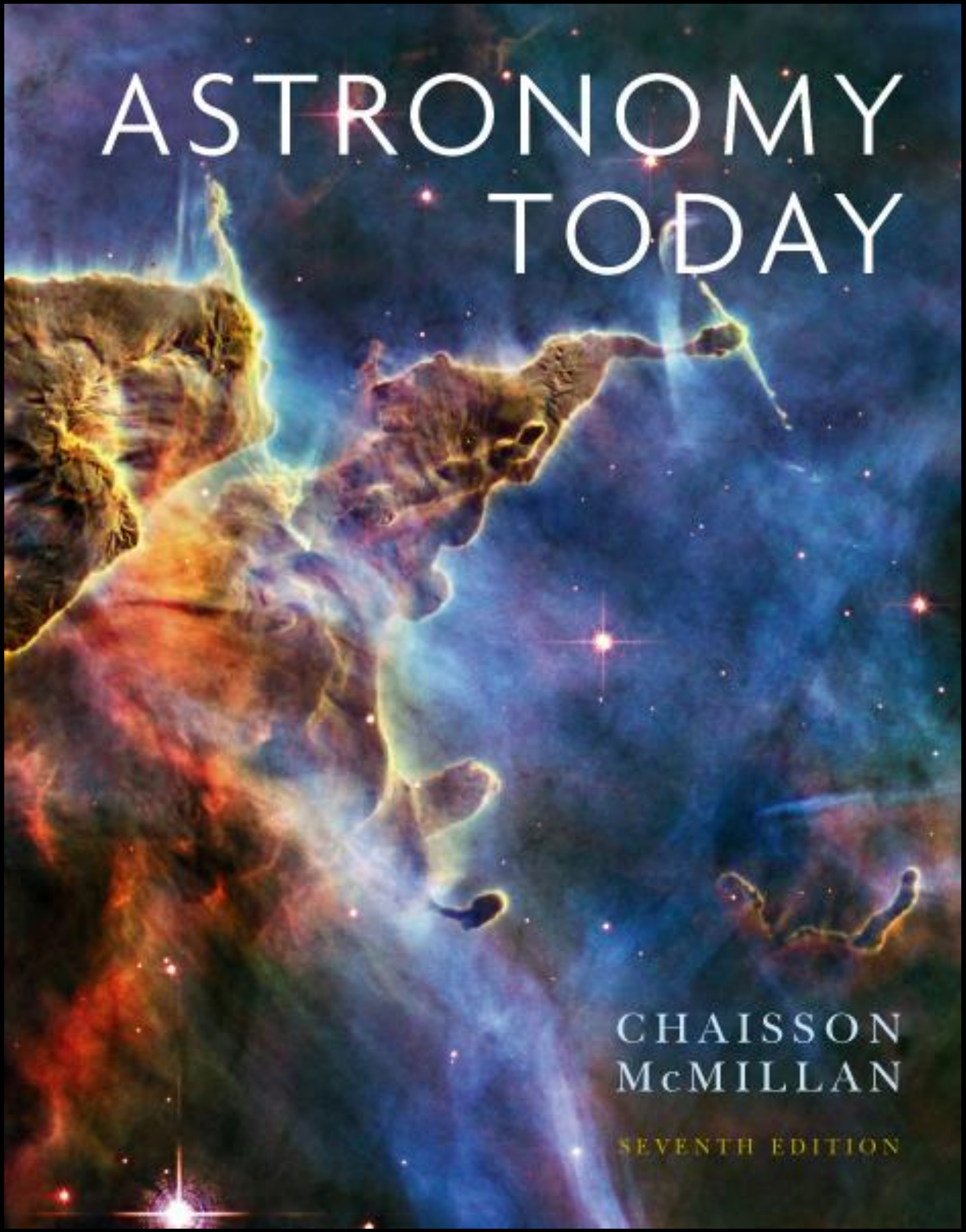


Lecture Outlines

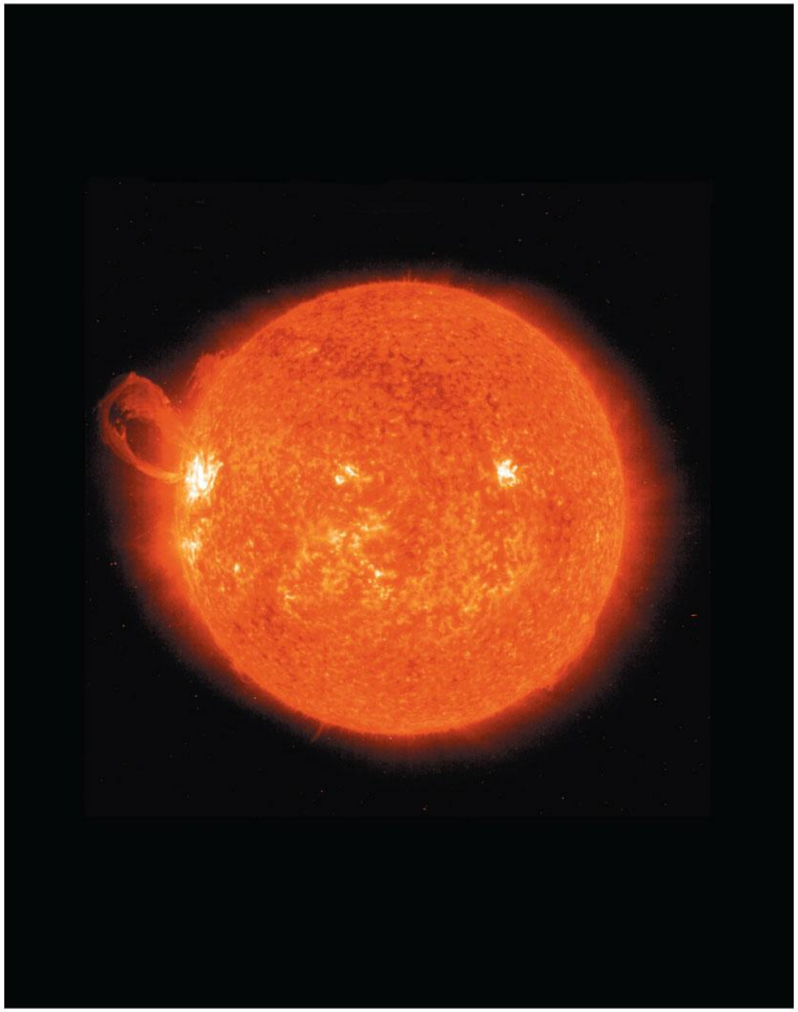
Chapter 16

Astronomy Today

7th Edition

Chaisson/McMillan

Chapter 16
The Sun



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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

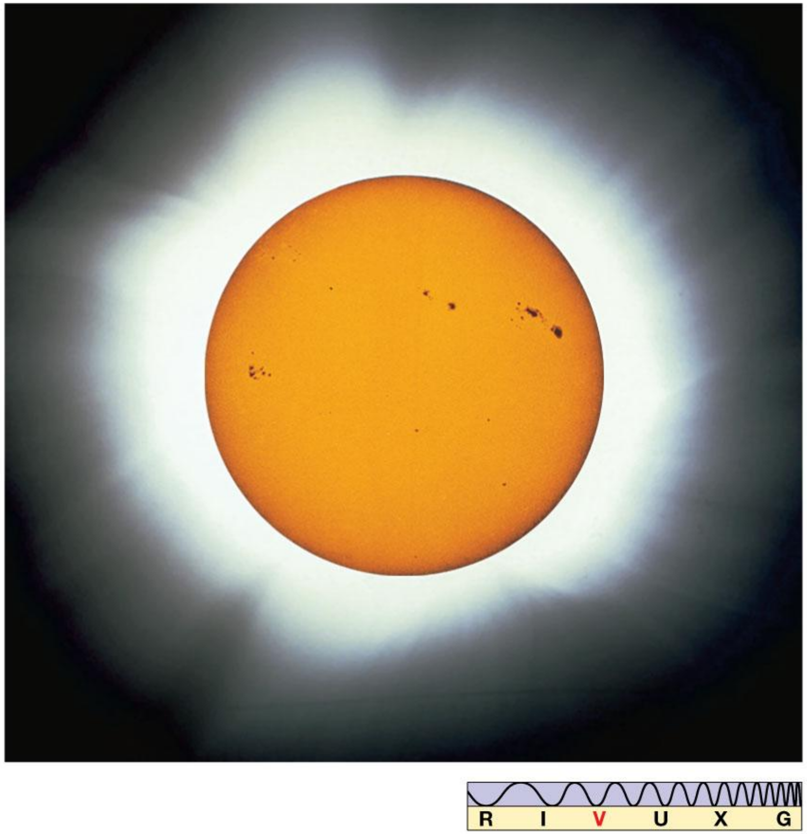
Rotation: Differential; period about a month

Surface temperature: 5800 K

Apparent surface of Sun is photosphere

16.1 Physical Properties of the Sun

This is a filtered image of the Sun showing sunspots, the sharp edge of the Sun due to the thin photosphere, and the corona

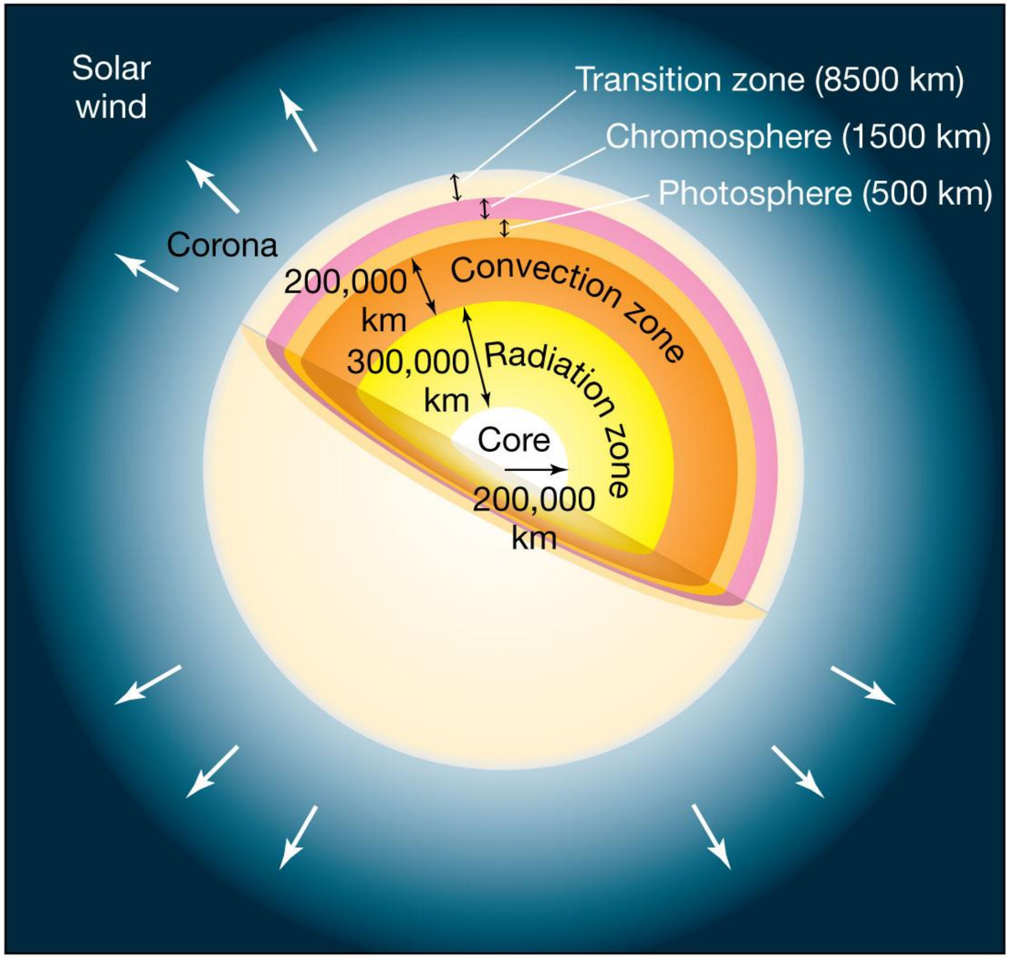


16.1 Physical Properties of the Sun

Interior structure of the Sun:

Outer layers are not to scale

The core is where nuclear fusion takes place



16.1 Physical Properties of the Sun

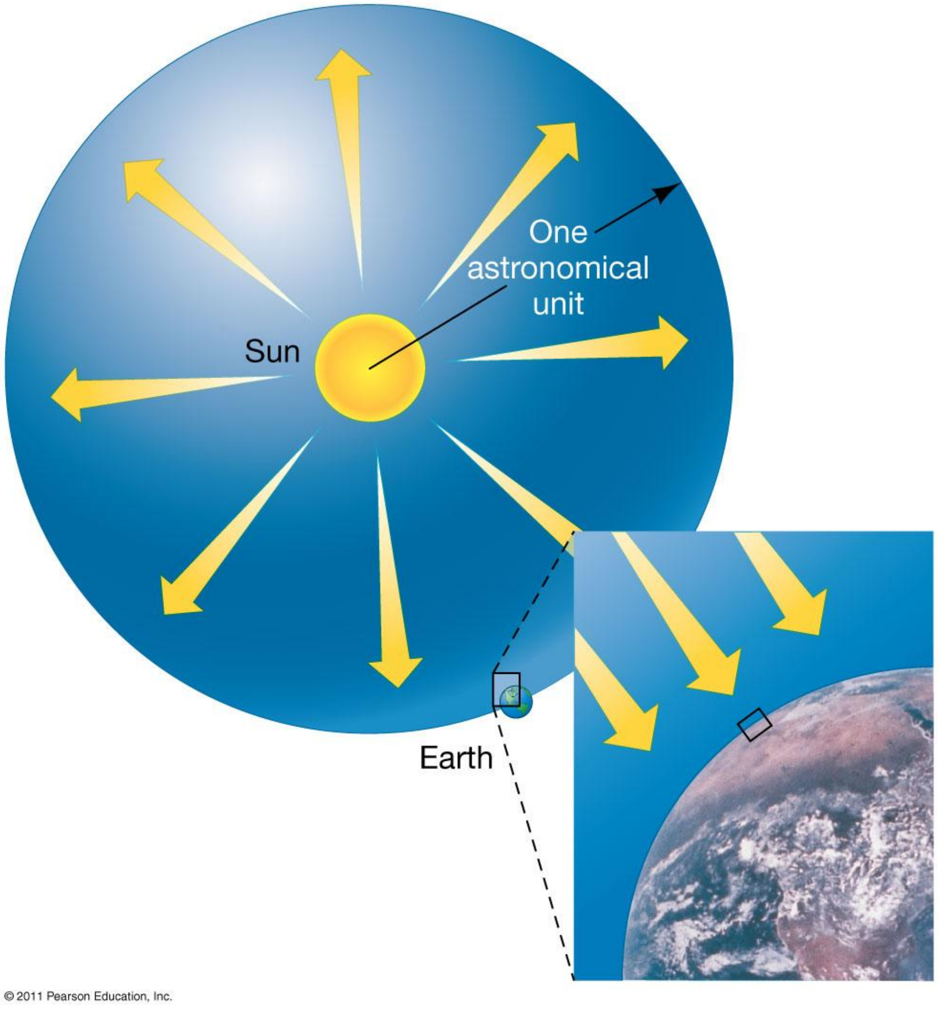
Luminosity—total energy radiated by the Sun— can be calculated from the fraction of that energy that reaches Earth.

Solar constant—amount of Sun's energy reaching Earth—is 1400 W/m^2.

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

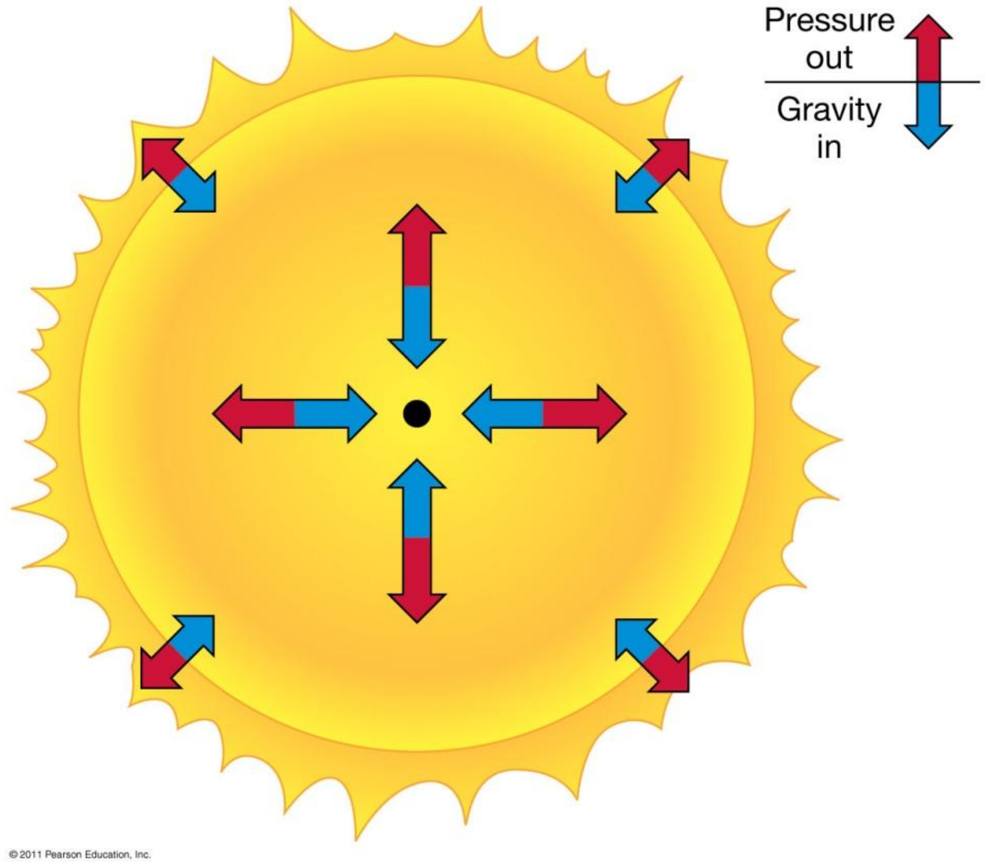
This diagram illustrates how one can extrapolate from the radiation hitting Earth to the entire output of the Sun



16.2 The Solar Interior

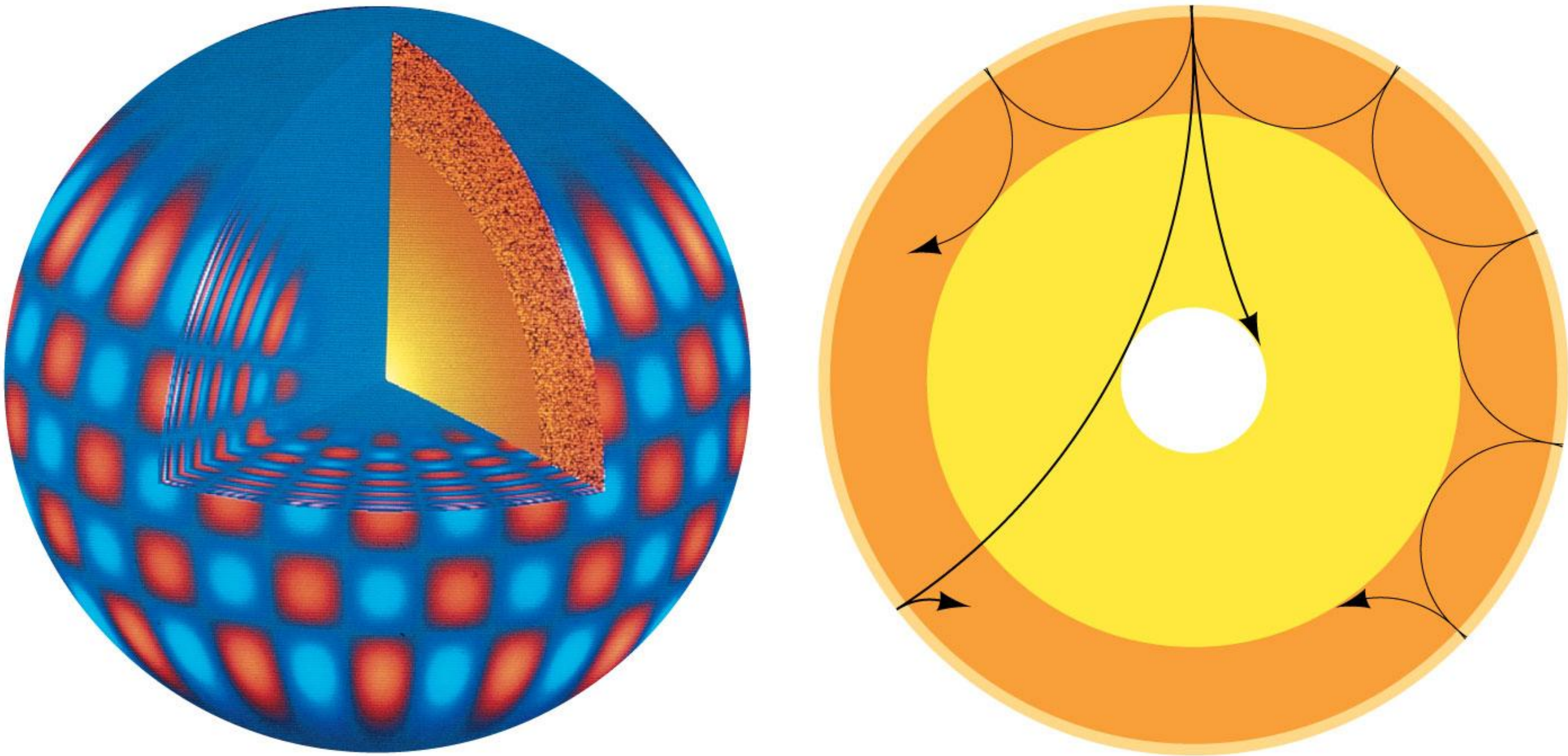
Mathematical models, consistent with observation and physical principles, provide information about the Sun's interior

In equilibrium, inward gravitational force must be balanced by outward pressure



16.2 The Solar Interior

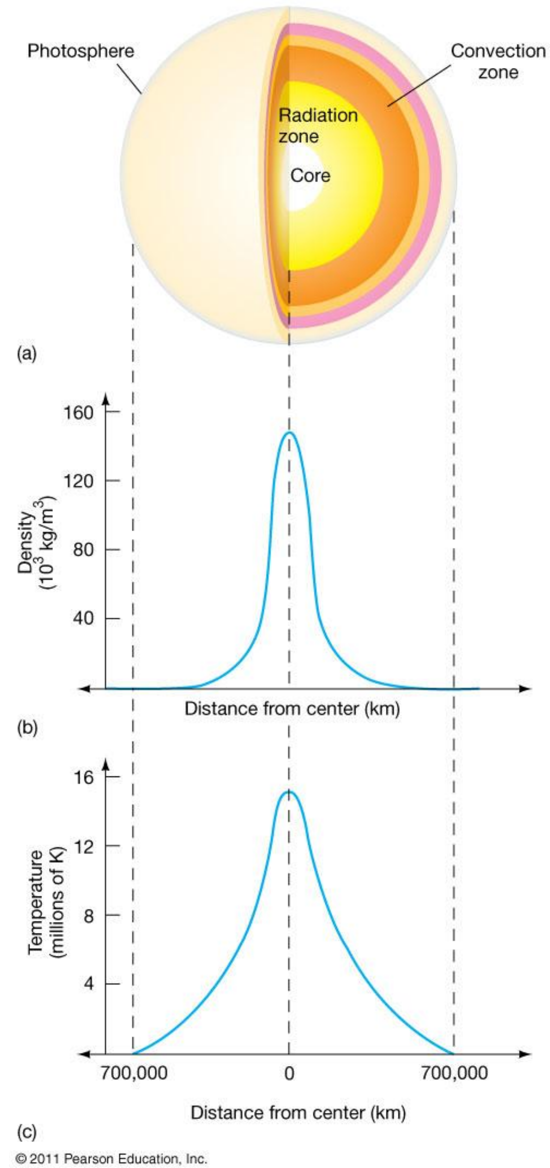
Doppler shifts of solar spectral lines indicate a complex pattern of vibrations



(a) (b)

16.2 The Solar Interior

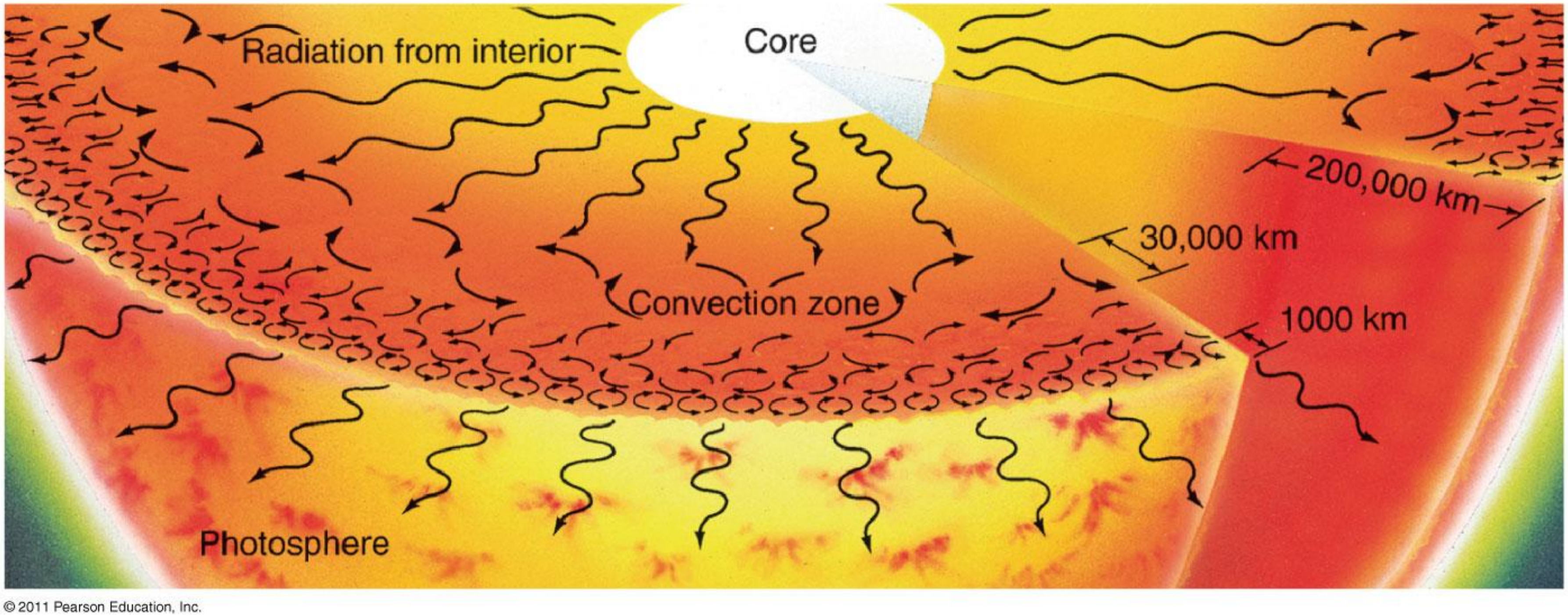
Solar density and temperature, according to the standard solar model



16.2 The Solar Interior

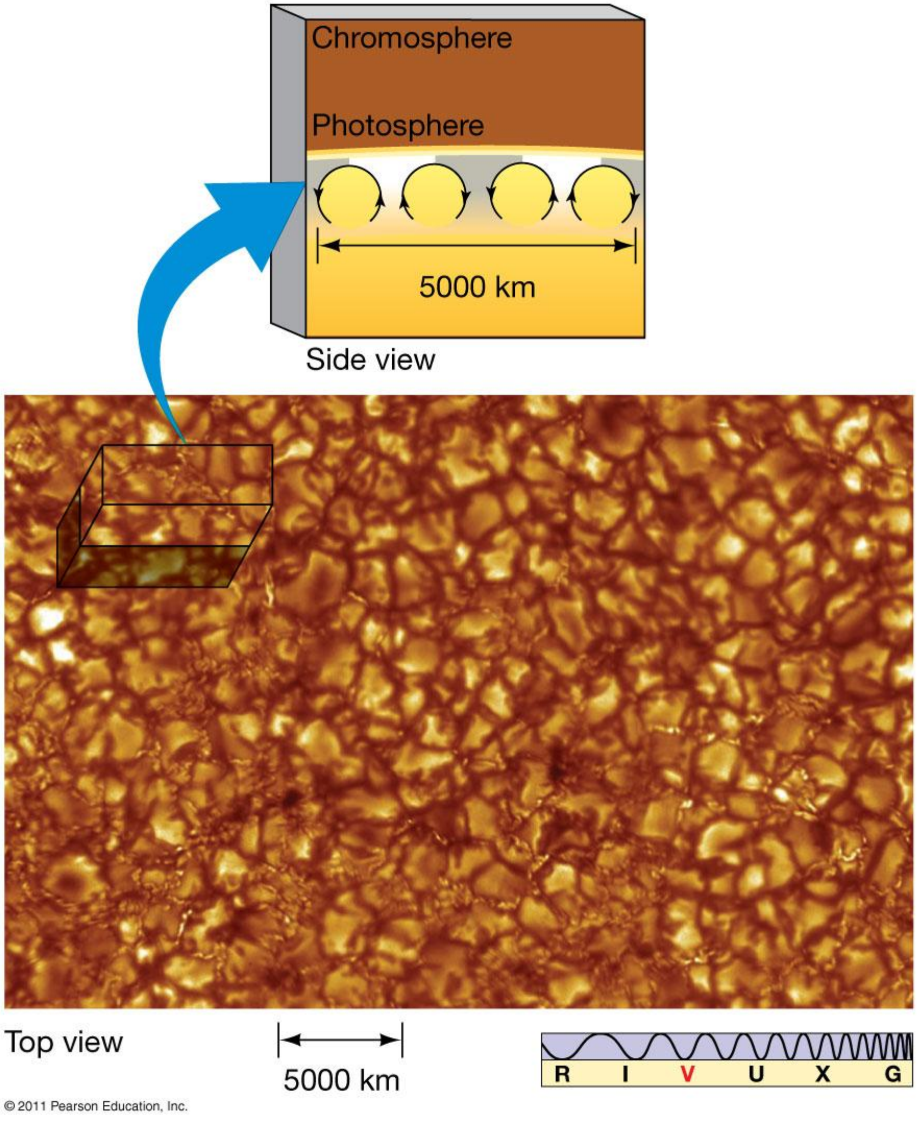
Energy transport:

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



16.2 The Solar Interior

The visible top layer of the convection zone is granulated, with areas of upwelling material surrounded by areas of sinking material

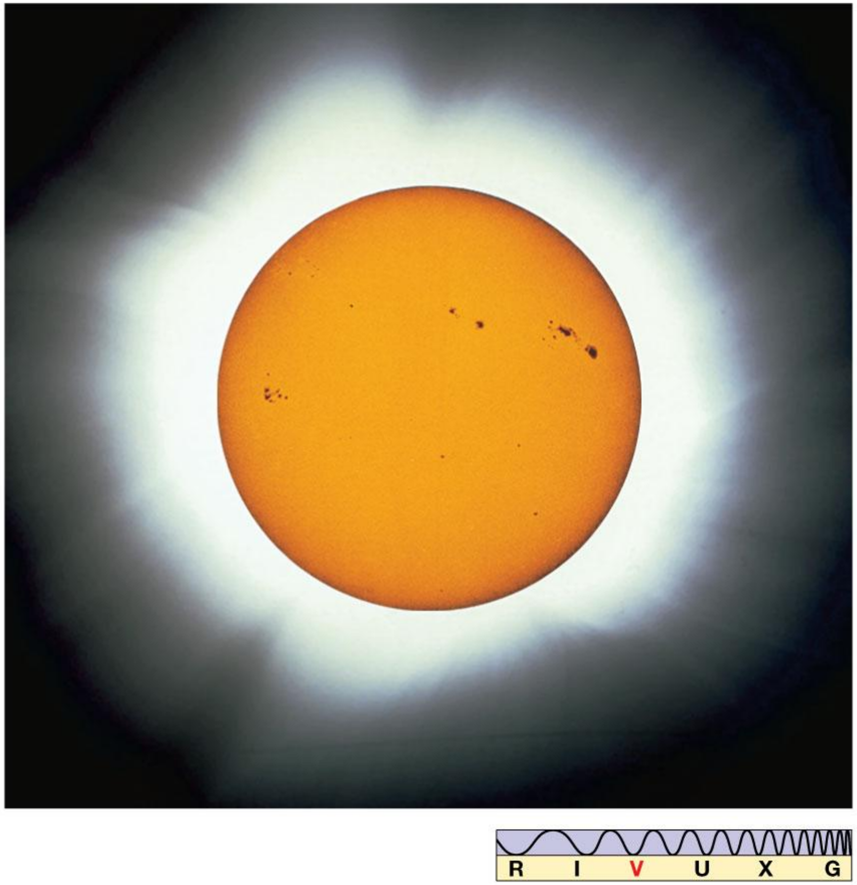


Discovery 16-1: SOHO: Eavesdropping on the Sun

SOHO: Solar and Heliospheric Observatory

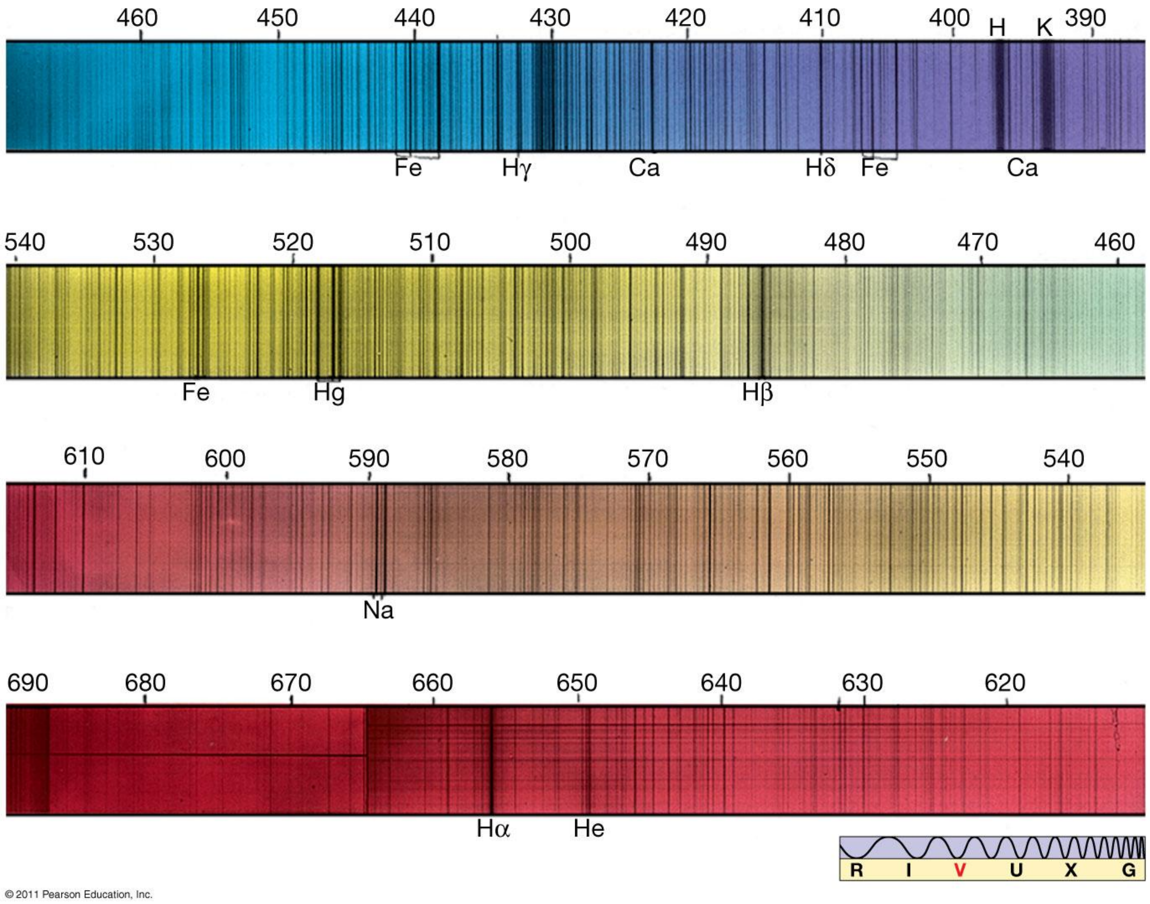
Orbits at Earth's L1 point, outside the magnetosphere

Multiple instruments measure magnetic field, corona, vibrations, and ultraviolet emissions



16.3 The Sun's Atmosphere

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



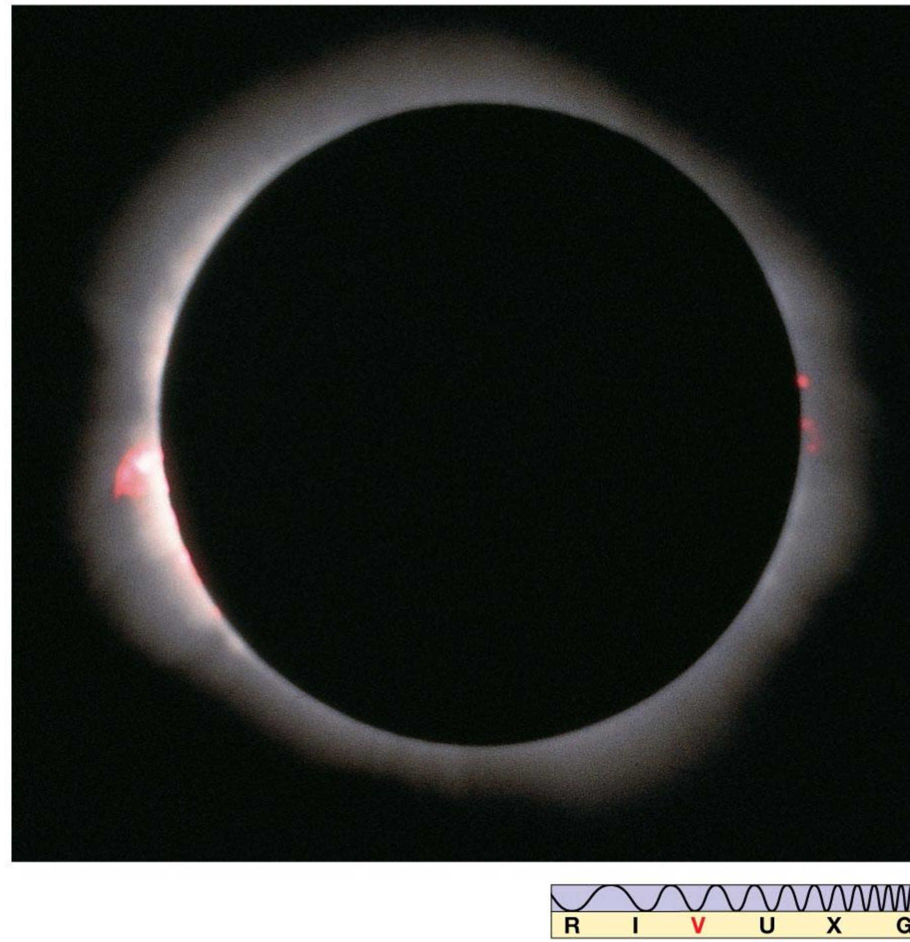
16.3 The Sun's Atmosphere

Spectral lines are formed when light is absorbed before escaping from the Sun; this happens when its energy is close to an atomic transition, so it is absorbed.

16.3 The Sun’s Atmosphere

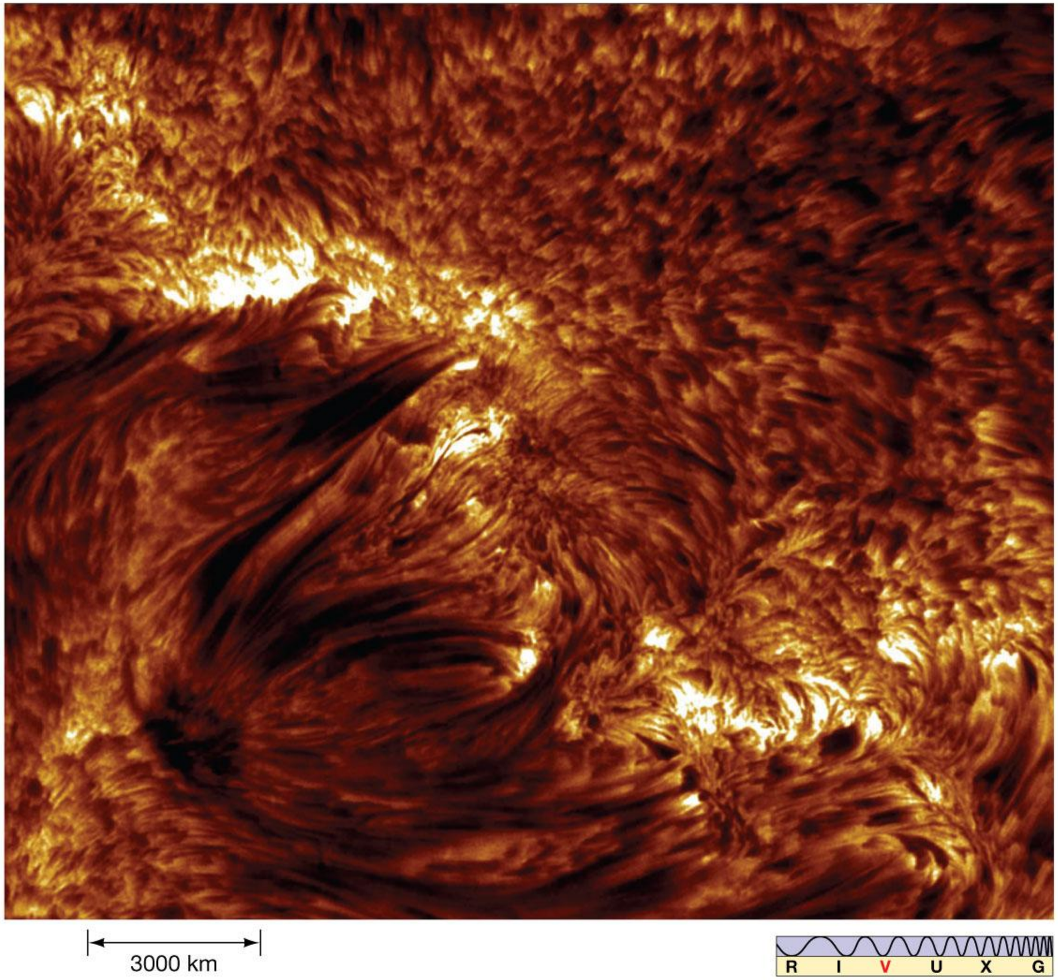
The cooler chromosphere is above the photosphere.

Difficult to see directly, as photosphere is too bright, unless Moon covers photosphere and not chromosphere during eclipse.



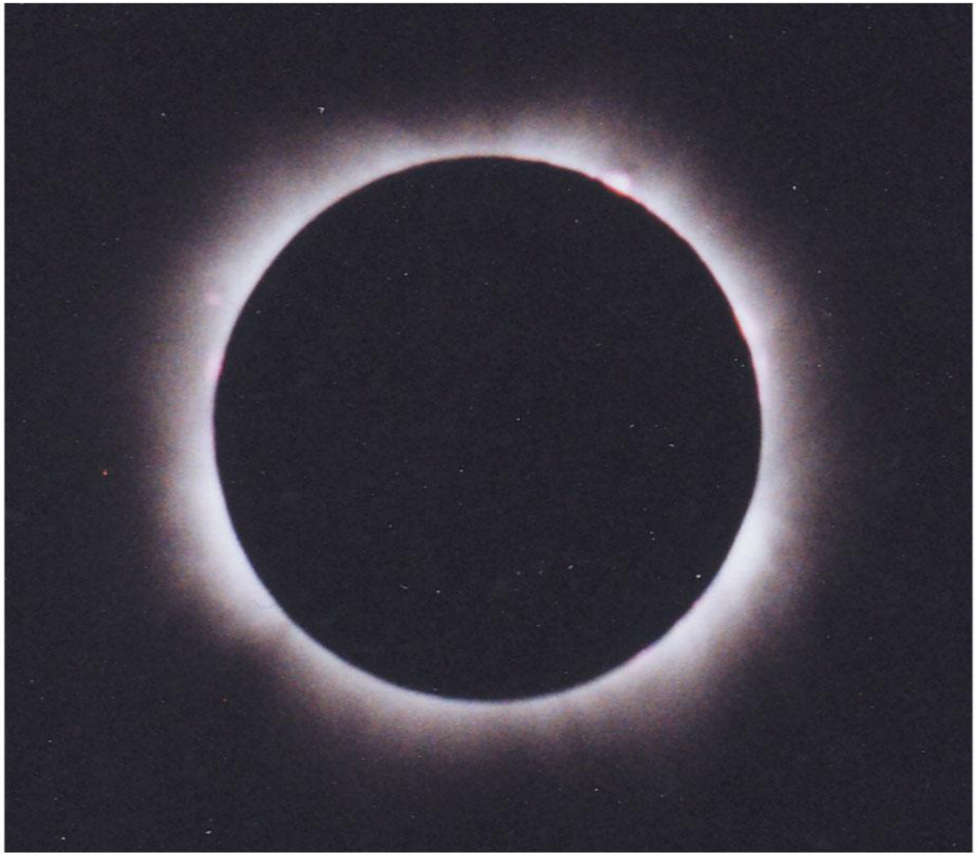
16.3 The Sun's Atmosphere

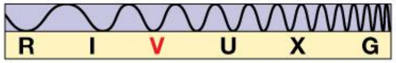
Small solar storms in chromosphere emit spicules



16.3 The Sun's Atmosphere

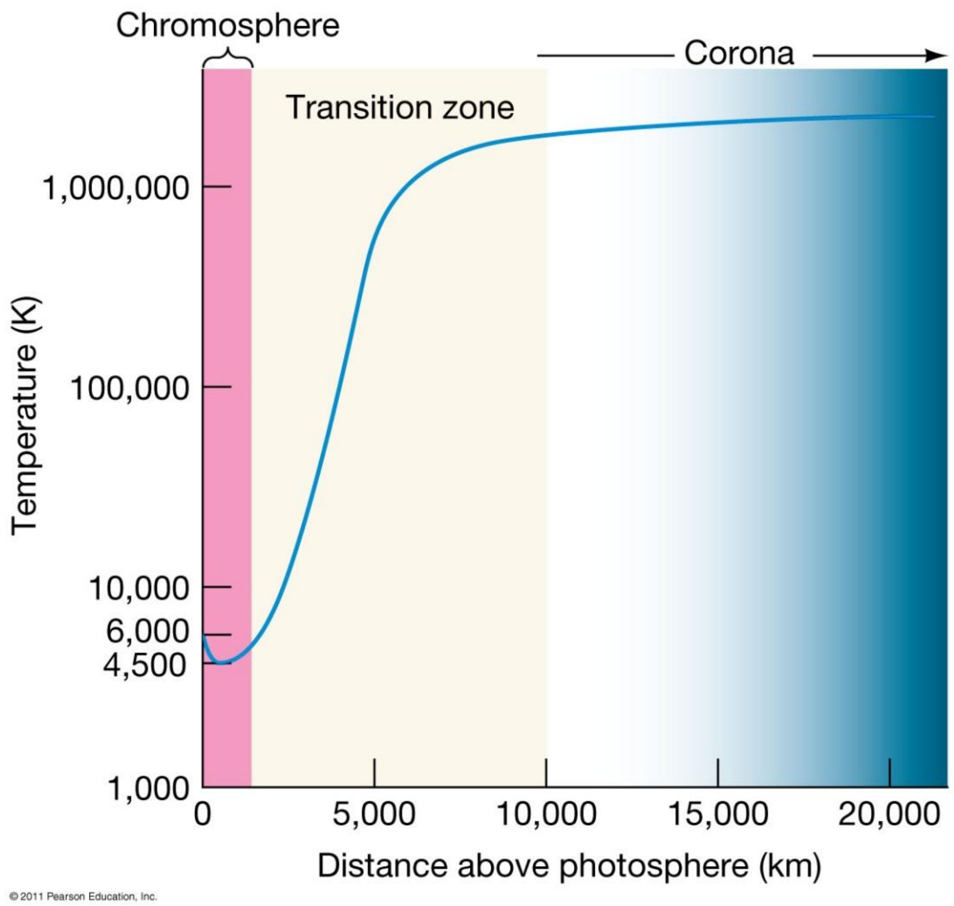
Solar corona can be seen during eclipse if both photosphere and chromosphere are blocked





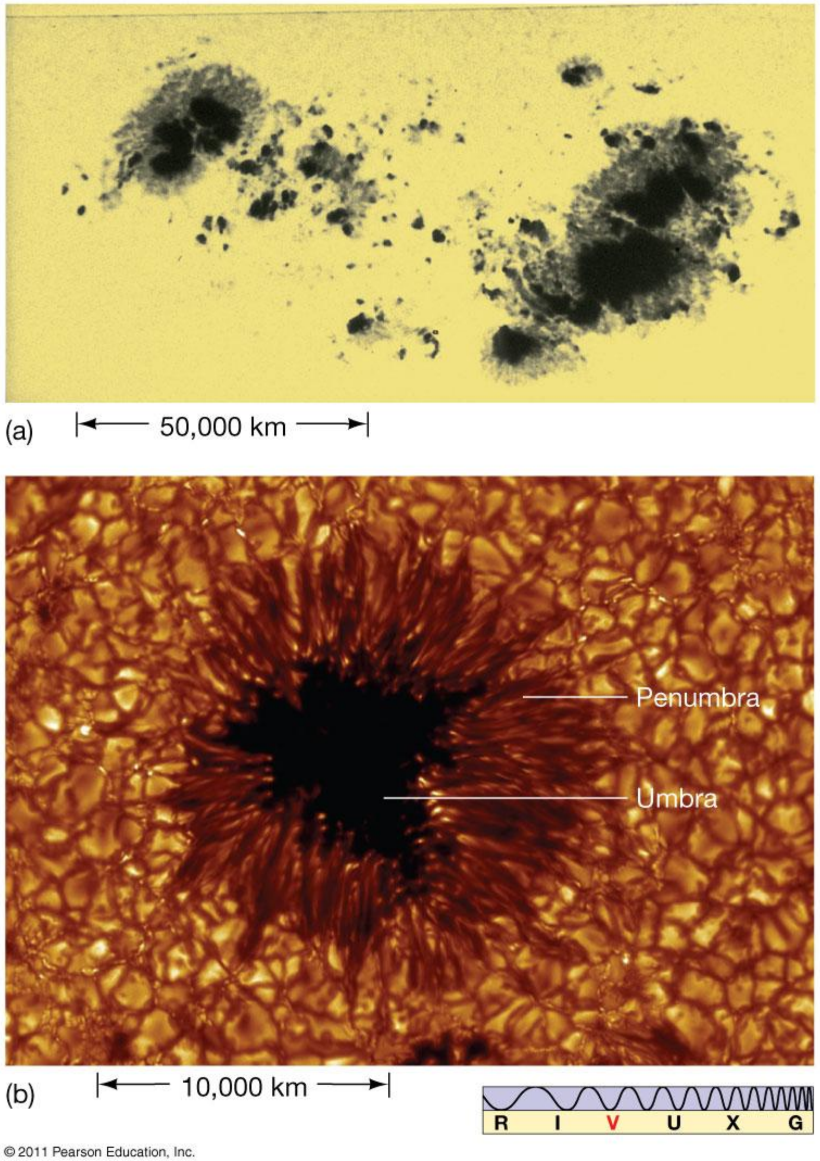
16.3 The Sun’s Atmosphere

Corona is much hotter than layers below it— must have a heat source, probably electromagnetic interactions



16.4 Solar Magnetism

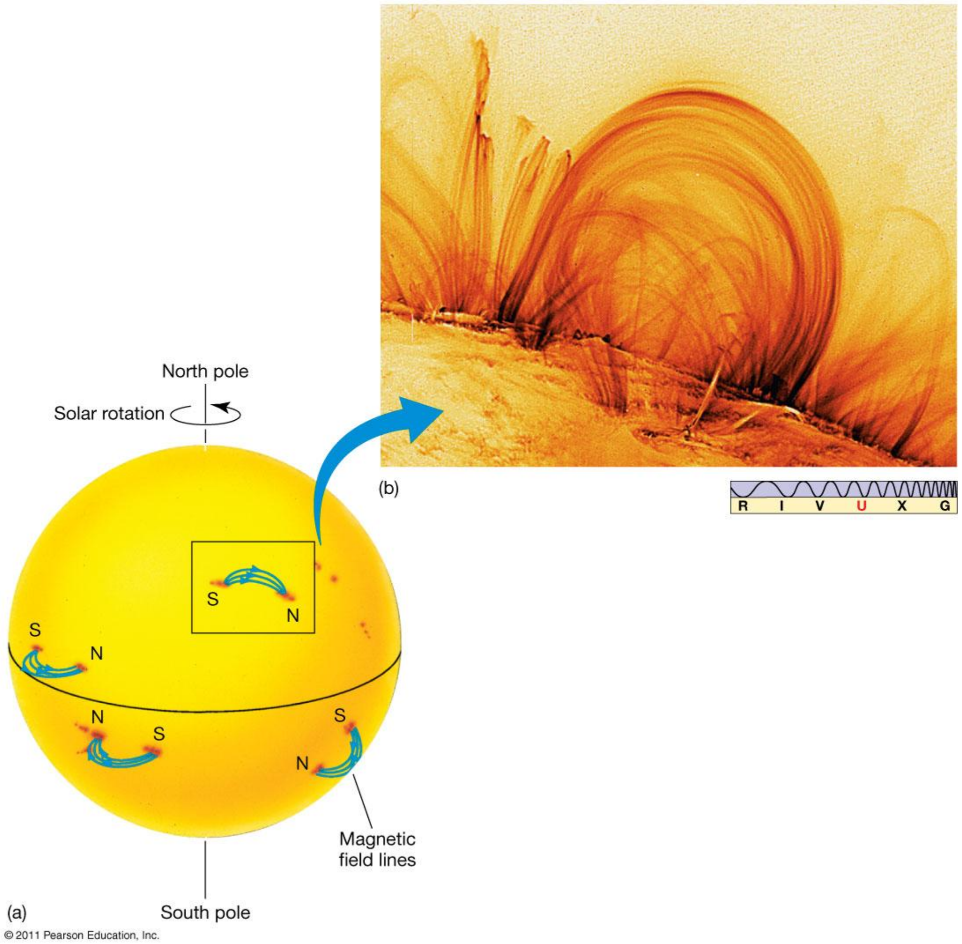
Sunspots: Appear dark because slightly cooler than surroundings



16.4 Solar Magnetism

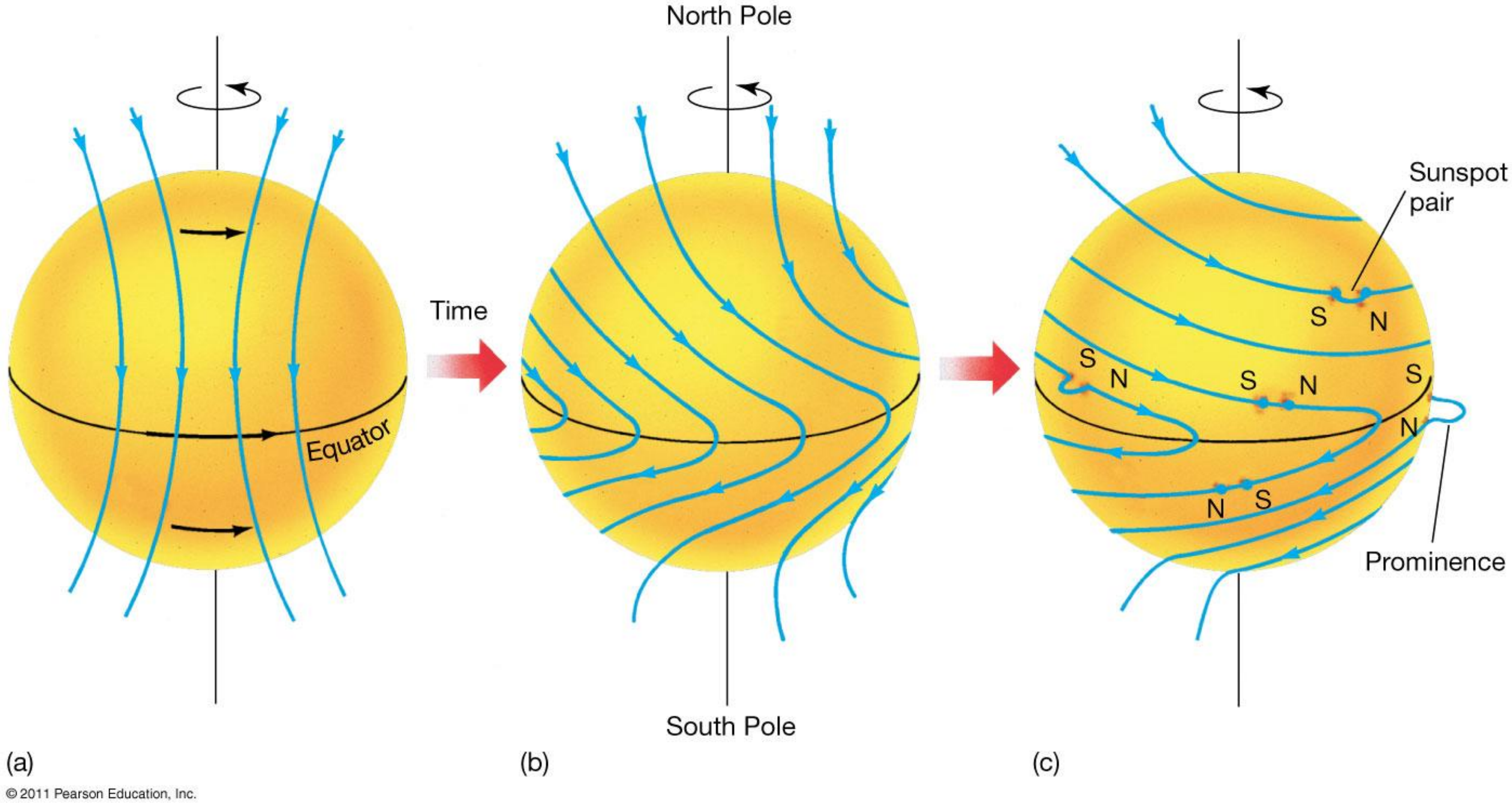
Sunspots come and go, typically in a few days.

Sunspots are linked by pairs of magnetic field lines.



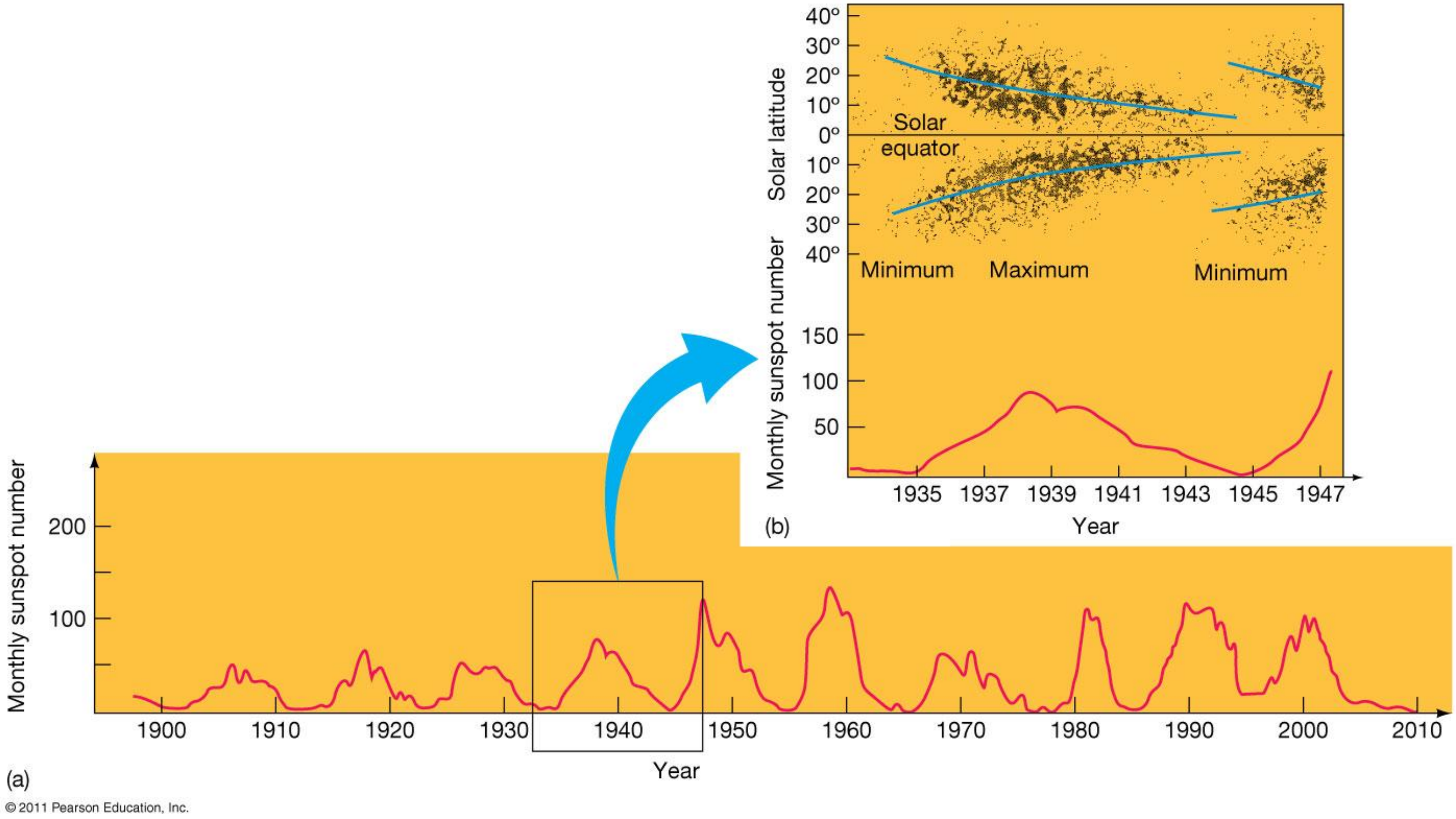
16.4 Solar Magnetism

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



16.4 Solar Magnetism

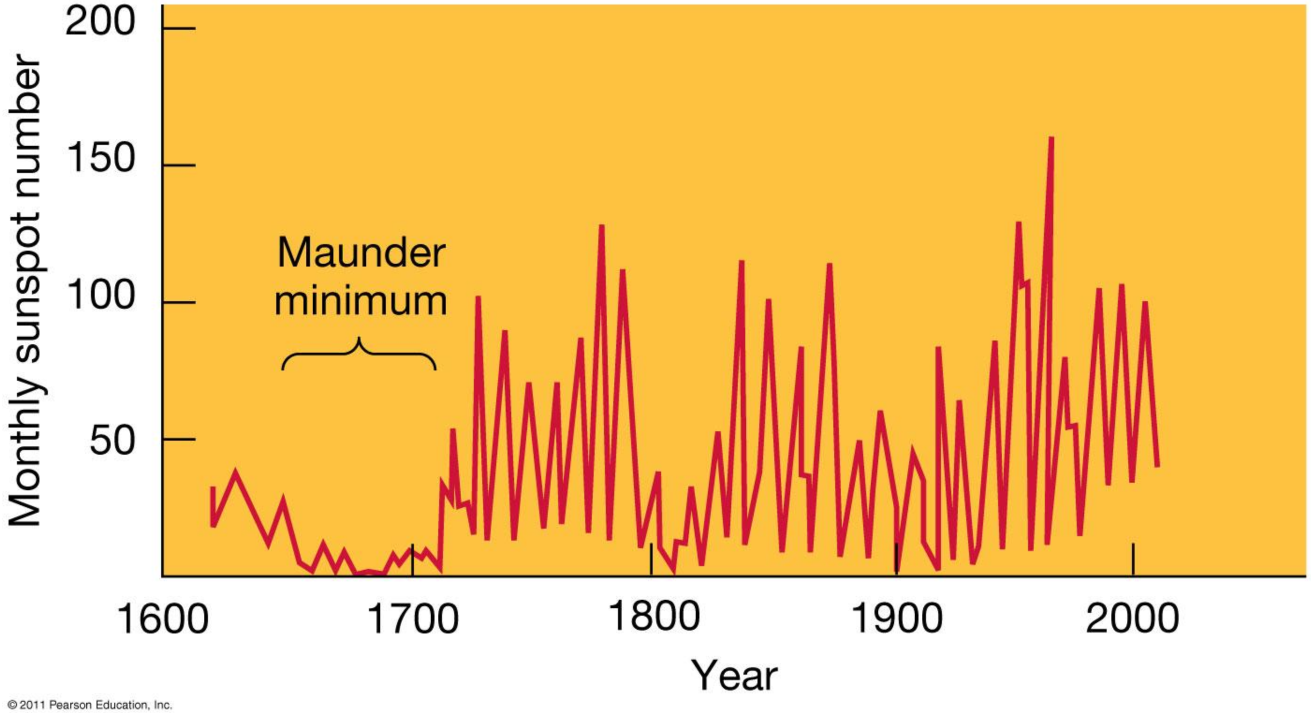
The Sun has an 11-year sunspot cycle, during which sunspot numbers rise, fall, and then rise again



16.4 Solar Magnetism

This is really a 22-year cycle, because the spots switch polarities between the northern and southern hemispheres every 11 years

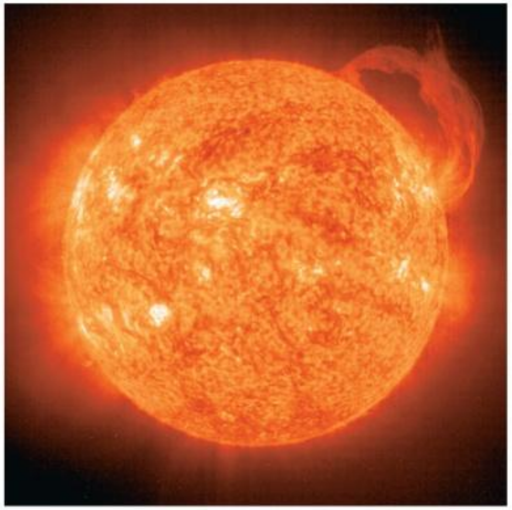
Maunder minimum: few, if any, sunspots



16.5 The Active Sun

Areas around sunspots are active; large eruptions may occur in photosphere

Solar prominence is large sheet of ejected gas



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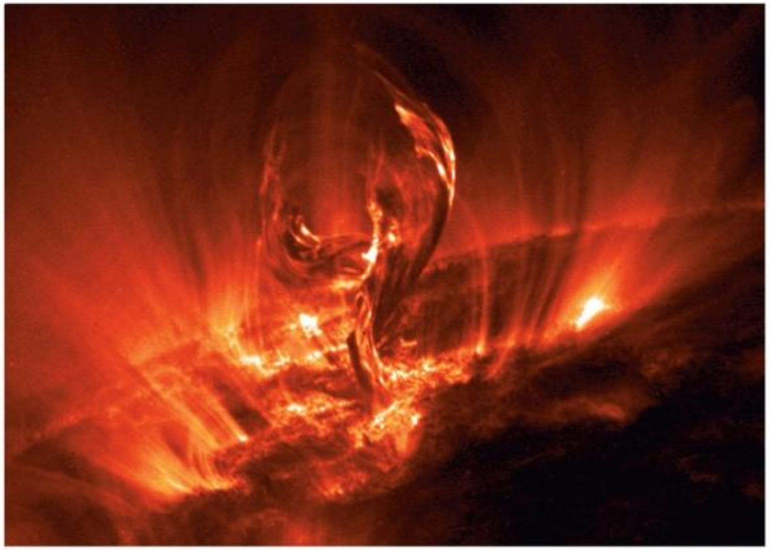
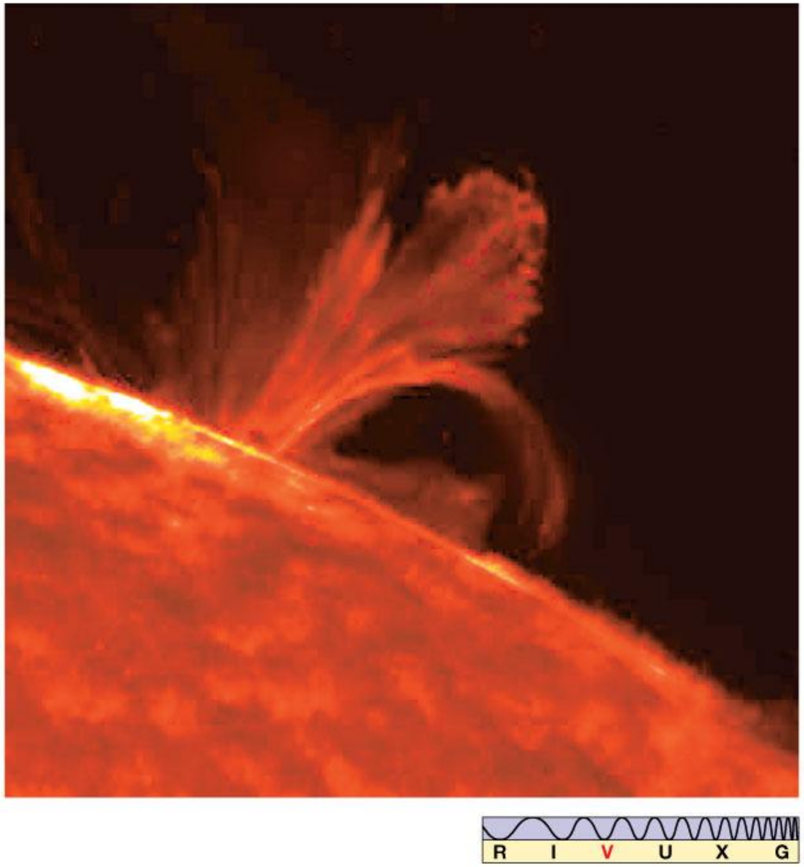


(b)

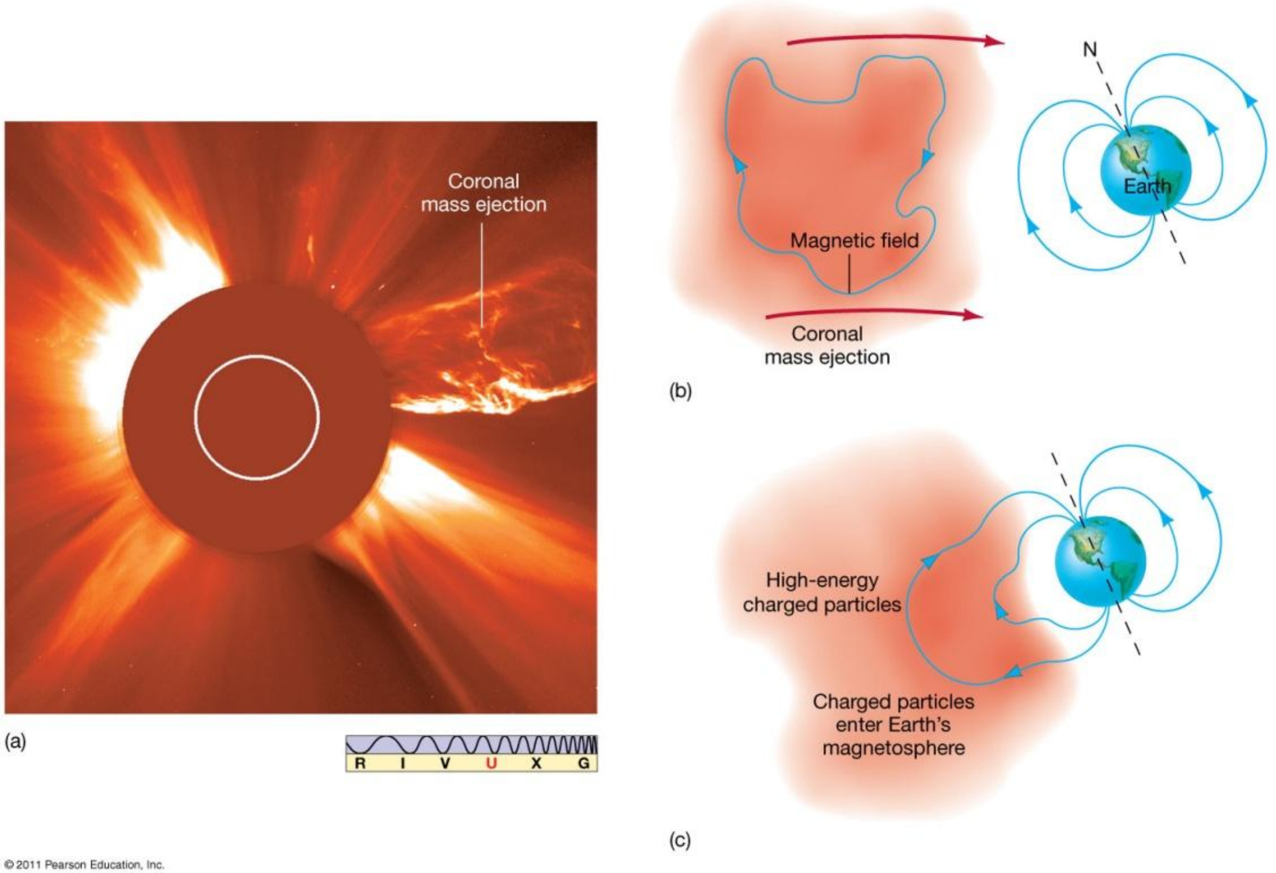
16.5 The Active Sun

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



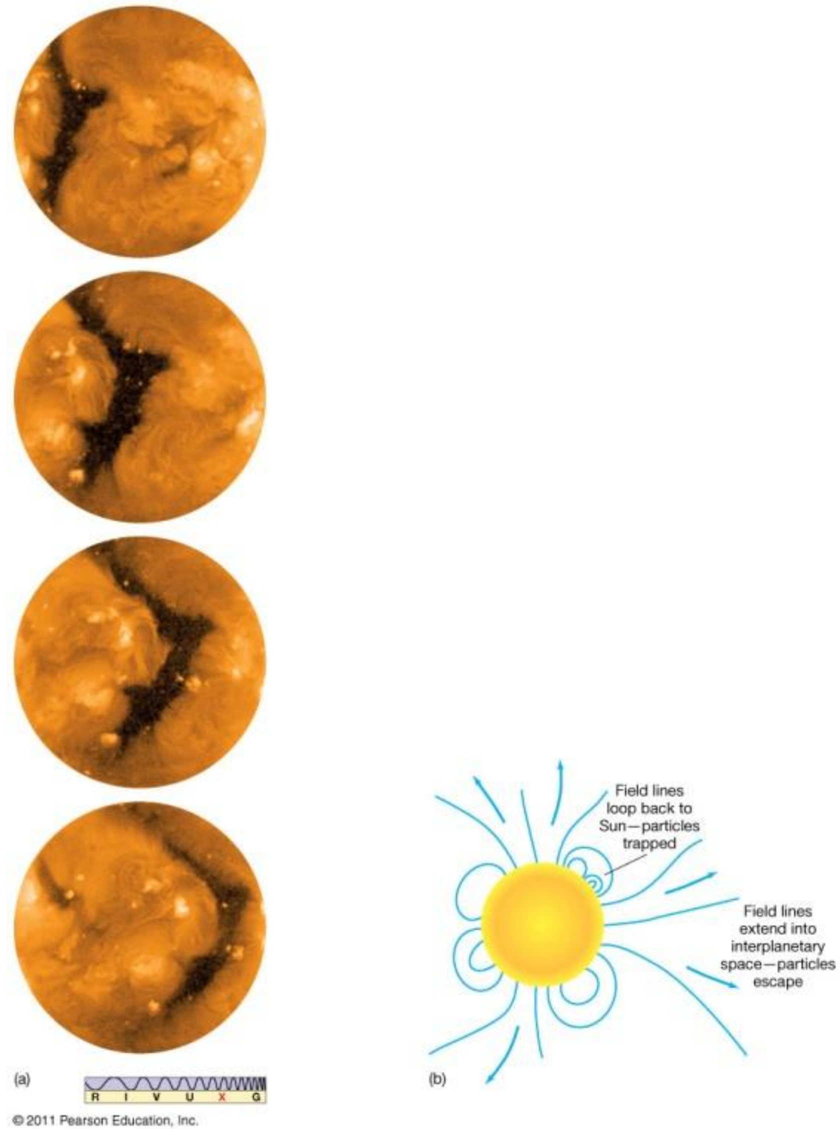
16.5 The Active Sun

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



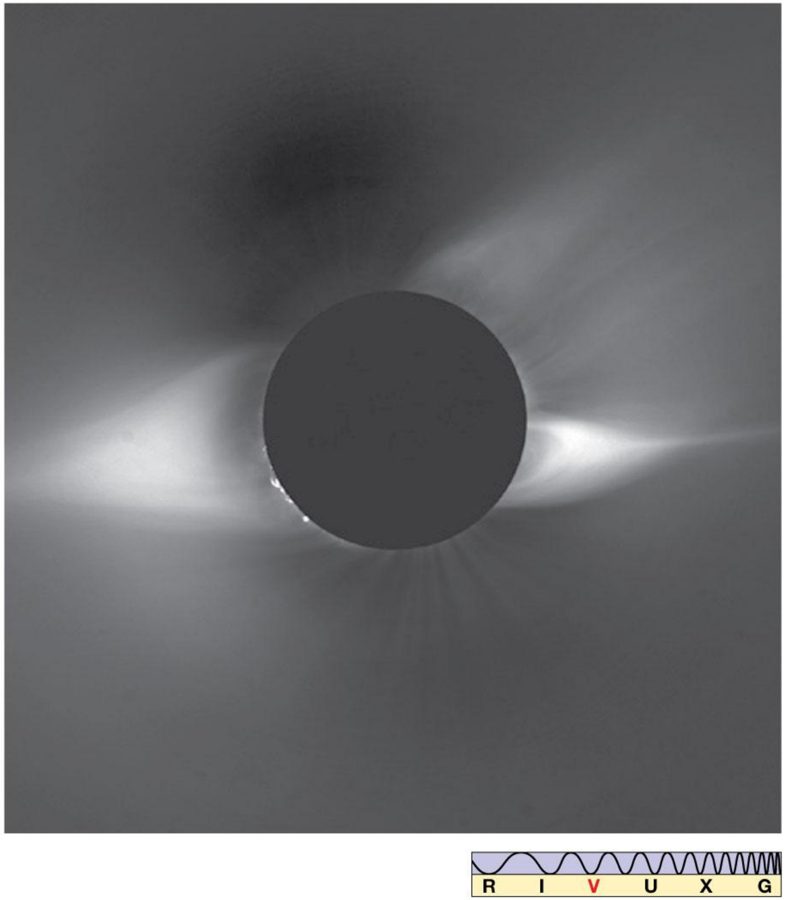
16.5 The Active Sun

Solar wind escapes Sun mostly through coronal holes, which can be seen in X-ray images



16.5 The Active Sun

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



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

Given the Sun's mass and energy production, we find that, on the average, every kilogram of the sun produces about 0.2 milliwatts of energy

This is not much—gerbils could do better—but it continues through the 10-billion-year lifetime of the Sun

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

Nuclear fusion is the energy source for the Sun.

In general, nuclear fusion works like this:

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

But where does the energy come from?

- It comes from the mass; if you add up the masses of the initial nuclei, you will find the result is more than the mass of the final nucleus.

16.6 The Heart of the Sun

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

$$E = mc^2$$

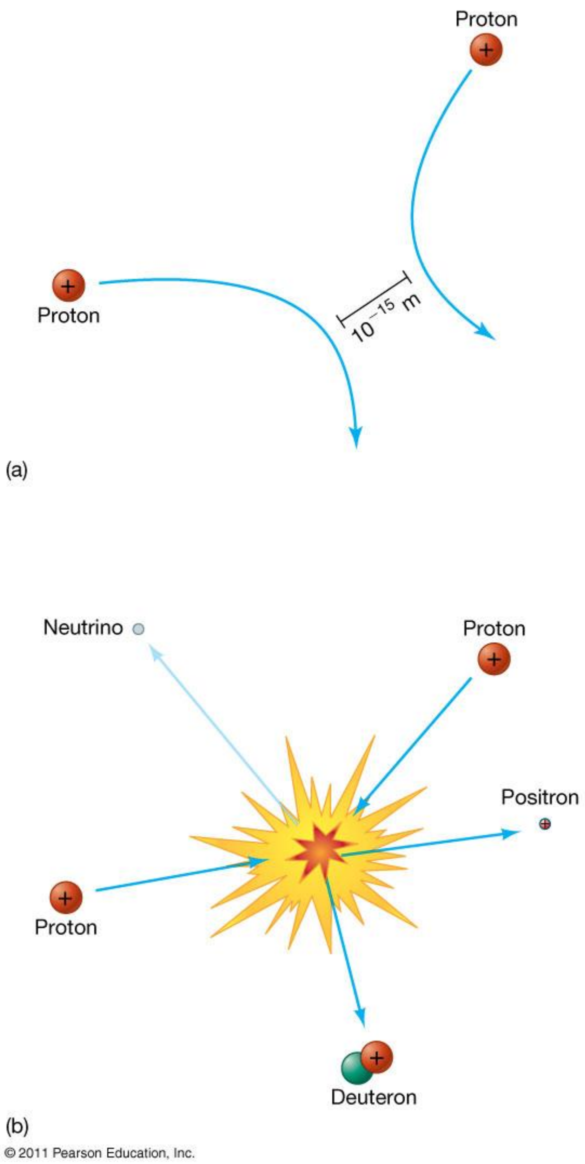
In this equation, c is the speed of light, which is a very large number.

What this equation is telling us is that a small amount of mass is the equivalent of a large amount of energy—tapping into that energy is how the Sun keeps shining so long.

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.



16.6 The Heart of the Sun

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

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

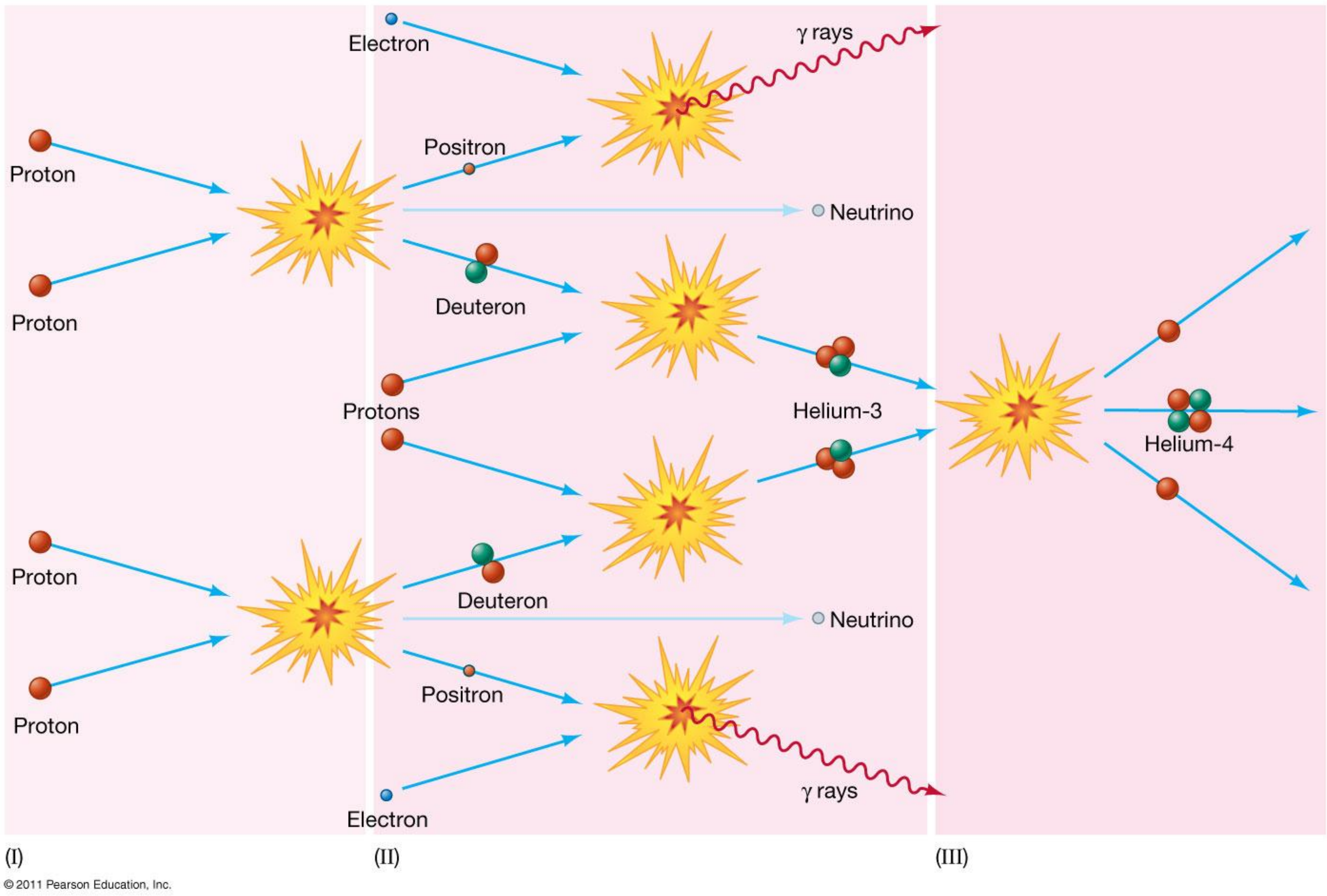
The positron is just like the electron except positively charged; the neutrino is also related to the electron but has no charge and very little, if any, mass.

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

The energy created in the whole reaction can be calculated by the difference in mass between the initial particles and the final ones—for each interaction it turns out to be 4.3×10^{-12} J.

This translates to 6.4×10^{14} J per kg of hydrogen, so the 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:

1. Gravity: Very weak, but always attractive and infinite in range
2. Electromagnetic: Much stronger, but either attractive or repulsive; infinite in range
3. Weak nuclear force: Responsible for beta decay; short range (1-2 proton diameters); weak
4. 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

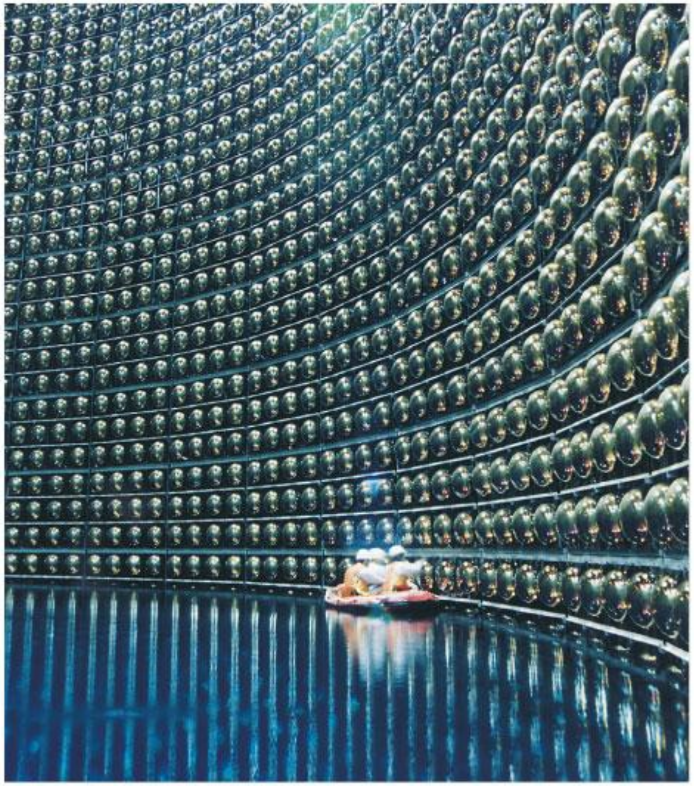
16.7 Observations of Solar Neutrinos

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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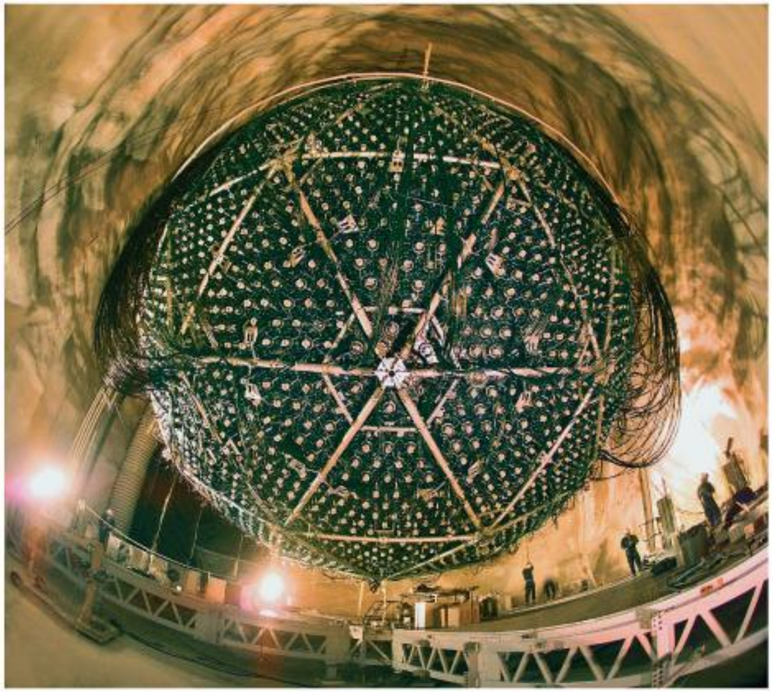

(b)

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