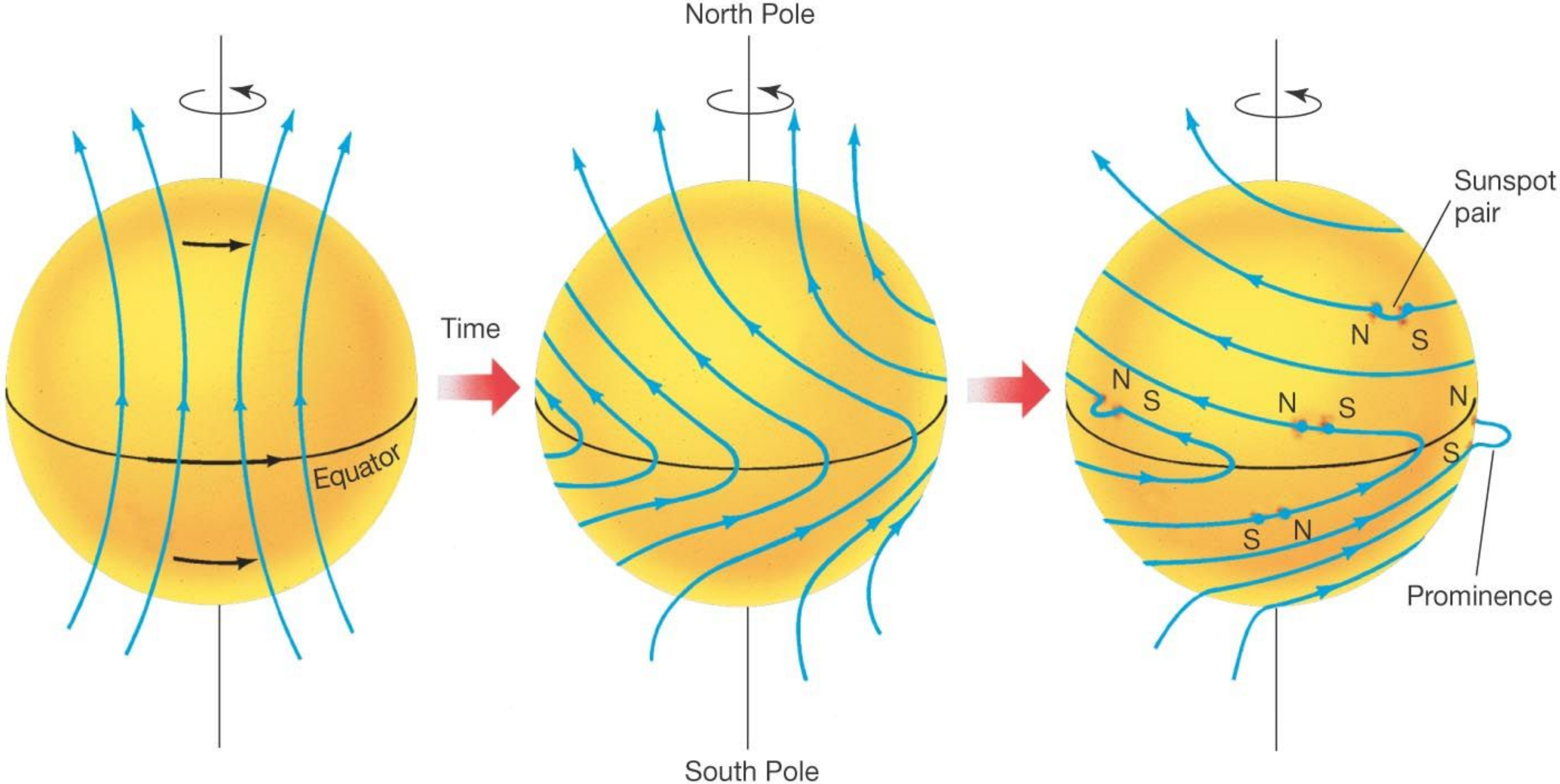
16.4 Solar Magnetism

The Zeeman Effect Is explained in terms of splitting energy levels in atoms.



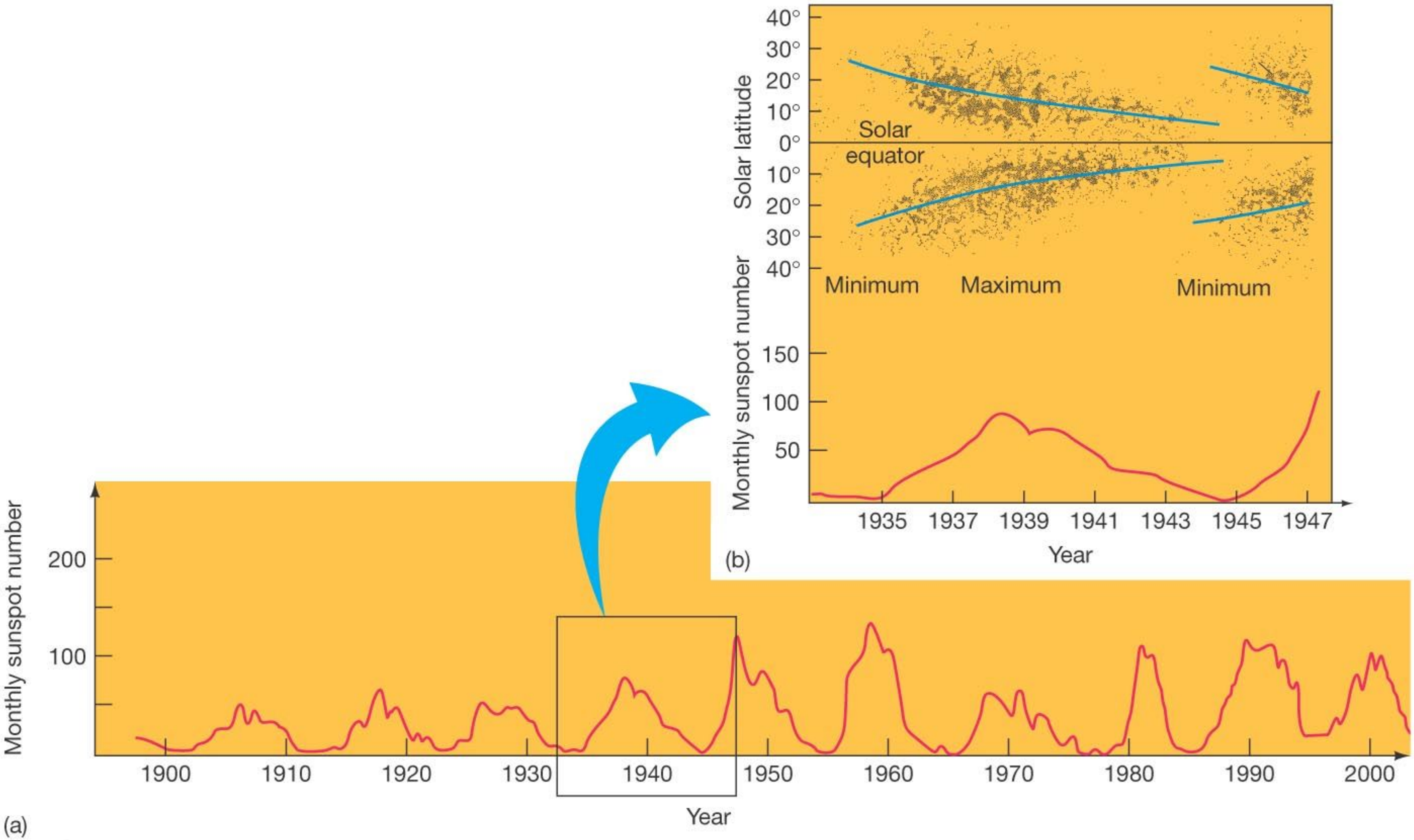
16.4 Solar Magnetism

Sunspots originate when magnetic field lines are distorted by Sun's differential rotation.



16.4 Solar Magnetism

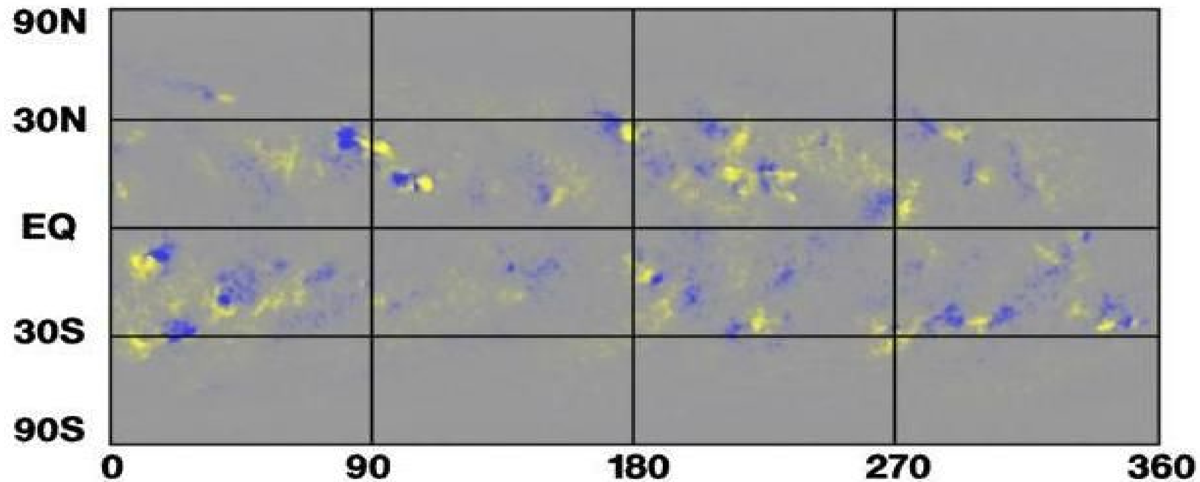
The Sun has an 11-year **sunspot cycle**.



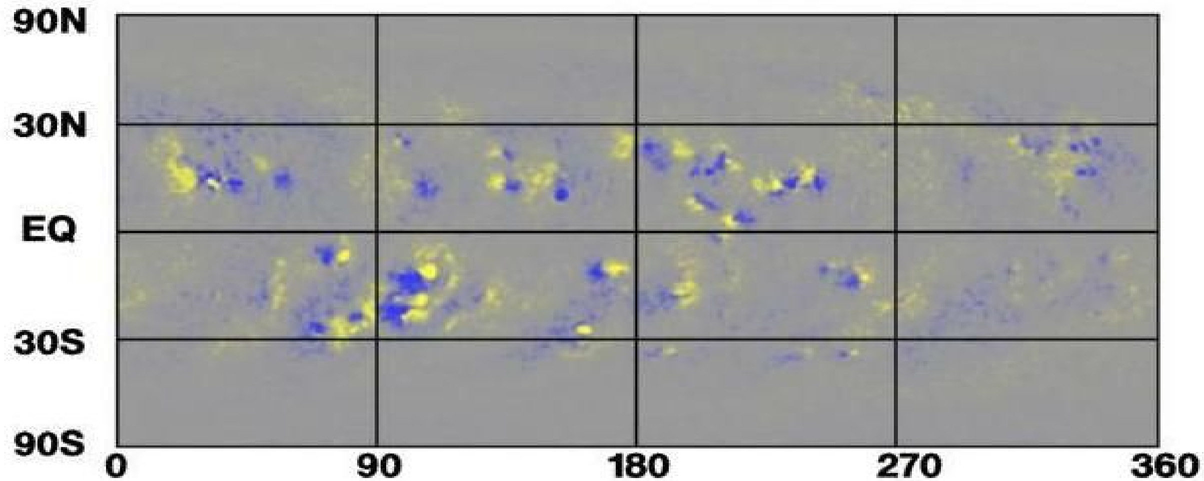
16.4 Solar Magnetism

This is really a 22-year cycle, because the spots switch polarities every 11 years.

Cycle 21



Cycle 22



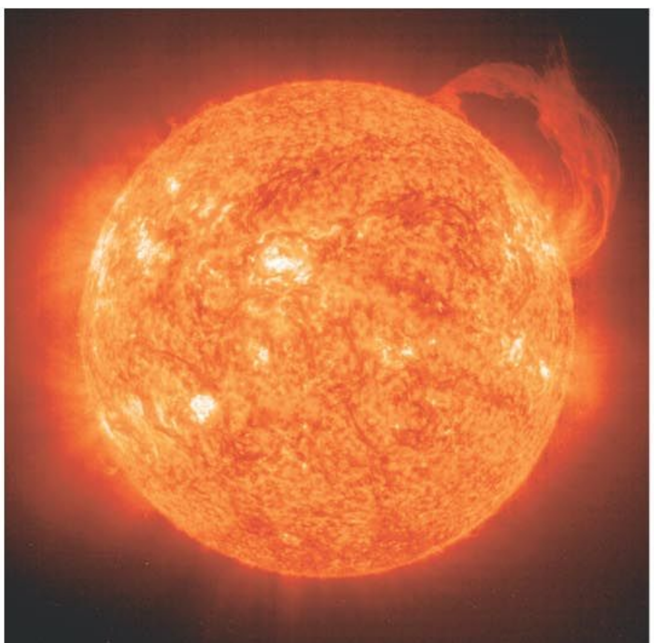
16.5 The Active Sun

Areas around sunspots are active.

Solar prominence : gas loop on limb

Solar Filament: gas loop viewed "head on"

Coronal mass ejection: loop breaks, gas ejected



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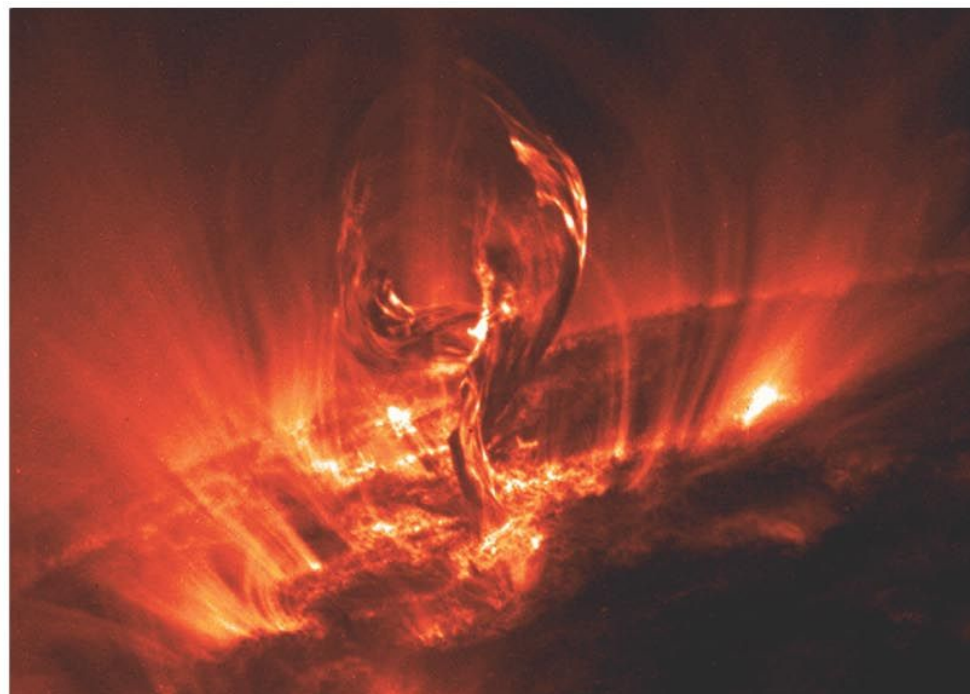

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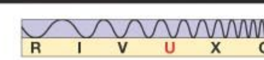
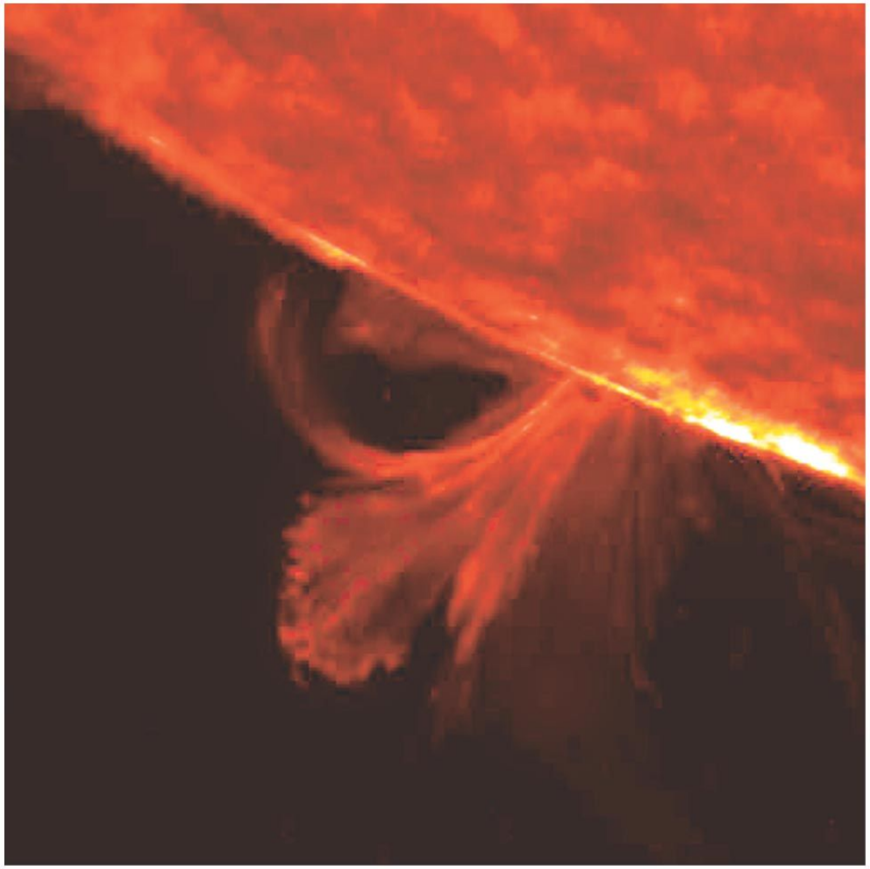
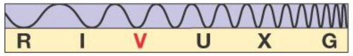


Solar Flare:

16.5 The Active Sun

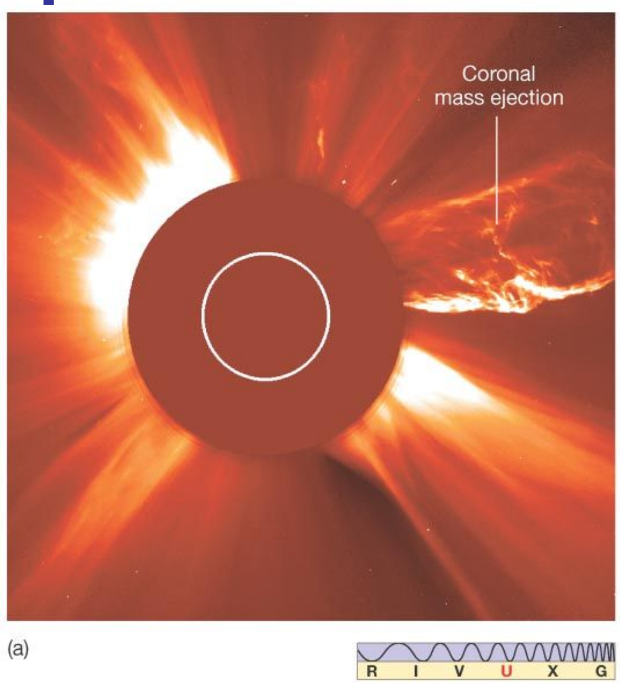
Solar flare is a large **explosion** on Sun's surface, emitting a similar amount of energy to a prominence, but in seconds or minutes rather than days or weeks:





16.5 The Active Sun

Coronal mass ejection occurs when a large "bubble" detaches from the Sun and escapes into space.



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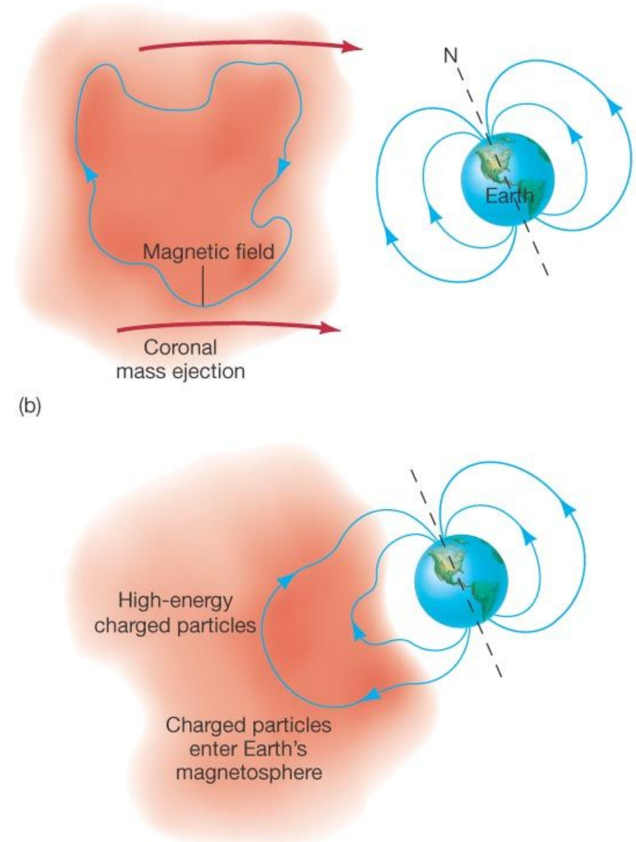

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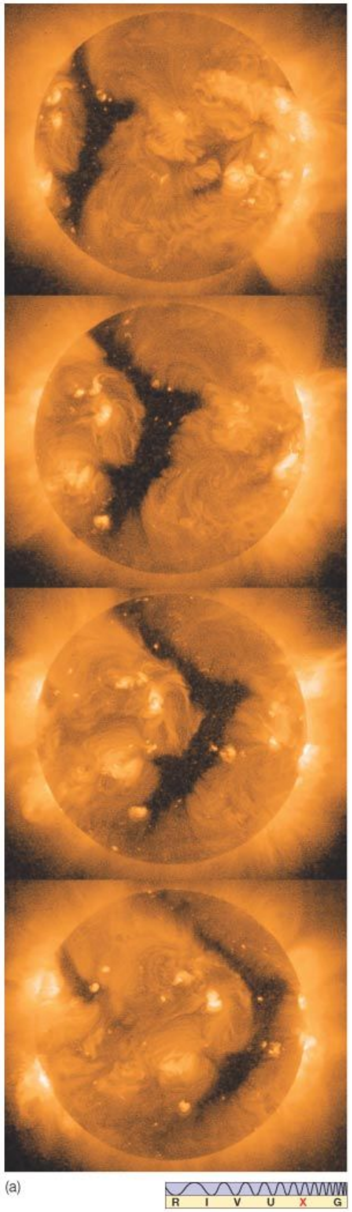
16.5 The Active Sun



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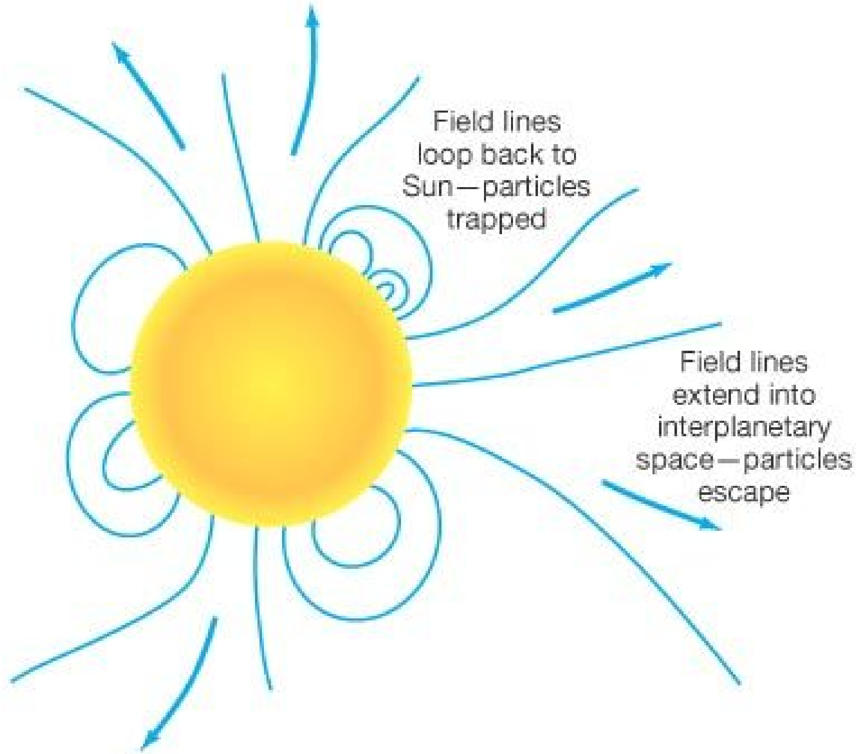
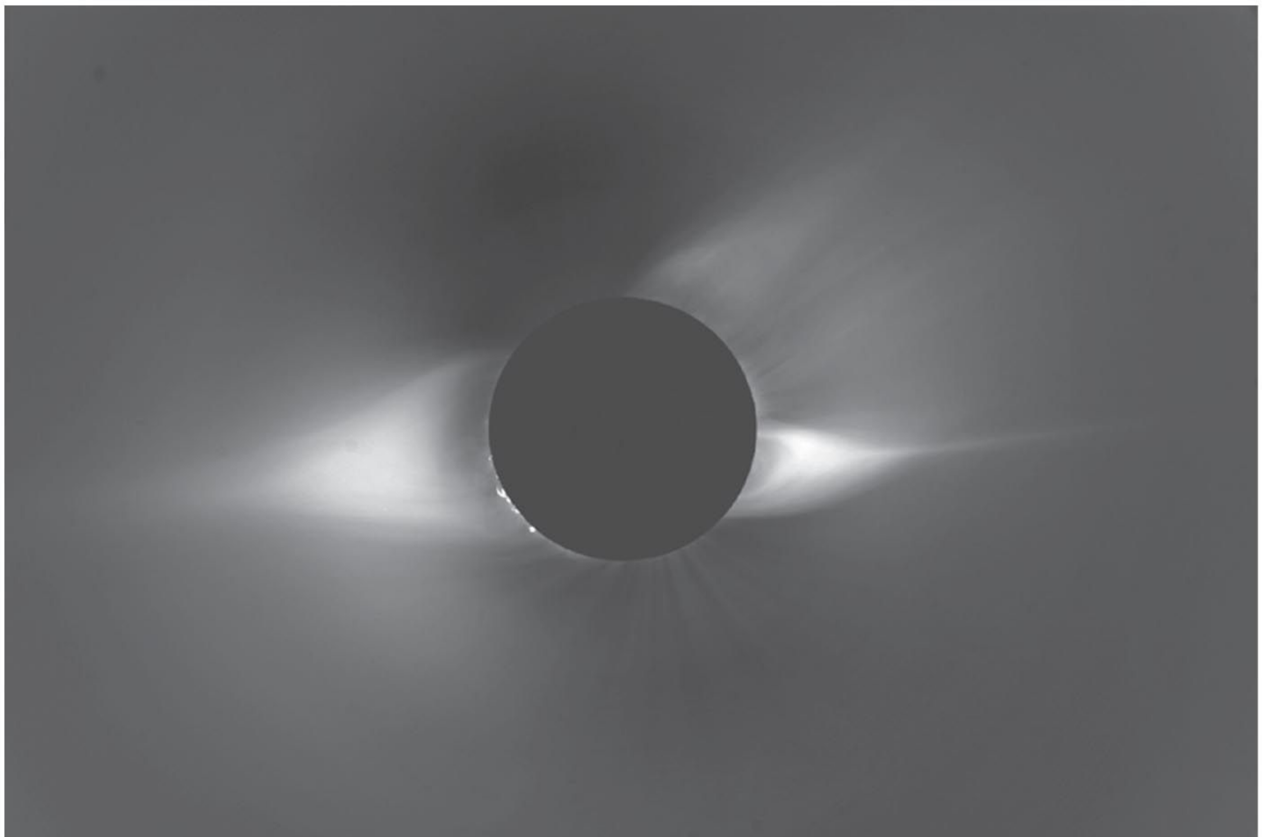


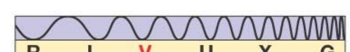
(b)

Solar wind escapes the Sun mostly through **coronal holes**, which can be seen in X-ray images as dark regions.

16.5 The Active Sun

Solar corona changes along with sunspot cycle; it is much larger and more irregular at sunspot peak.





16.5 The Active Sun

See YouTube video "Sun Montage – SOHO" for video of all of the preceding phenomena.

Discovery 16-2: Solar–Terrestrial Relations

Does Earth feel effects of 22-year solar cycle directly?

Possible correlations seen; cause not understood, as energy output doesn’t vary much

Solar flares and coronal mass ejections ionize atmosphere, disrupting electronics and endangering astronauts

16.6 The Heart of the Sun

What powers the Sun??

It emits energy at the rate of $4X10^{26}$ W.

It continues emitting for 10 billion years.

We find that the total lifetime energy output is about 3×10^{13} J/kg

This is a lot, and it is produced steadily, not explosively. How?

16.6 The Heart of the Sun

Gravitational contraction? no
Combustion? no
Nuclear fusion yes!
In general, nuclear fusion works like this:

$$\textbf{nucleus 1} + \textbf{nucleus 2} \rightarrow \textbf{nucleus 3} + \textbf{energy}$$

But where does the energy come from?

- **It comes from the mass:**

The initial mass is greater than the final mass.

The total mass-energy must stay constant.

16.6 The Heart of the Sun

The conversion between mass and energy comes from Einstein's famous equation:

$$E = mc^2$$

E **= energy**

c **is the speed of light**

m**=difference between final and initial mass**

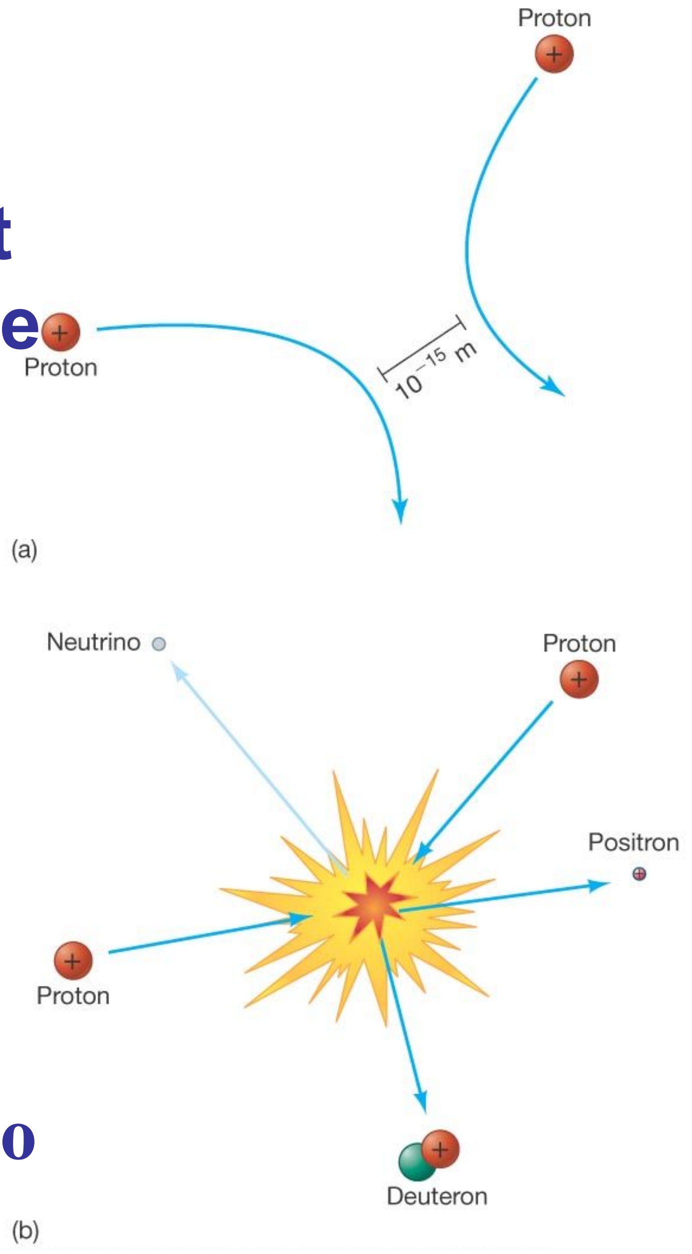
→ a small amount of mass becomes a large amount of energy

16.6 The Heart of the Sun

Nuclear fusion requires that like-charged nuclei get close enough to each other to fuse.

This can happen only if the **temperature** is extremely high—over 10 million K.

$^1H + {}^1H \rightarrow {}^2H$ + positron + neutrino



16.6 The Heart of the Sun

The previous image depicts **proton–proton fusion**. In this reaction:

$$\text{proton} + \text{proton} \rightarrow \text{deuteron} + \text{positron} + \text{neutrino}$$

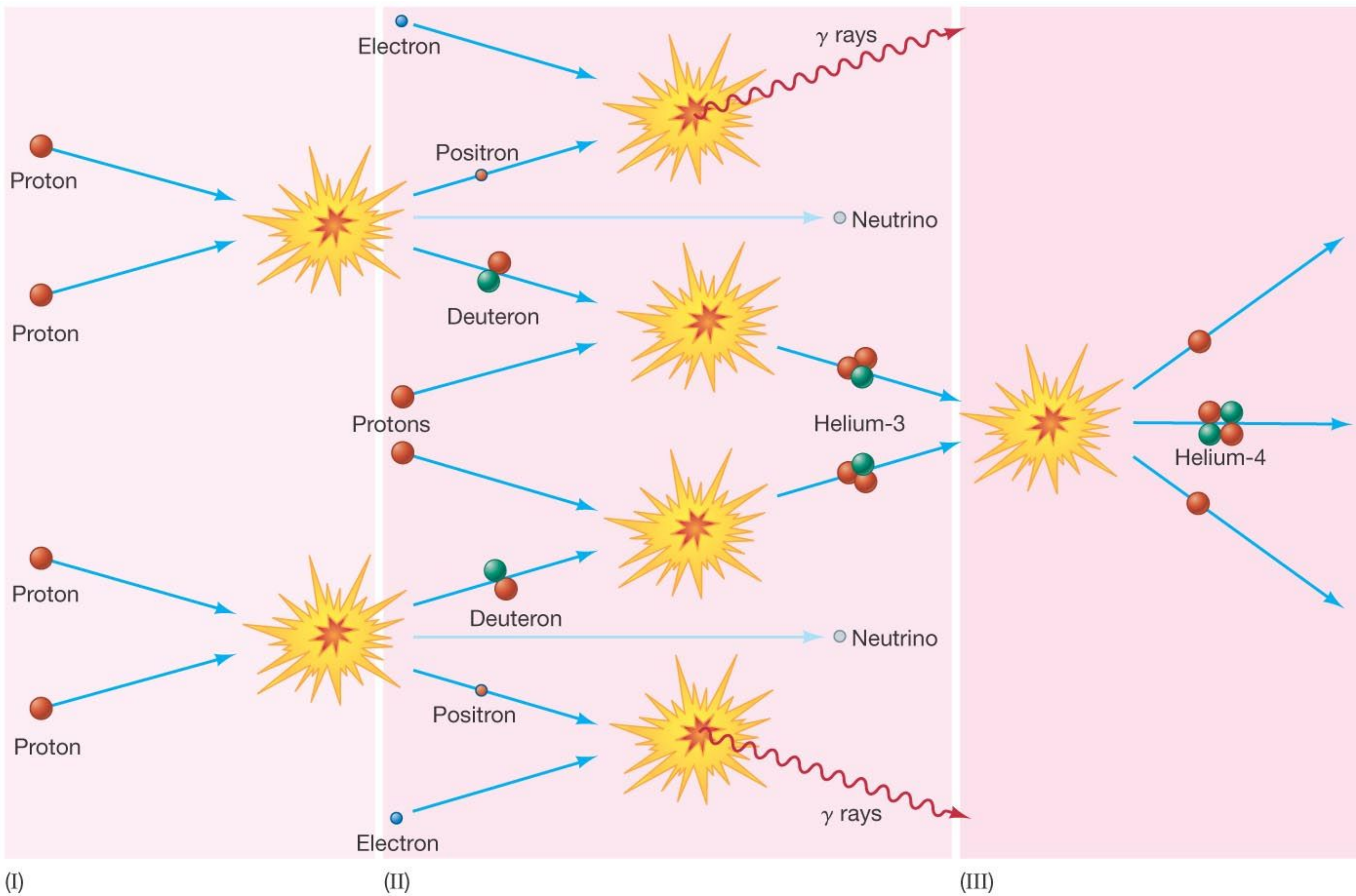
The **positron** is just like the electron except positively charged; the **neutrino** is also related to the electron but has no charge and very little, if any, mass.

In more conventional notation:

$$^{1}\text{H} + {}^{1}\text{H} \rightarrow {}^{2}\text{H} + \text{positron} + \text{neutrino}$$

16.6 The Heart of the Sun

This is the first step in a **three-step fusion process** that powers most stars:



16.6 The Heart of the Sun

The **second step** is the formation of an isotope of **helium**:

$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \text{energy}$$

The final step takes two of the **helium-3** isotopes and forms **helium-4** plus two protons:

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + {}^{1}H + {}^{1}H + \text{energy}$$

16.6 The Heart of the Sun

The **ultimate result** of the process:

$$4(^{1}H) \rightarrow {}^{4}He + \text{energy} + 2 \text{ neutrinos}$$

The **helium** stays in the core.

The energy is in the form of **gamma rays**, which gradually lose their energy as they travel out from the core, emerging as visible light.

The **neutrinos** escape without interacting.

16.6 The Heart of the Sun

Sun must convert 4.3 million tons of matter into energy every second.

The Sun has enough hydrogen left to continue fusion for about another 5 billion years.

More Precisely 16-1: Fundamental Forces

Physicists recognize four fundamental forces in nature:

- Gravity: Very weak, but always attractive and infinite in range
- Electromagnetic: Much stronger, but either attractive or repulsive; infinite in range
- Weak nuclear force: Responsible for beta decay; short range (1-2 proton diameters); weak
- Strong nuclear force: Keeps nucleus together; short range; very strong

More Precisely 16-2: Energy Generation in the Proton–Proton Chain

Mass of four protons: 6.6943×10^{-27} kg

Mass of helium nucleus: 6.6466×10^{-27} kg

Mass transformed to energy: 0.0477×10^{-27} kg (about 0.71%)

Energy equivalent of that mass: 4.28×10^{-12} J

Energy produced by fusion of one kilogram of hydrogen into helium: 6.40×10^{14} J

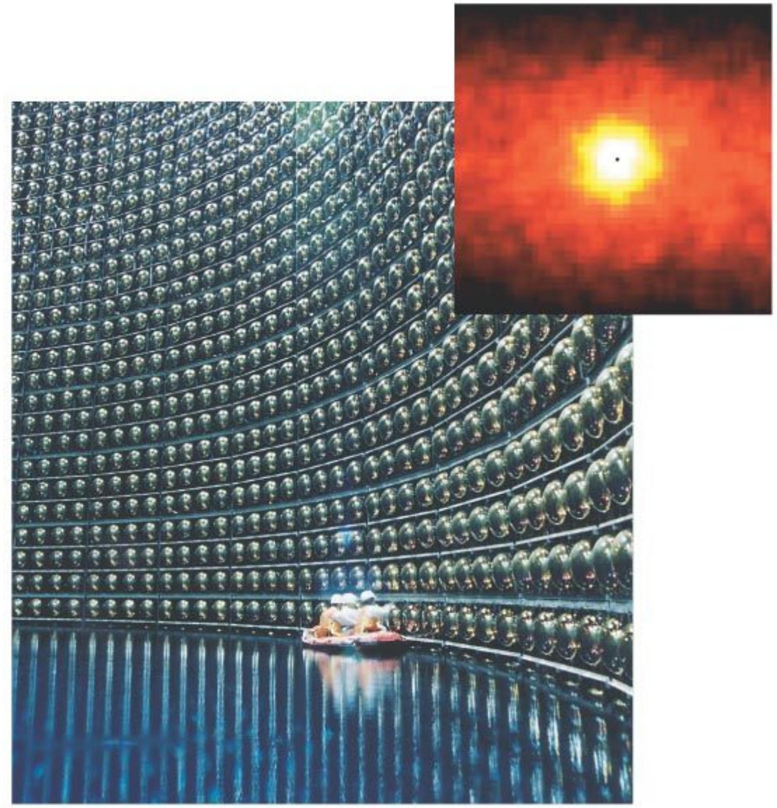
16.7 Observations of Solar Neutrinos

Neutrinos are emitted directly from the core of the Sun and **escape**, interacting with virtually nothing. Being able to observe these neutrinos would give us a **direct picture** of what is happening in the core.

Unfortunately, they are no more likely to interact with Earth-based detectors than they are with the Sun; the only way to spot them is to have a huge **detector volume** and to be able to observe **single interaction events**.

16.7 Observations of Solar Neutrinos

Typical solar neutrino detectors; resolution is very poor



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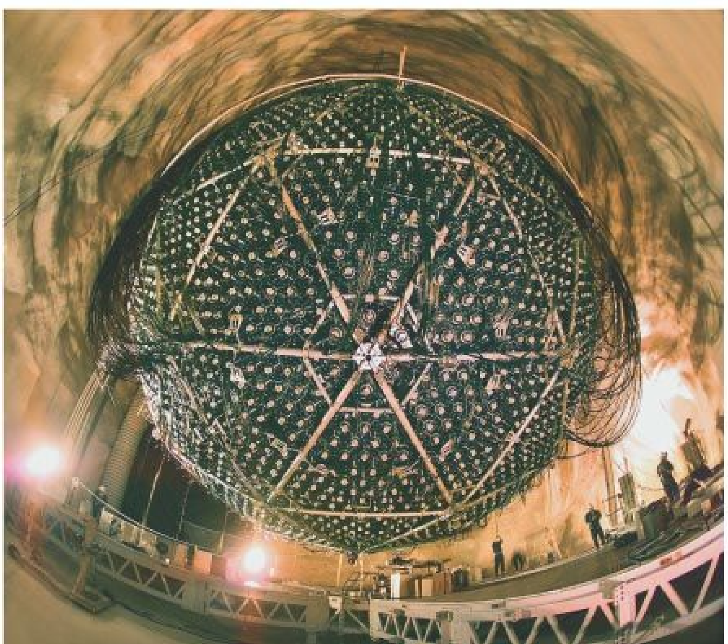

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16.7 Observations of Solar Neutrinos

Detection of solar neutrinos has been going on for more than 30 years now; there has always been a deficit in the type of neutrinos expected to be emitted by the Sun.

Recent research proves that the Sun is emitting about as many neutrinos as the standard solar model predicts, but the neutrinos change into other types of neutrinos between the Sun and the Earth, causing the apparent deficit.

Summary of Chapter 16

- **Main interior regions of Sun: core, radiation zone, convection zone, photosphere, chromosphere, transition region, corona, solar wind**
- **Energy comes from nuclear fusion; produces neutrinos along with energy**
- **Standard solar model is based on hydrostatic equilibrium of Sun**
- **Study of solar oscillations leads to information about interior**

Summary of Chapter 16 (cont.)

- Absorption lines in spectrum tell composition and temperature

- Sunspots associated with intense magnetism

- Number of sunspots varies in an 11-year cycle

- Large solar ejection events: prominences, flares, and coronal ejections

- Observations of solar neutrinos show deficit, due to peculiar neutrino behavior