Astronomy

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Small 239

Office hours:

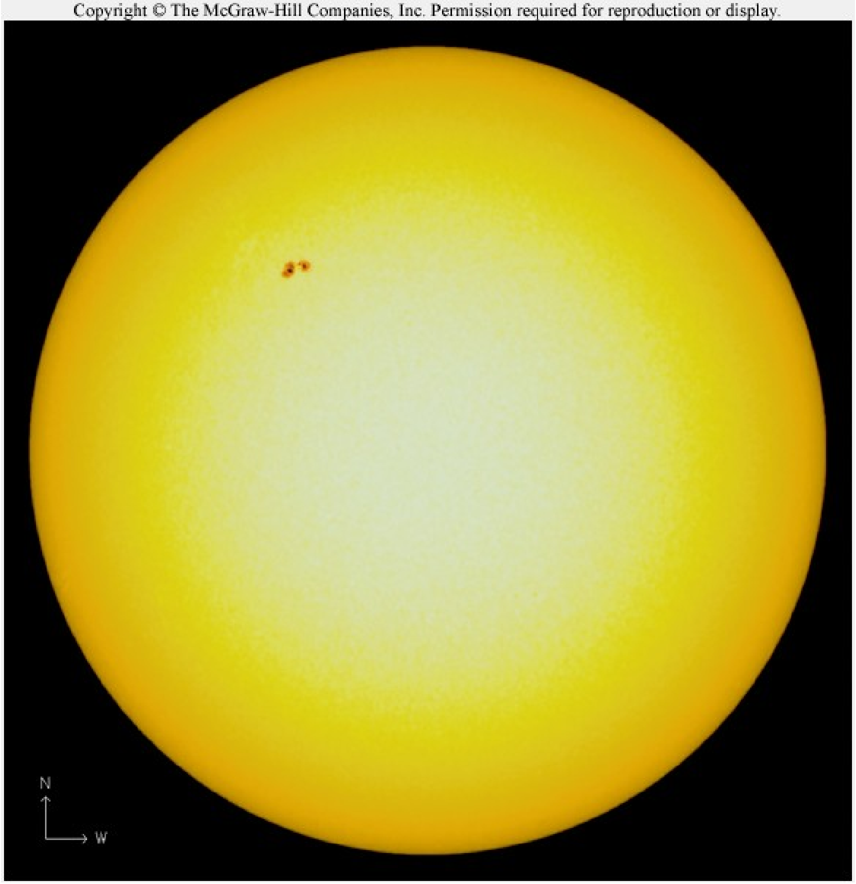
MTWR 10-11am

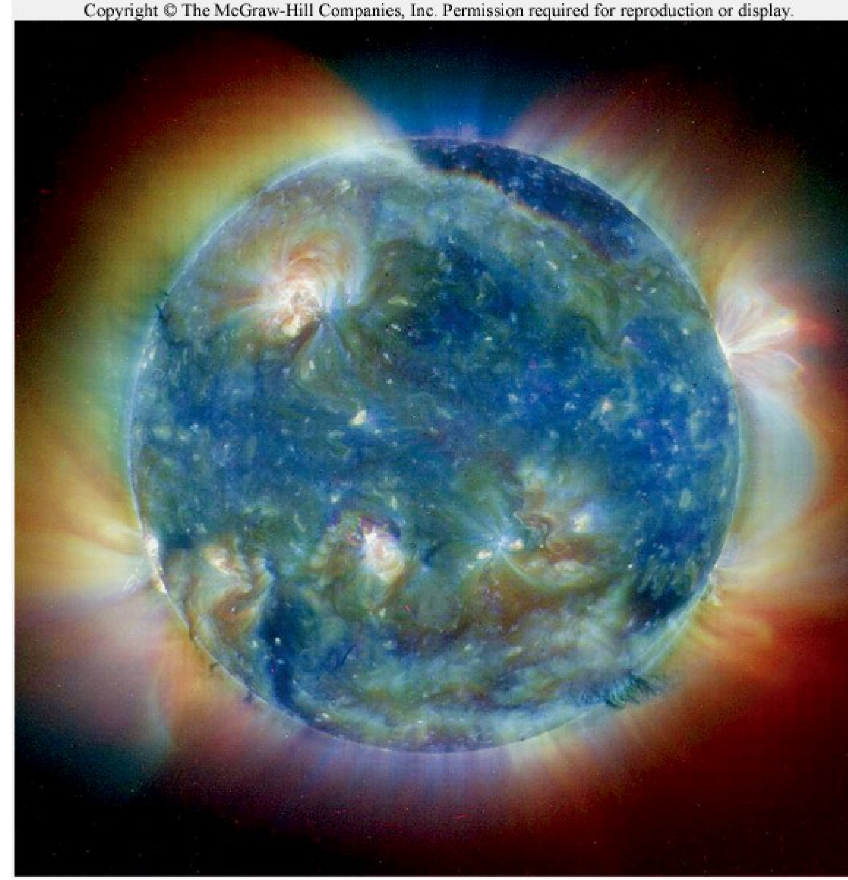
Our Star, The Sun

- The source of the Sun's heat and light
- Models of the Sun's interior
- The Sun's vibrations
- Probing the energy generating core
- Why the outer gaseous layers appear to have sharp edges
- Emission spectra of upper regions
- The corona and the solar wind
- Sunspots
- Sunspots and magnetic fields
- Magnetic reconnection power solar eruptions

http:// physics.wm.edu/~hancock/171/

The Sun Our Nearby Star





visible

UV

The Sun

TABLE 16-1 Sun Data

Distance from Earth:	Mean: 1 AU = 149,598,000 km Maximum: 152,000,000 km Minimum: 147,000,000 km
Light travel time to Earth:	8.32 min
Mean angular diameter:	32 arcmin
Radius:	696,000 km = 109 Earth radii
Mass:	1.9891×10^{30} kg = 3.33×10^{5} Earth masses
Composition (by mass):	74% hydrogen, 25% helium, 1% other elements
Composition (by number of atoms):	92.1% hydrogen, 7.8% helium, 0.1% other elements
Mean density:	1410 kg/m^3
Mean temperature:	Surface: 5800 K; Center: 1.55×10^{7} K
Luminosity:	3.9×10^{26} W
Distance from center of Galaxy:	8000 pc = 26,000 ly
Orbital period around center of Galaxy:	220 million years
Orbital speed around center of Galaxy:	220 km/s

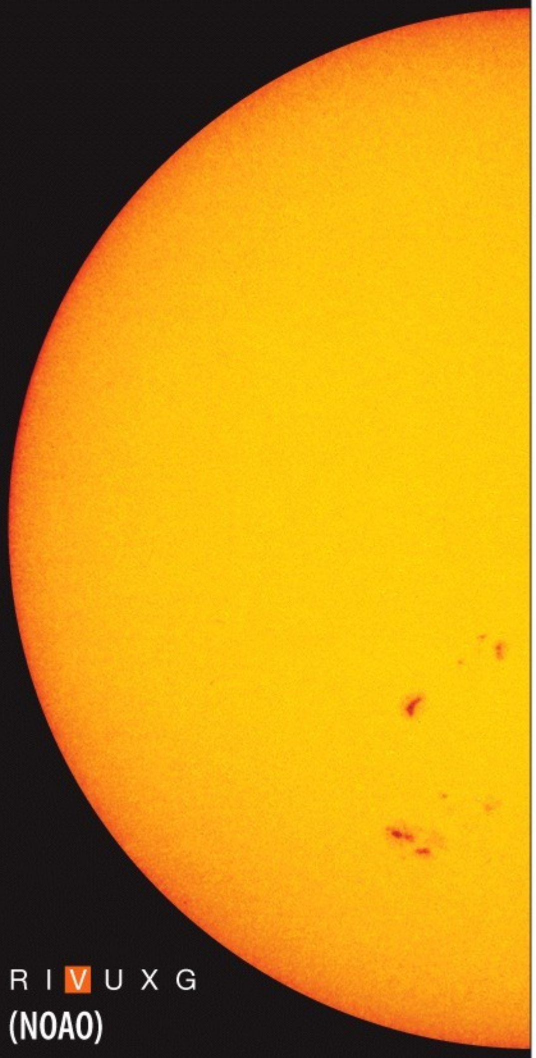


Table 16-1
Universe, Tenth Edition

The Sun Energy

Figure 16-1
Universe, Tenth Edition
Jeremy Woodhouse/PhotoDisc

- Many ancients thought it was literally on fire
- 1800's:
  - chemical burning?
  - gravitational contraction?
  - As the Sun shrinks, gravitational potential energy is converted into radiative energy

- But, neither of these provide enough energy…
  Sun would last only a short time

The Sun Energy

The Sun's energy output is about 3.9×10^{26} joules/sec. A chemical reaction provides roughly 10^{-19} joules/atom. For the Sun to gets its energy from chemical reactions, it would have to react about 3.0×10^{45} atoms/sec. Since the Sun contains about 10^{57} atoms, the Sun would use all of its energy and go dark in 3×10^{11} seconds or about 10,000 years. The solar system has been here for 4.6 billion years.

Gravitational contraction (Kelvin-Helmholtz) could provide some of the Sun's energy? While the math is a little more involved, the number is about 8 million years of energy from gravitational contraction. That is far short of 4.6 billion years.

So where does the Sun get its energy?

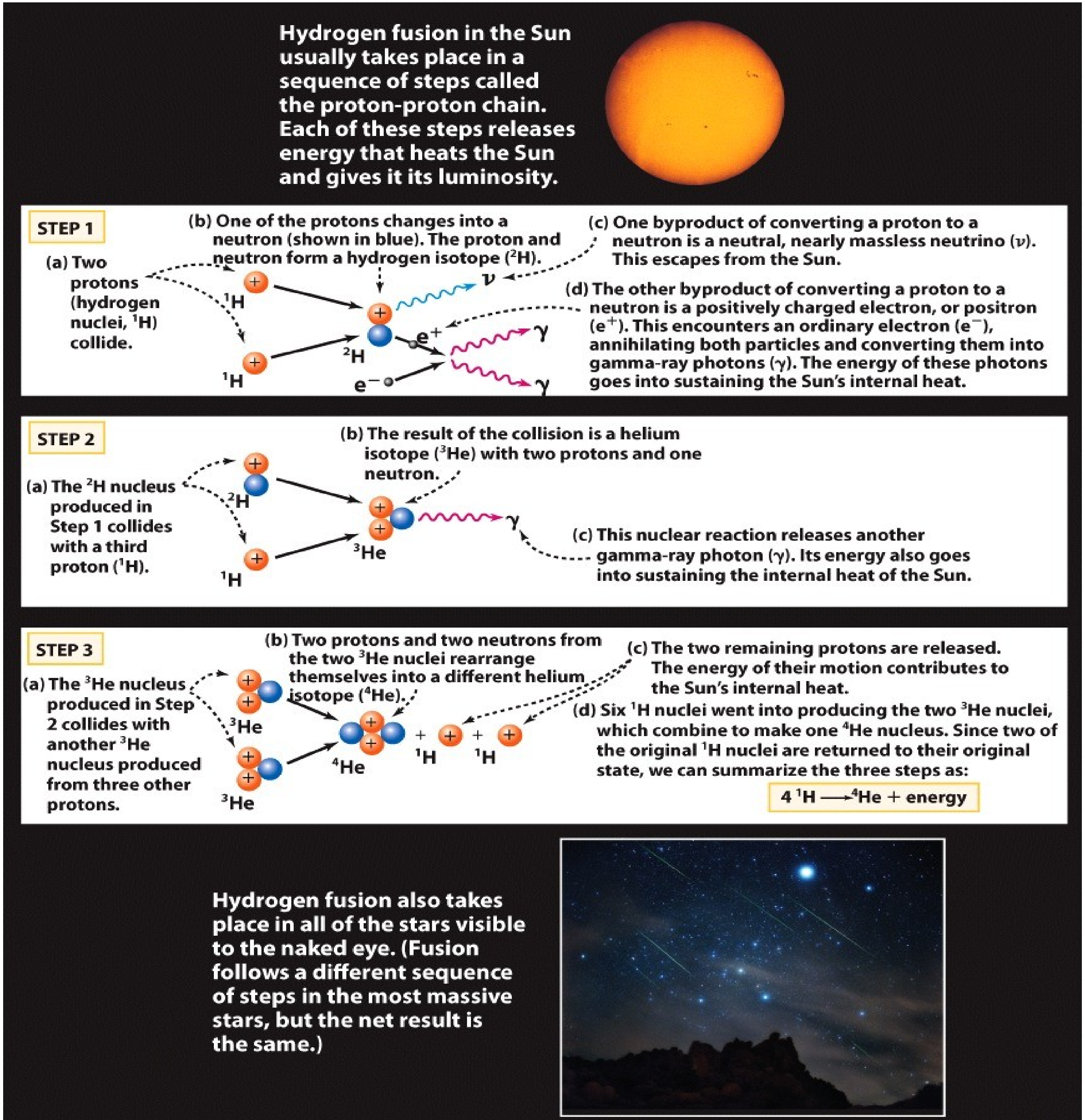
The Sun's Energy

The answer: mass is converted to radiative energy!

$$E = mc^2$$

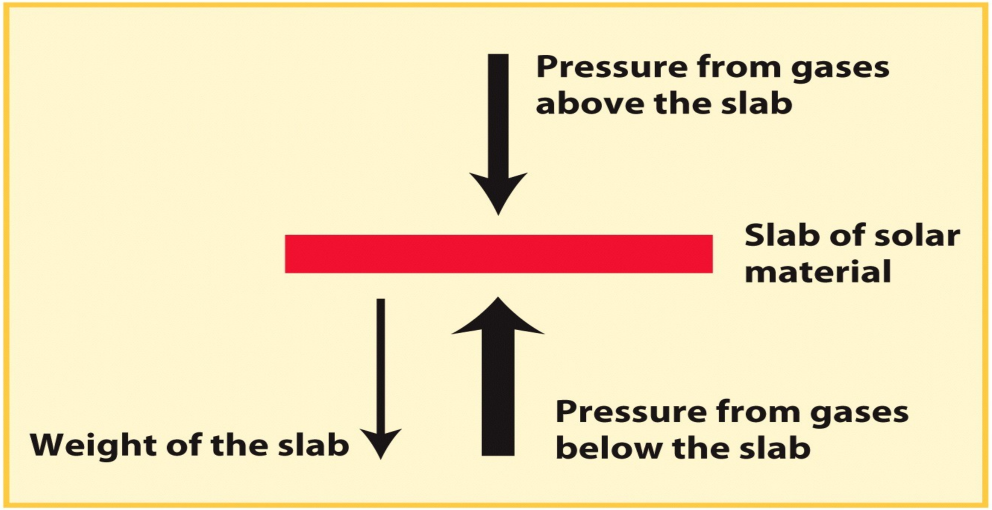
This is Einstein's famous relationship that says a small amount of mass (m) multiplied by c^2 can be converted to an enormous amount of energy (E). The actual process deep inside the Sun is nuclear fusion. The Sun converts about 600 million tons /sec into energy.

The Sun



The nuclear fusion process converts 4 protons into energy and one helium nucleus with 2 protons and 2 neutrons. The chain of reactions is known as the proton-proton chain. About 600 million tons of hydrogen are converted to helium each second.

Models of the Sun Energy.



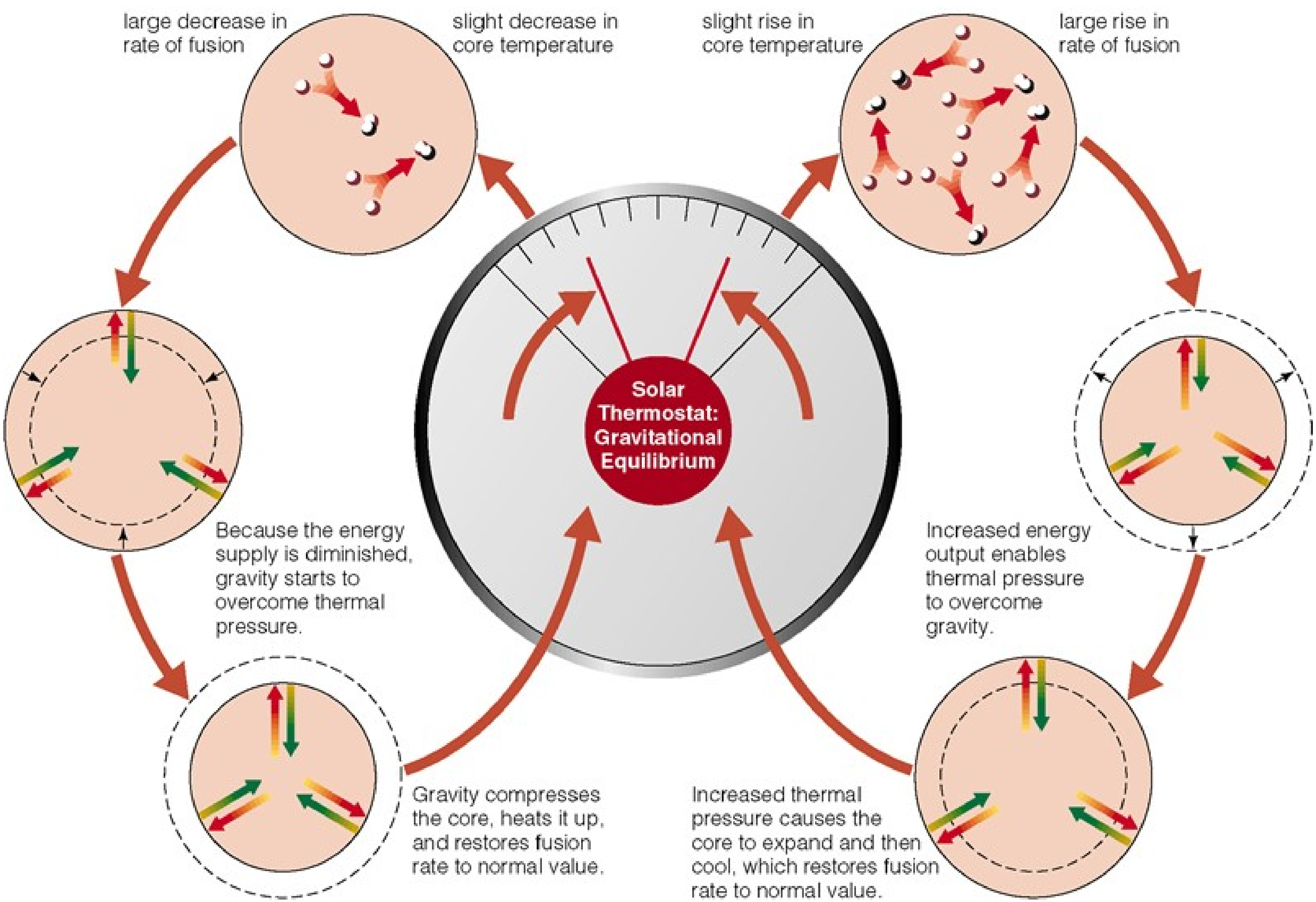
Material inside the sun is in hydrostatic equilibrium, so forces balance

Figure 16-2a
Universe, Tenth Edition

The fusion process takes place deep in the Sun's core where the temperature is 1.5 x 10^7 K. The Sun is in both hydrostatic equilibrium and thermal equilibrium. Hydrostatic equilibrium is when the outward (upward) force of the expanding gas (plasma) is balanced by the down gravitational pressure from the material above. While the temperature may be significantly different between the core and the surface, thermal equilibrium means that the temperature is the same at a given depth.

The Solar Thermostat

The rate of fusion is highly sensitive to temperature, thanks to hydrostatic equilibrium



Energy transport from the Sun's Core

Heat is normally transported by three methods

- Conduction
- Convection
- Radiative diffusion

Conduction is not efficient with a gas (or plasma) even in the Sun. Convection is the circulation of a fluid with the hotter fluid rising and the colder fluid sinking. Radiative diffusion is the process of photons being absorbed by atoms and electrons and being re-emitted. Photons then travel outward by continuously being absorbed and re-emitted.

Theoretical Models of the Sun

TABLE 16-2 A Theoretical Model of the Sun

Distance from the Sun's center (solar radii)	Fraction of luminosity	Fraction of of mass	Temperature ($\times 10^6$ K)	Density (kg/m^3)	Pressure relative to pressure at center
0.0	0.00	0.00	15.5	160,000	1.00
0.1	0.42	0.07	13.0	90,000	0.46
0.2	0.94	0.35	9.5	40,000	0.15
0.3	1.00	0.64	6.7	13,000	0.04
0.4	1.00	0.85	4.8	4,000	0.007
0.5	1.00	0.94	3.4	1,000	0.001
0.6	1.00	0.98	2.2	400	0.0003
0.7	1.00	0.99	1.2	80	4×10^{-5}
0.8	1.00	1.00	0.7	20	5×10^{-6}
0.9	1.00	1.00	0.3	2	3×10^{-7}
1.0	1.00	1.00	0.006	0.00030	4×10^{-13}

***Note:** The distance from the Sun's center is expressed as a fraction of the Sun's radius ($R_\odot$). Thus, 0.0 is at the center of the Sun and 1.0 is at the surface. The fraction of luminosity is that portion of the Sun's total luminosity produced within each distance from the center; this is equal to 1.00 for distances of 0.25 $R_\odot$ or more, which means that all of the Sun's nuclear reactions occur within 0.25 solar radius from the Sun's center. The fraction of mass is that portion of the Sun's total mass lying within each distance from the Sun's center. The pressure is expressed as a fraction of the pressure at the center of the Sun.*

Table 16-2
Universe, Tenth Edition

This table shows a typical solar model. The temperature in the core is 15.5 x 10^6 K and the density is 1.6 x 10^5 kg/m^3 (14 time the density of lead!).

Theoretical Models of the Sun

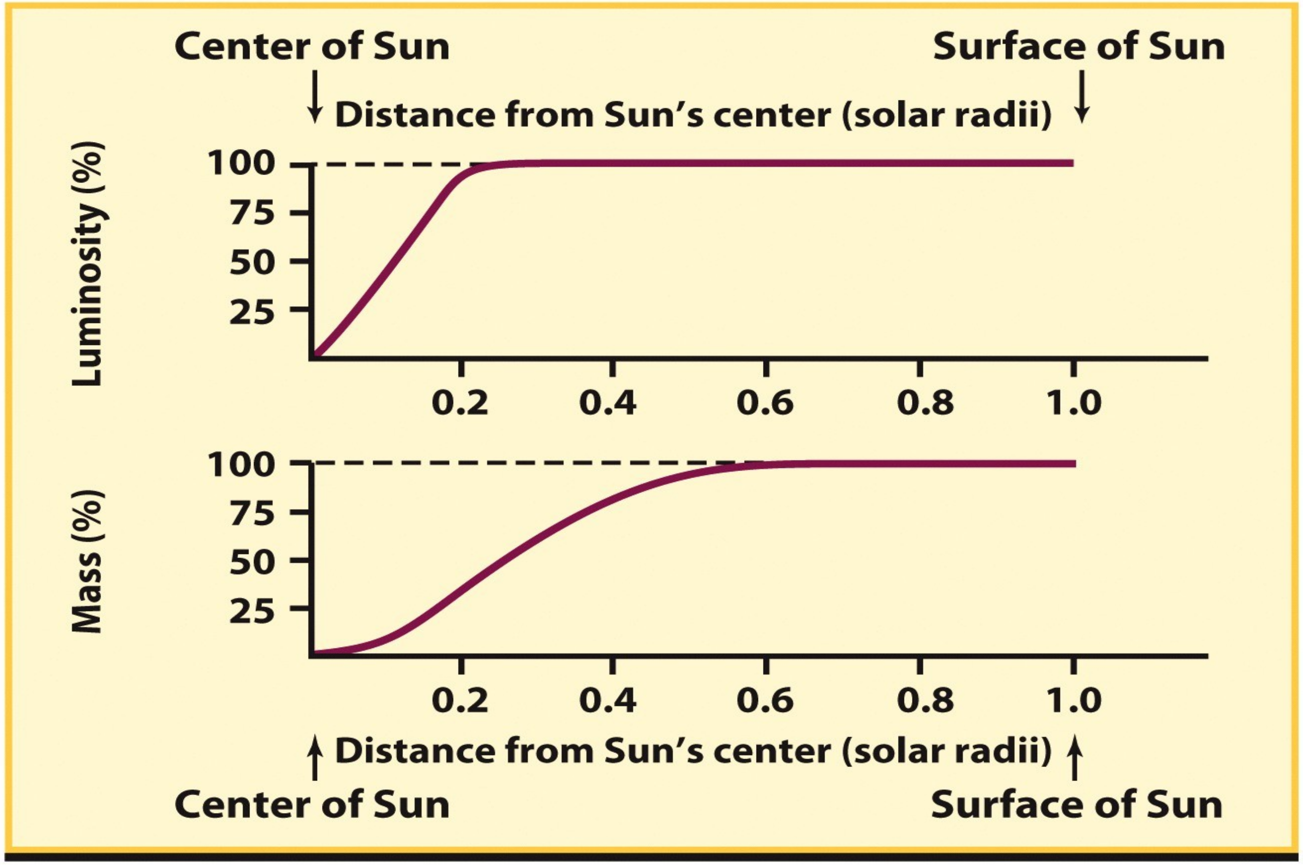


Figure 16-3 part 1
Universe, Tenth Edition

The core that produces energy by fusion is about 0.25 $R_\odot$ ($R_\odot$ the solar radius of 696,000 km). About 94% of the mass of the Sun is found in the inner ½$R_\odot$.

Theoretical Models of the Sun

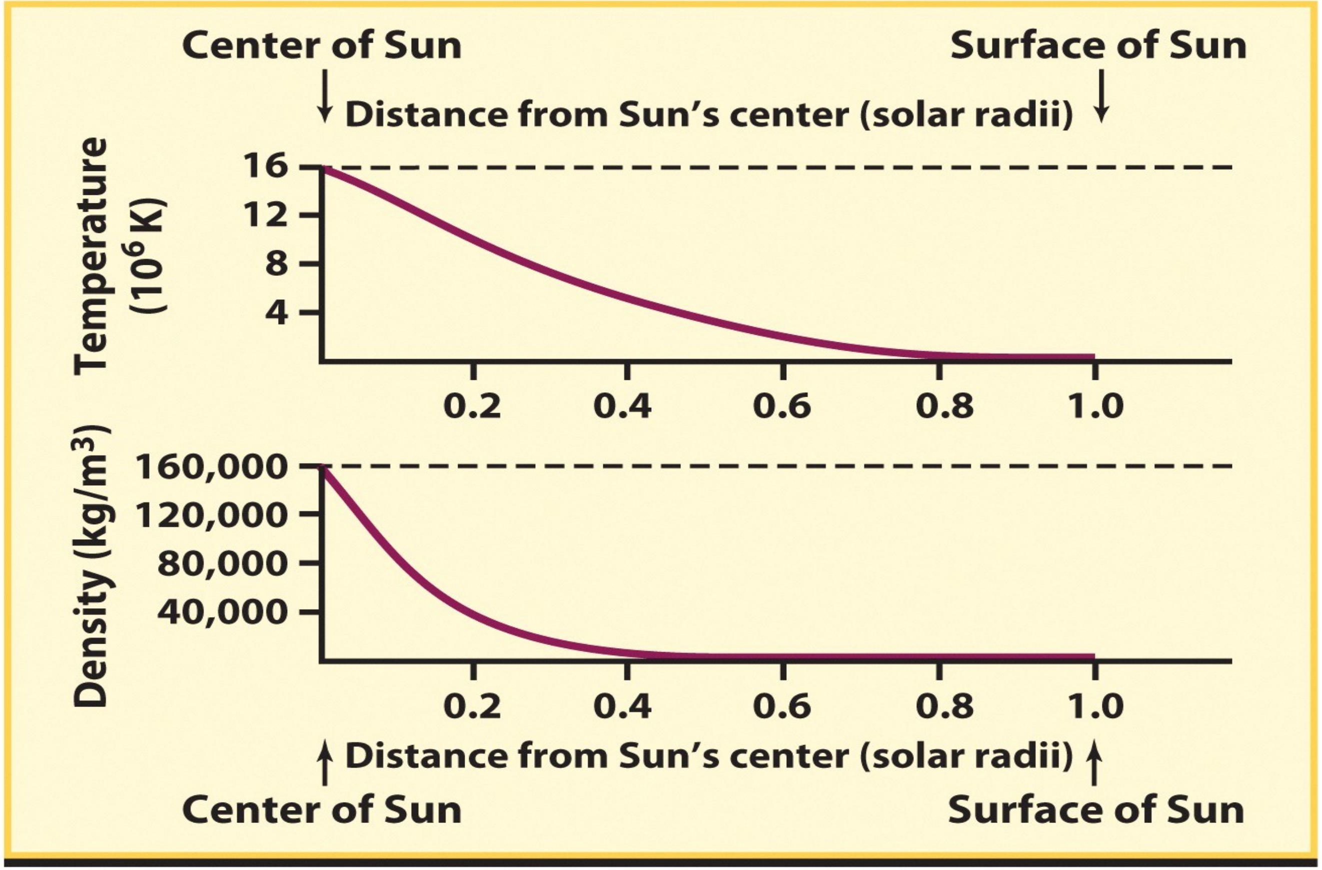


Figure 16-3 part 2
Universe, Tenth Edition

The density falls rapidly outside of the energy producing core. The temperature falls more slowly as you move away from the core.

Theoretical Models of the Sun

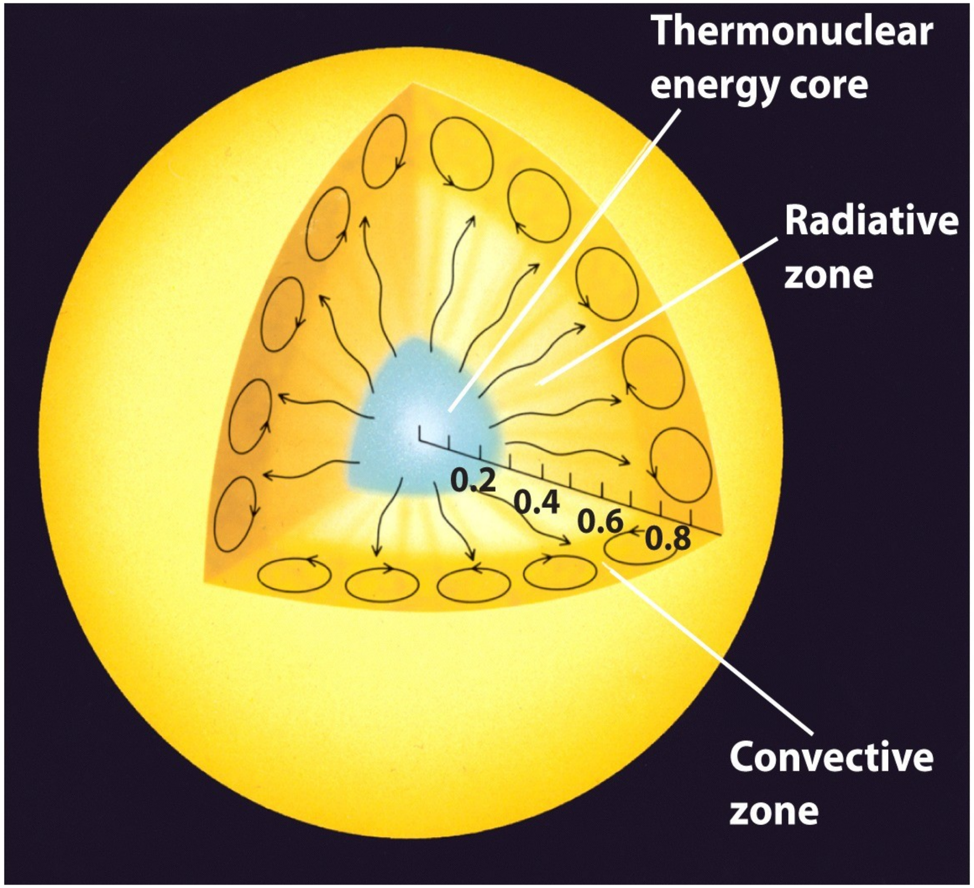


Figure 16-4
Universe, Tenth Edition

From the center of the Sun out to 0.71 $R_{\odot}$, energy is transported by radiative diffusion in a zone called called the radiative zone. Beyond 0.71 $R_{\odot}$ energy is transported by convection in the convection zone. In the radiative zone the energy travels as photons. The matter in this zone is very dense so the photons are constantly absorbed and re-emitted. It takes 170,000 years for a photon to travel from the core to the surface 696,000 km away. This is a speed of about ½ meter/hour or 20 times slower than a snail!

Helioseismology

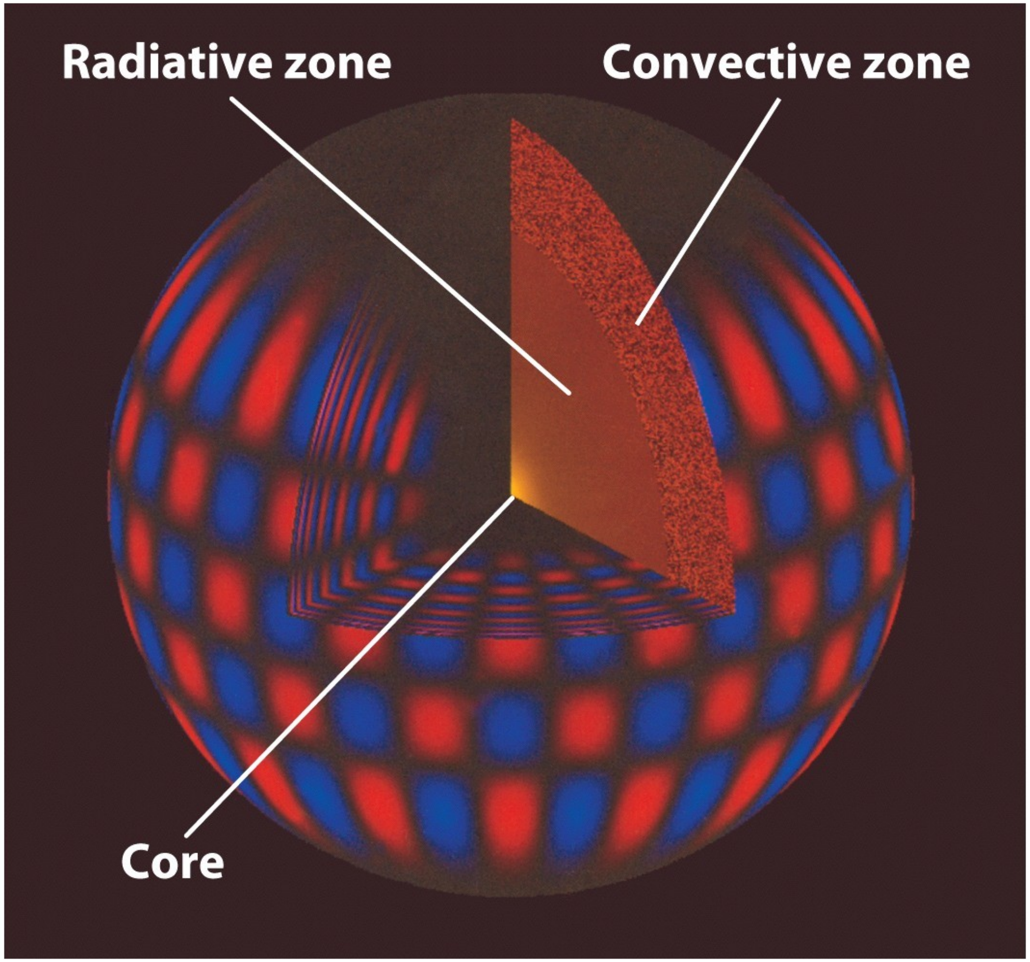


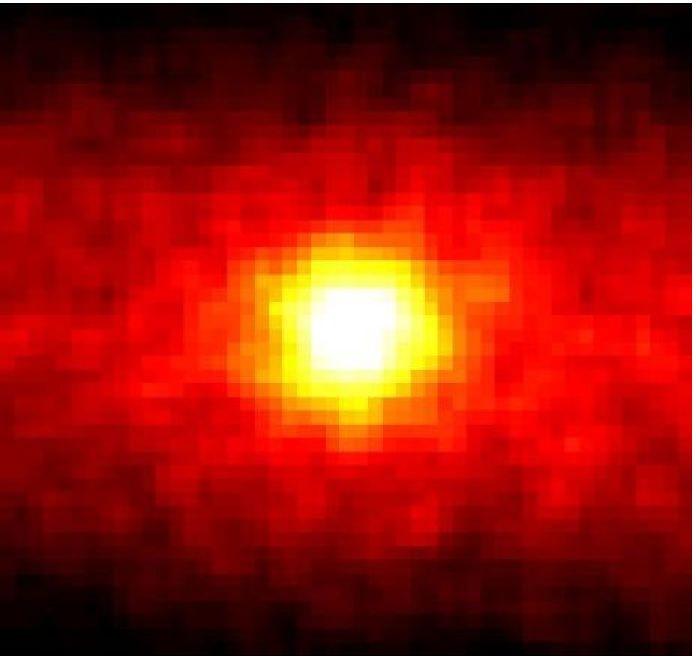
Figure 16-5
Universe, Tenth Edition
National Solar Observatory

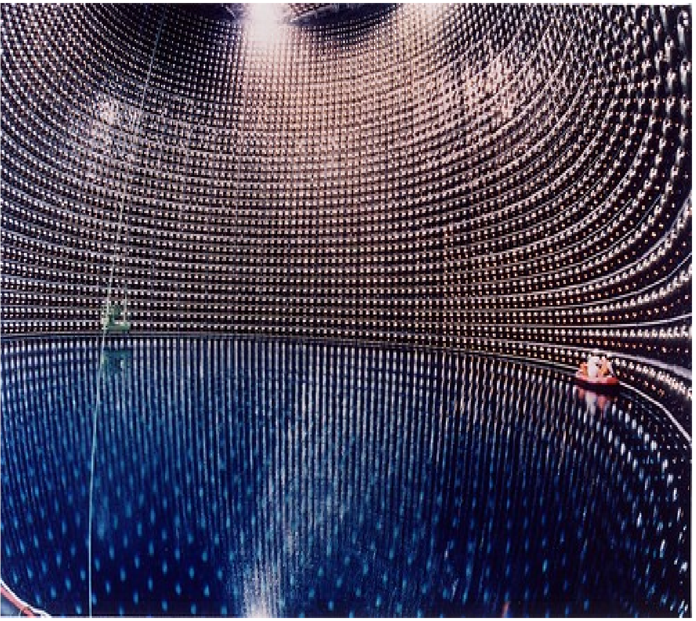
The Sun vibrates at various frequencies much like a ringing a bell. These vibrations bounce off of the surface and are reflected downward where the higher density and temperature bend the wave upward. The strongest of the wave have a frequency of 0.003 Hz (well below human hearing) These vibrations can be detected by measuring the movement of the Sun's upper regions using the *Doppler shift. The* Pattern depends on temperature, density, etc. This method confirms the solar model.

Solar Neutrinos and the Solar Neutrino Problem

Neutrinos are 'ghostly' particles that have very tiny masses and hardly interact with anything (only via the weak interaction). Most neutrinos pass through the Earth without interacting. Neutrinos are produced in fusion reaction like the reactions that produce energy in the Sun. The neutrinos produced in the core of the Sun escape from the Sun and a very small number can interact with a giant underground particle detectors. This is a giant tank of clean fluid (C_2Cl_4) that was used by Ray Davis and collaborators for 40 years to detected neutrinos in a deep gold mine. But there was a problem. The number of neutrinos observed was 1/3 of what was predicted by solar model calculations.

Solar Neutrinos and the Solar Neutrino Problem





Several ideas were proposed to explain the missing solar neutrinos. The problem was not the detector or the theoretical models of how the neutrinos are produced in the Sun. The problem was the neutrinos were changing their identity. There are three 'flavors' of neutrinos (electron, muon and tau). The Sun only produces electron neutrinos. In 1998 Kamiokande II (a tank of 3000 tons of water with 1100 light detectors deep under a mountain) in Japan showed neutrons do oscillate (change flavors). The top image is the Sun in neutrinos. The bottom image is inside the partially drained tank during repairs. Note the small raft.

Solar Neutrinos and the Solar Neutrino Problem

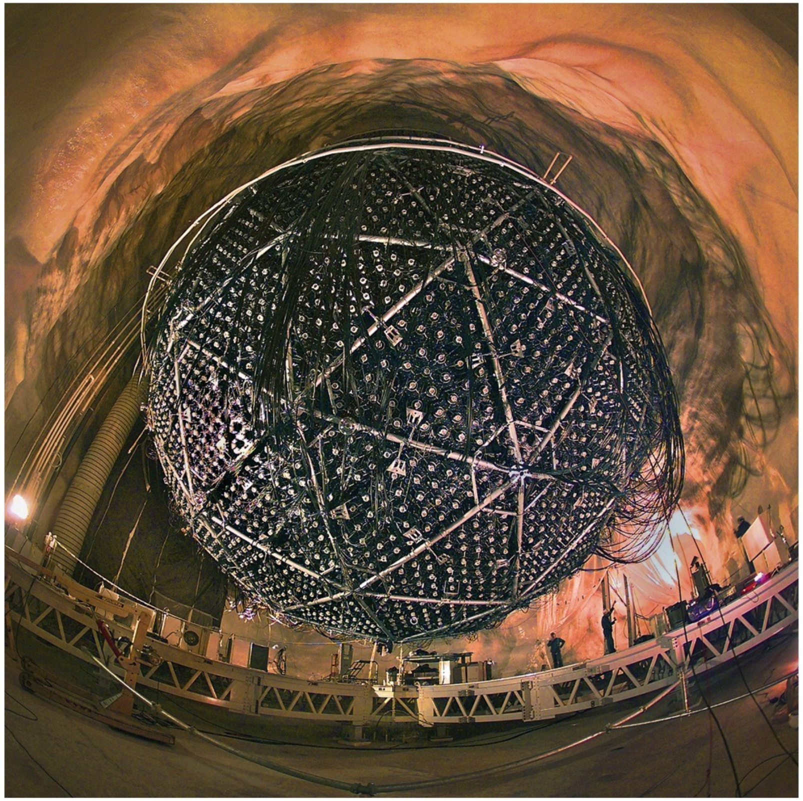


Figure 16-6
Universe, Tenth Edition
Science Source

On the way to Earth, some of the electron neutrinos were changing into muon and tau neutrinos leaving only 1/3 of the original solar electron neutrons. This was confirmed by the SNO (Sudbury Neutrino Observatory) in a deep nickel mine in Canada. The detector contained 1000 tons of heavy water.

The fusion reaction model in the core of the Sun has been confirmed by direct observation of neutrinos.

The Photosphere

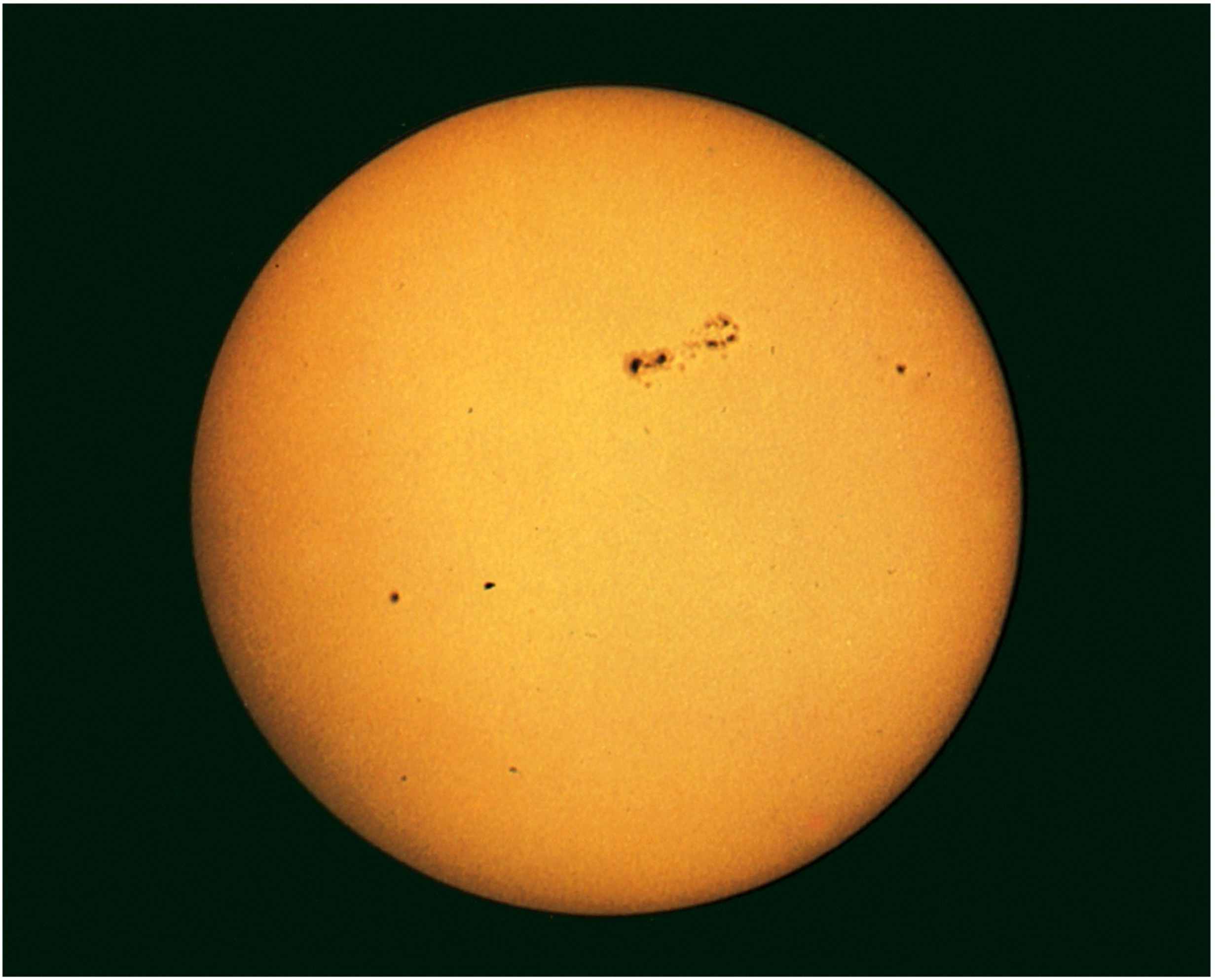


Figure 16-7
Universe, Tenth Edition
Celestron International

The Sun appears to have a surface in visible light but this is an illusion. The Sun is a ball of gas (plasma) and does not have a solid surface. All of the visible light comes from a single thin layer (400 km) of gas called the photosphere.

The Photosphere

Figure 16-7
Universe, Tenth Edition
Celestron International

The photosphere has a density of only 10^{-24} kg/m^3 or 0.01% of Earth's atmosphere. It is very opaque to visible light because of some of the hydrogen is H^- ions (a proton with two electrons). The extra electron is loosely bound and can be detached by a photon of any energy. When the electron attaches back to a hydrogen atom it emits a photon a photon in a random direction. The H- ions absorb visible light very efficiently making the photosphere opaque and nearly a perfect blackbody spectrum.

Photosphere Limb Darkening

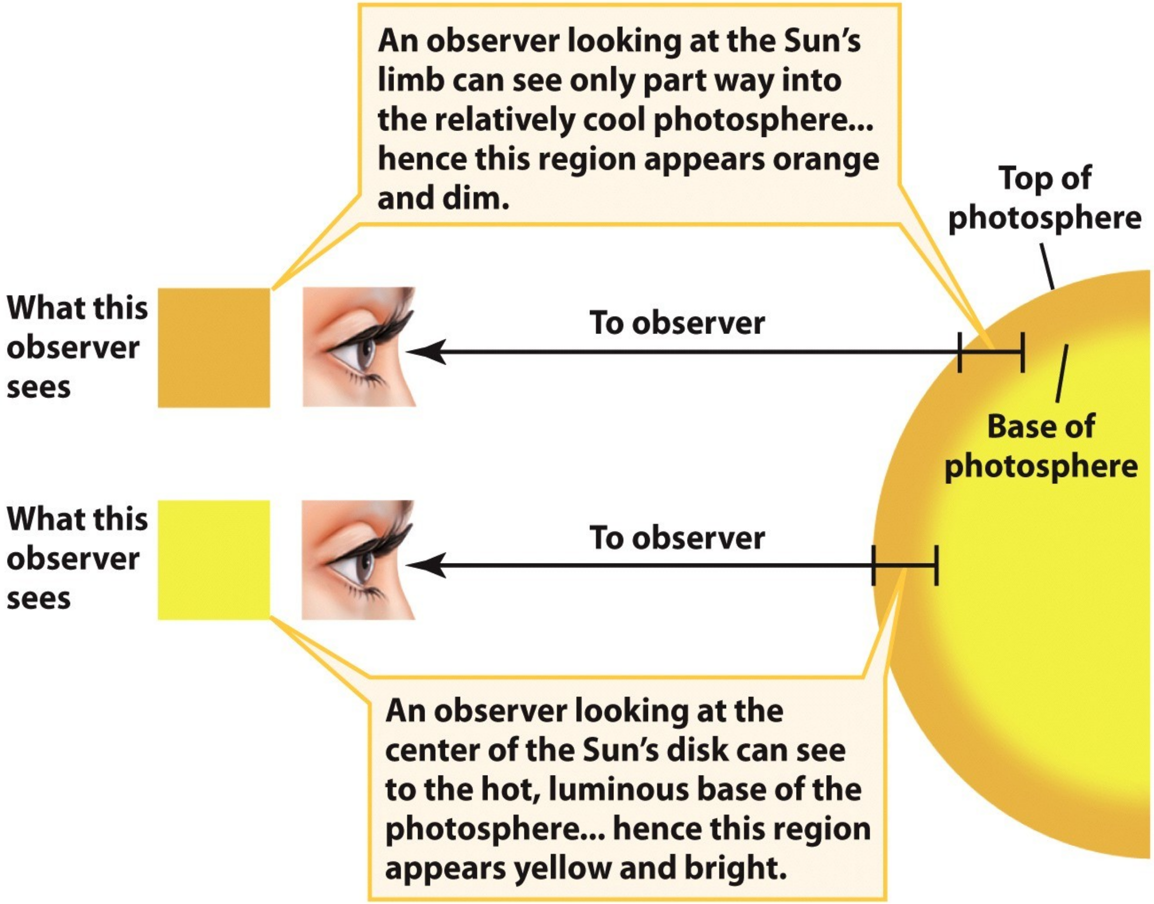
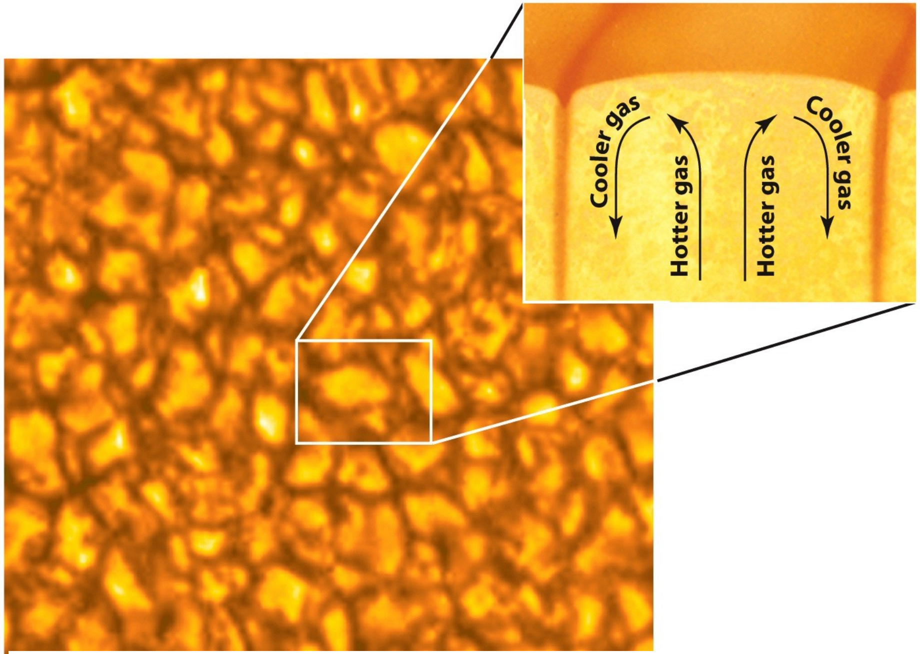


Figure 16-8
Universe, Tenth Edition

The photosphere looks like a perfect blackbody spectrum at 5800 K. It is heated from below so the photosphere temperature should decrease as you go upward. But superimposed on this blackbody spectrum are many dark absorption lines. These are from the cooler regions of the upper photosphere at 4400 K. Because we don't see as deep into the photosphere around the edges (or limbs) of the photosphere, these regions appear to be orange and darker. This effect is call photosphere limb darkening.

Photosphere Granules and Supergranules



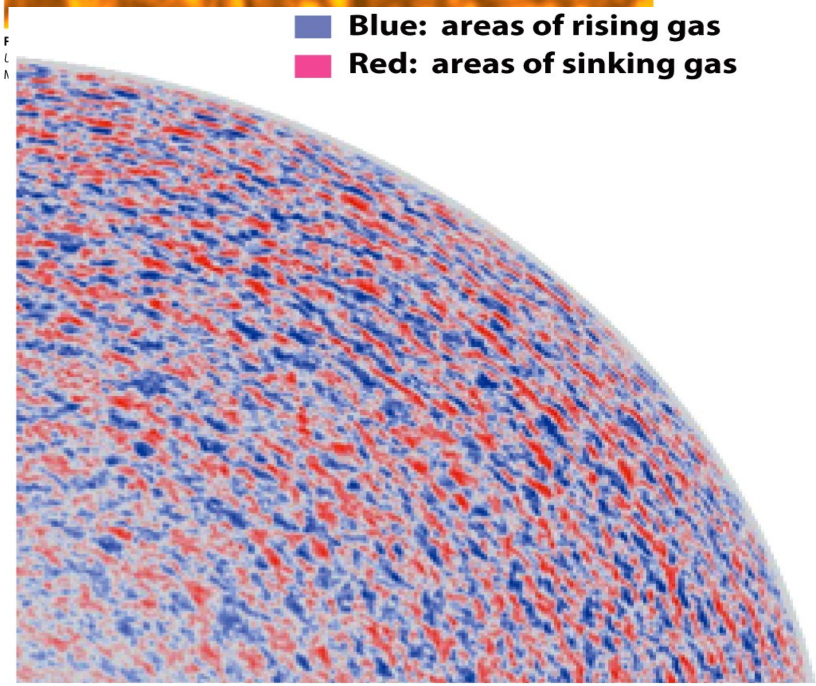


Figure 16-10
Universe, Tenth Edition
David Hathaway, MSFC/NASA

High resolution images of the Sun show blotchy granulated areas. (Never look directly at the Sun with or without a telescope!) These granulations are ~100 km across. These areas are due to raising hot gas and descending cooler gas. Superimposed on the granulations are large convection cells called supergranules. These can be 35,000 km. These supergranules move at 0.4 km/s which is about one tenth the speed of the gases in the smaller granules.

The Chromosphere

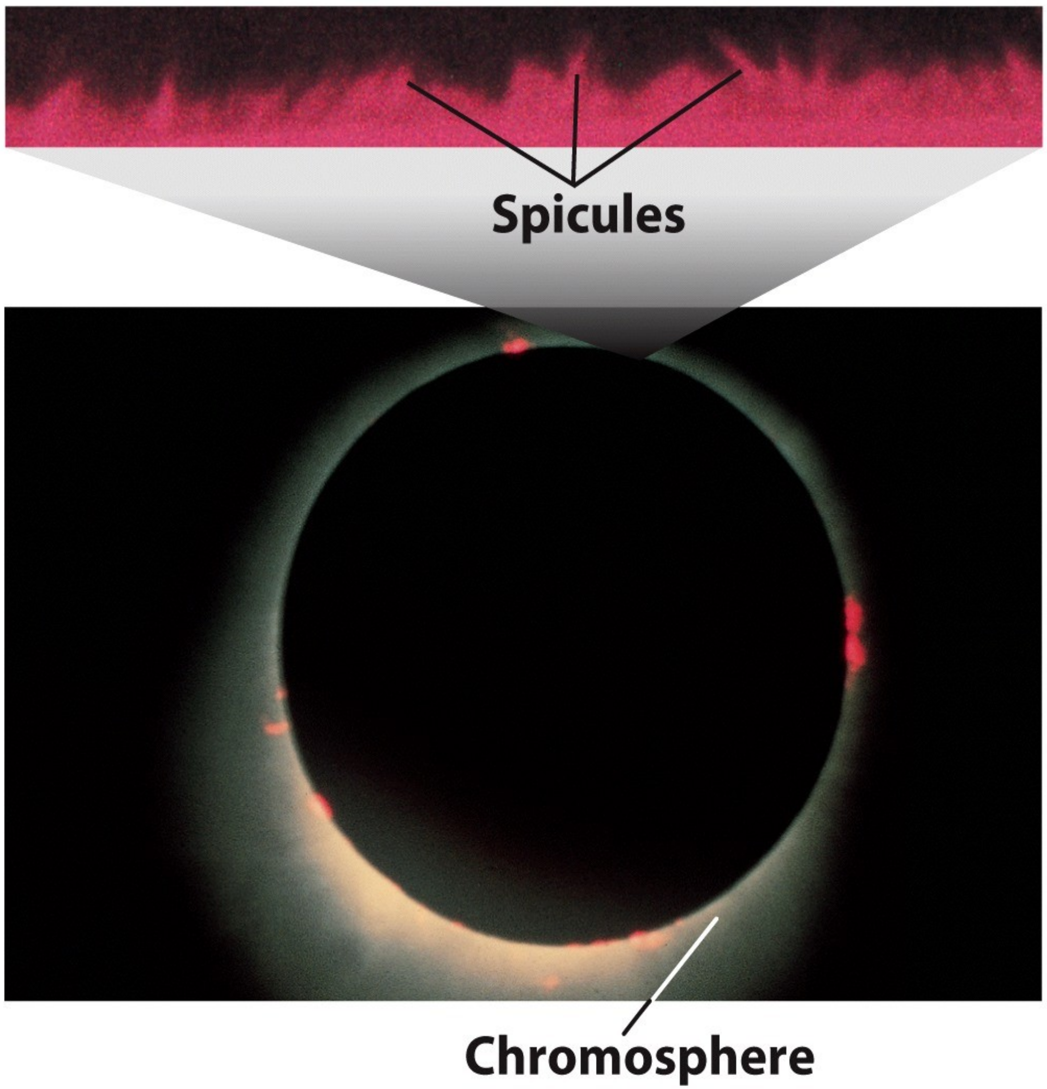
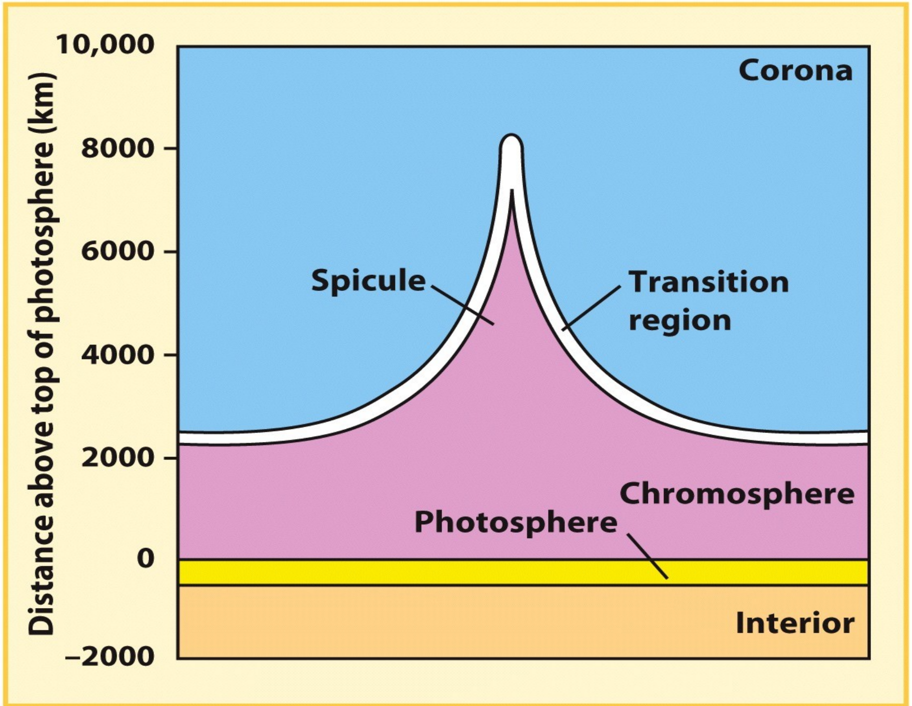


Figure 16-11
Universe, Tenth Edition
NOAO

When an eclipse blocks out the photosphere, a region called the chromosphere is revealed. This region is only about 10^{-4} as dense as the photosphere. Temperature increase with height in the chromosphere. Its spectrum show emission lines of H, He and Ca. The pink color comes from the H_{α} line of hydrogen at 656 nm. Helium was discovered in the chromosphere 30 years before it was discovered on Earth.

Spicules in the Chromosphere



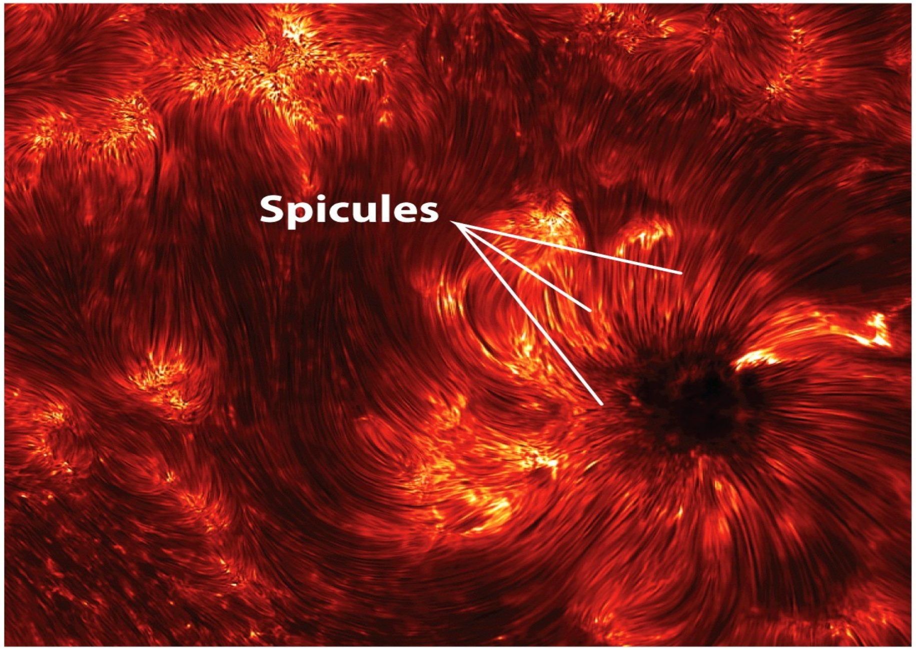


Figure 16-13
Universe, Tenth Edition

Spicules are jets of rising gas that stick out of the chromosphere. Spicules move at 20 km/s and last about 15 minutes. Hundreds of thousands of the spicules exist at any given time. Spicules can extend out to 10,000 km above the photosphere. Spicules appear to be related to the Sun's magnetic field but the details are not understood.

The Corona

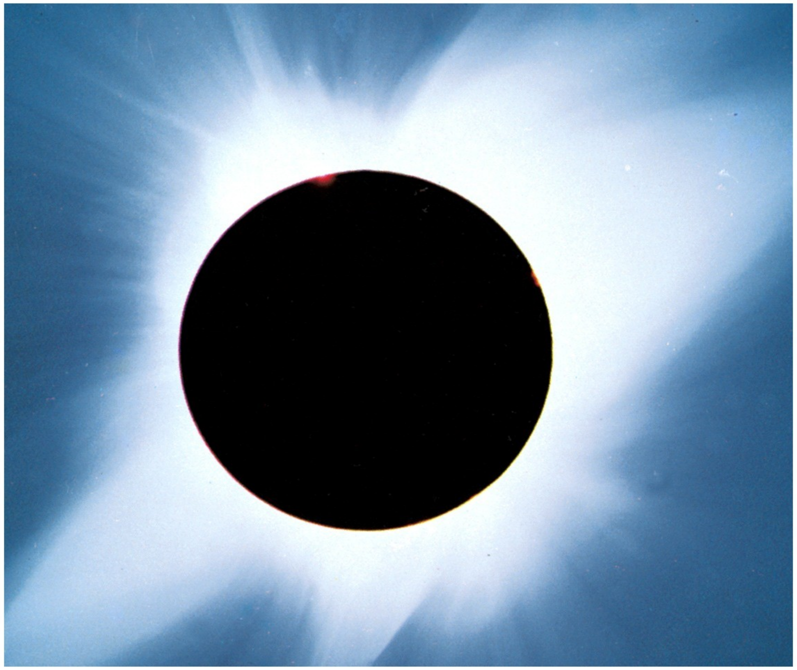


Figure 16-14
Universe, Tenth Edition

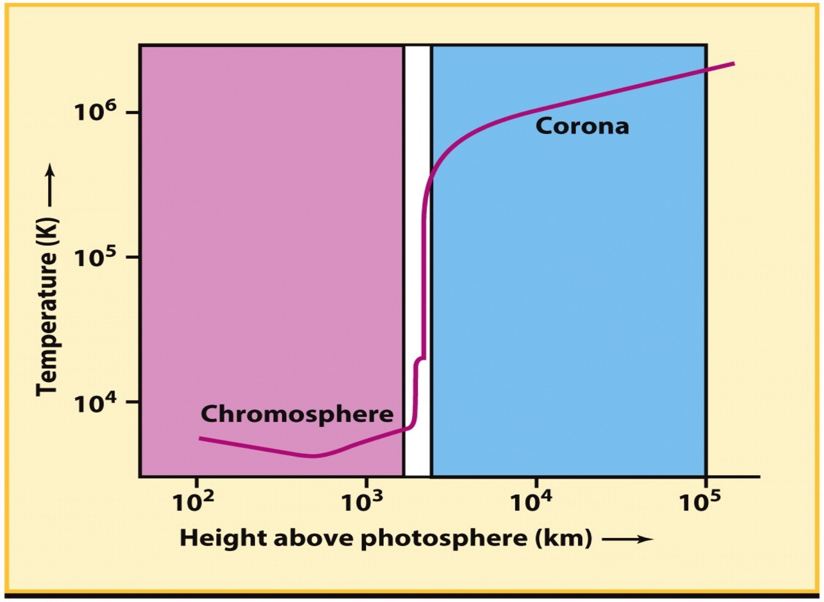


Figure 16-15a
Universe, Tenth Edition

The Corona is the region above the chromosphere and the outer most region of the Sun. It is not spherical and the streams change over time. The corona extends out to millions of km. The density of the gas in the corona is very tenuous. Its emission spectra are from atoms that are highly ionized. It has a very high temperature (up to 2×10^6 K)

The Sun's Atmosphere

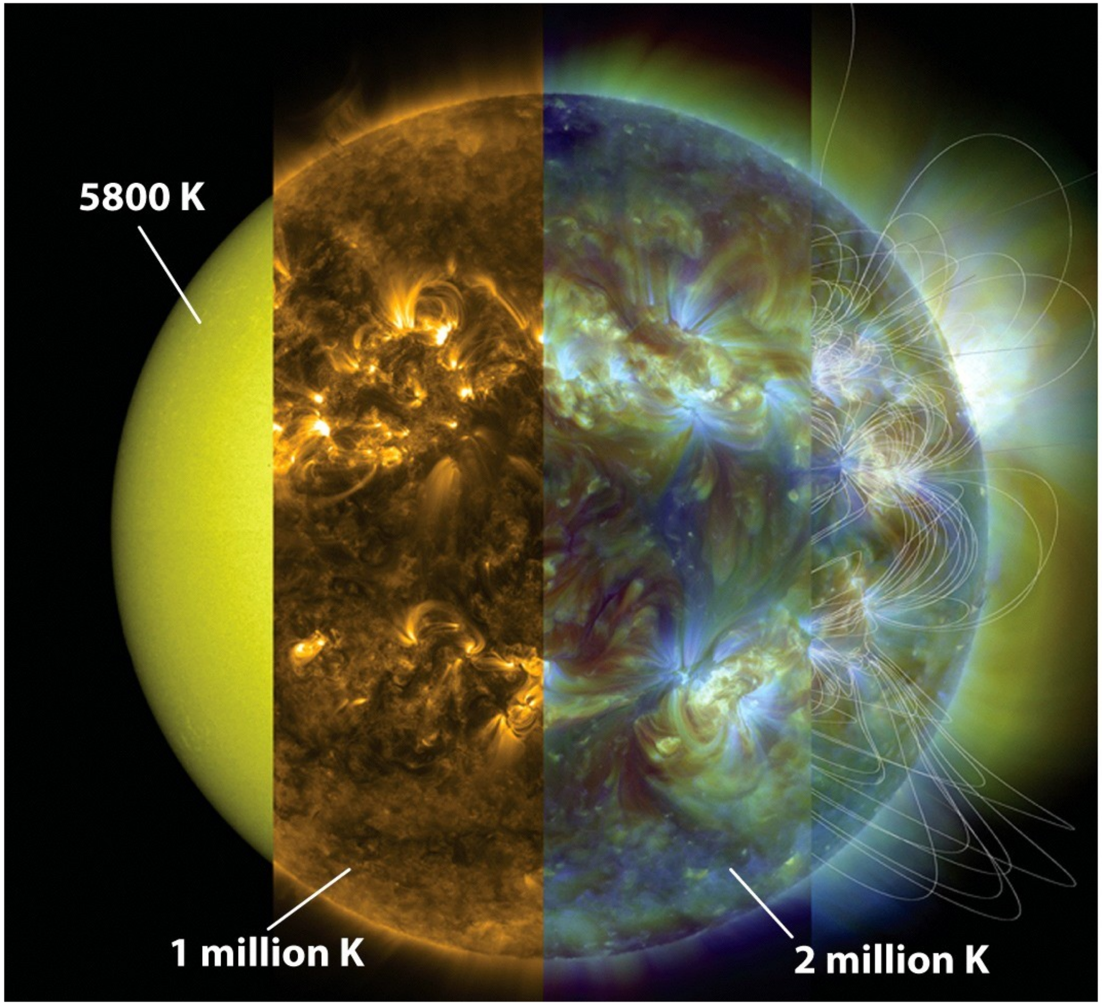


Figure 16-15b
Universe, Tenth Edition
NASA

This composite image shows the Sun's atmosphere at different temperature. In visible light the 5800 K photosphere is visible. The UV images show features at 1 and 2 million K. Magnetic field lines are superimposed at the right.

The Solar Wind

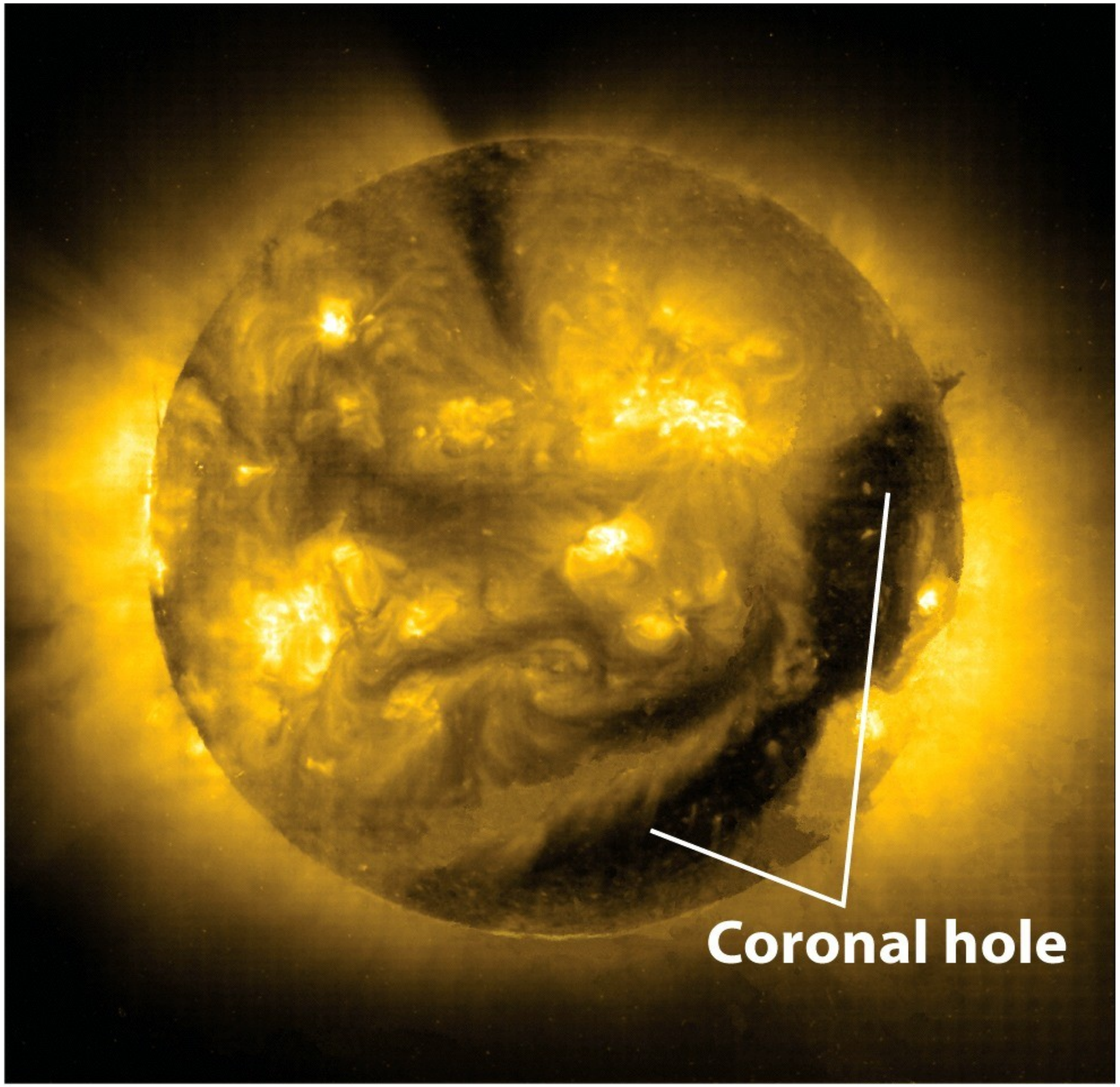


Figure 16-16
Universe, Tenth Edition
SOHO/EIT/ESA/NASA

The Sun's gravity holds the atoms of the photosphere and chromosphere. Because of the high temperature in the corona, some of the atoms and ions are moving at ~1,000,000 km/hr. These can escape the Sun's gravity and become the solar wind. The mass ejected as solar wind is about 10^9 kg/s. It is mainly electron, hydrogen and helium ions.

The Solar Wind

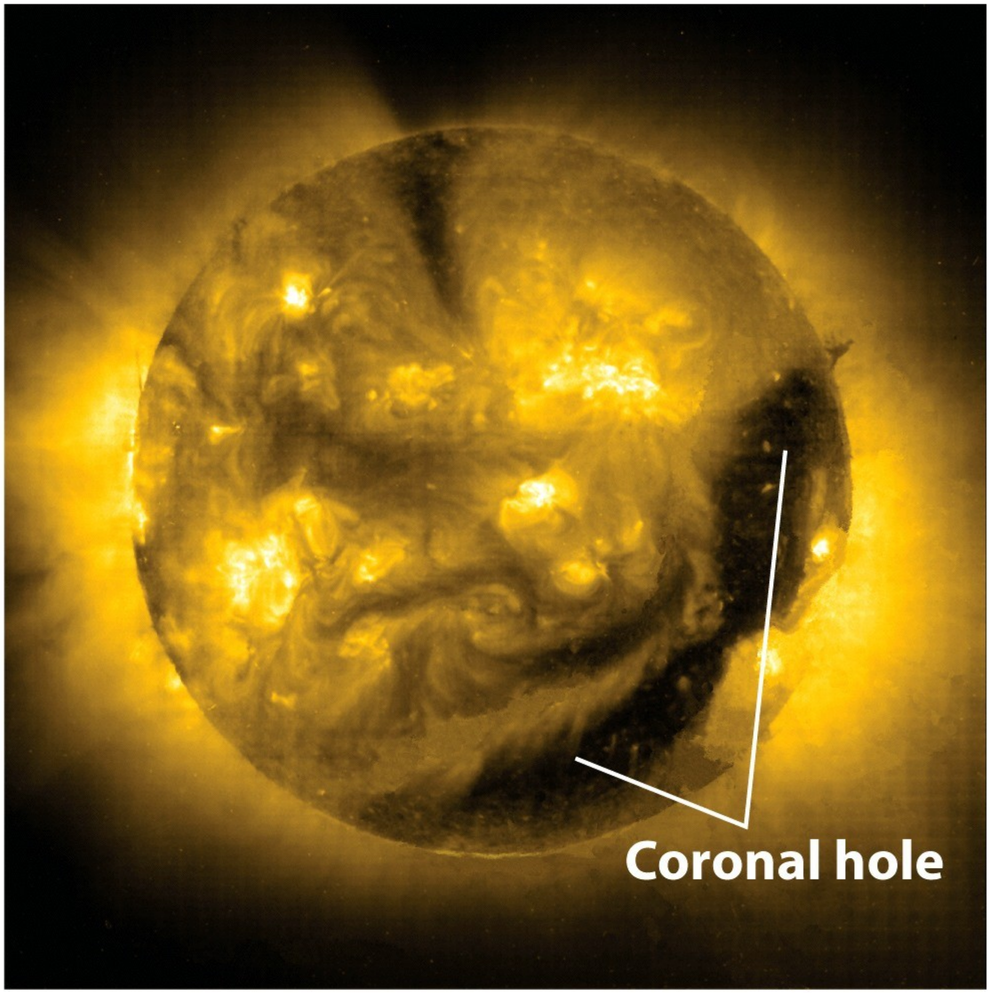


Figure 16-16
Universe, Tenth Edition
SOHO/EIT/ESA/NASA

The dark areas in this image of the corona are thin low temperature regions knowns as corona holes. This corona holes are devoid of luminous gas. They offer an escape corridor for the solar wind. The Ulysses spacecraft flew over the north and south poles of the Sun. There are permanent corona holes over the poles. Ulysses measured an increased solar wind at the poles.

The Temperature of the Corona

The high temperature of the corona and chromosphere are not what we would expected. We expect the temperature to decrease as we move further away from the sun. Some recent evidence suggest that part of the heating of the corona is caused by spicules. These spicules are millions of degrees and shoot gas high speed particles 10,000 km into the corona. However this can not be the whole story concerning the heating of the corona. Sunspots also play a role.

The Sunspots

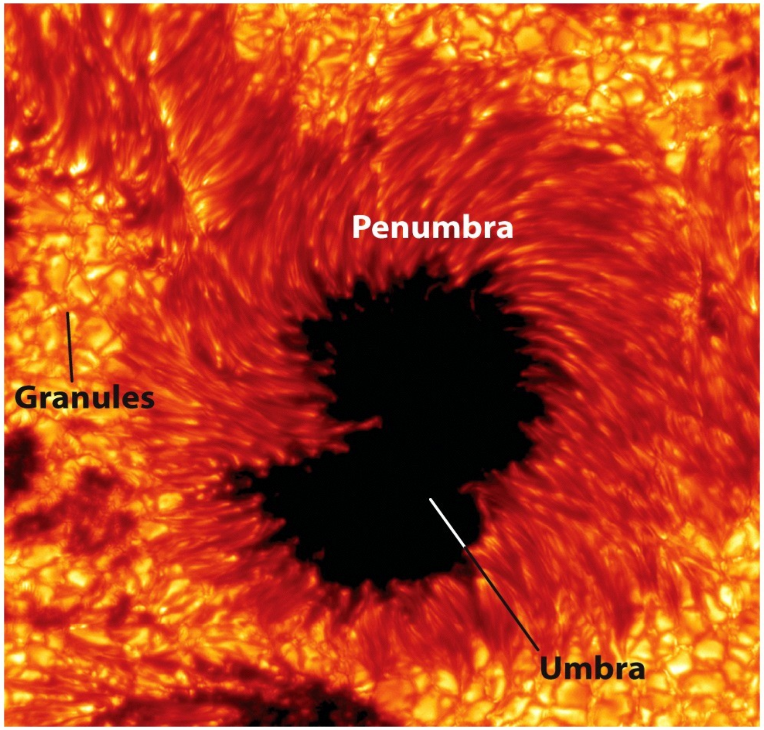


Figure 16-17a
Universe, Tenth Edition
Scharmer et al., Royal Swedish Academy of Sciences/Science Source

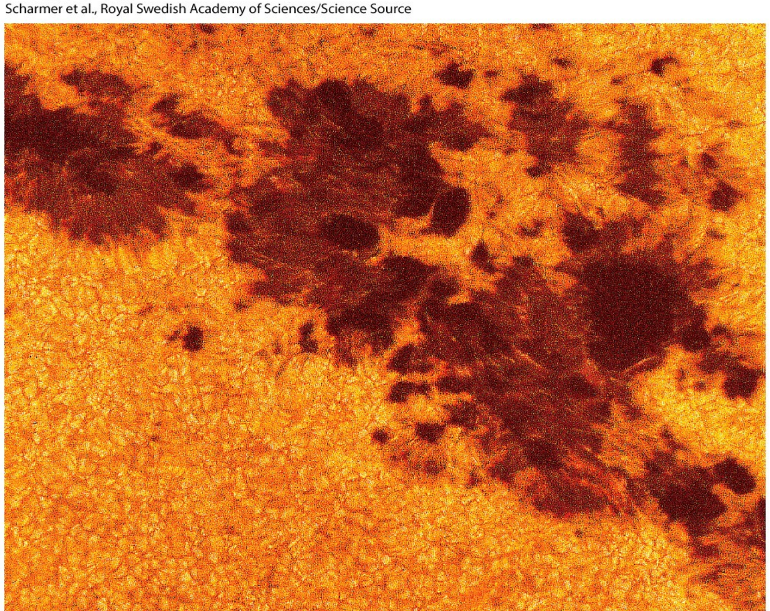


Figure 16-17b
Universe, Tenth Edition

Sunspots are irregularly shaped dark regions on the photosphere. They vary in size but are typically about the size of the Earth. They are an active feature of the Sun. The dark region is called the umbra and the lighter surrounding area is the penumbra. Sunspots are cooler regions of the photosphere with the umbra having a temperature of ~4300K.
The Stefan-Boltzmann law gives a flux of only 30% of the amount of light compared to the surrounding photosphere. The lower image shows a group of sunspots.

The Sunspots

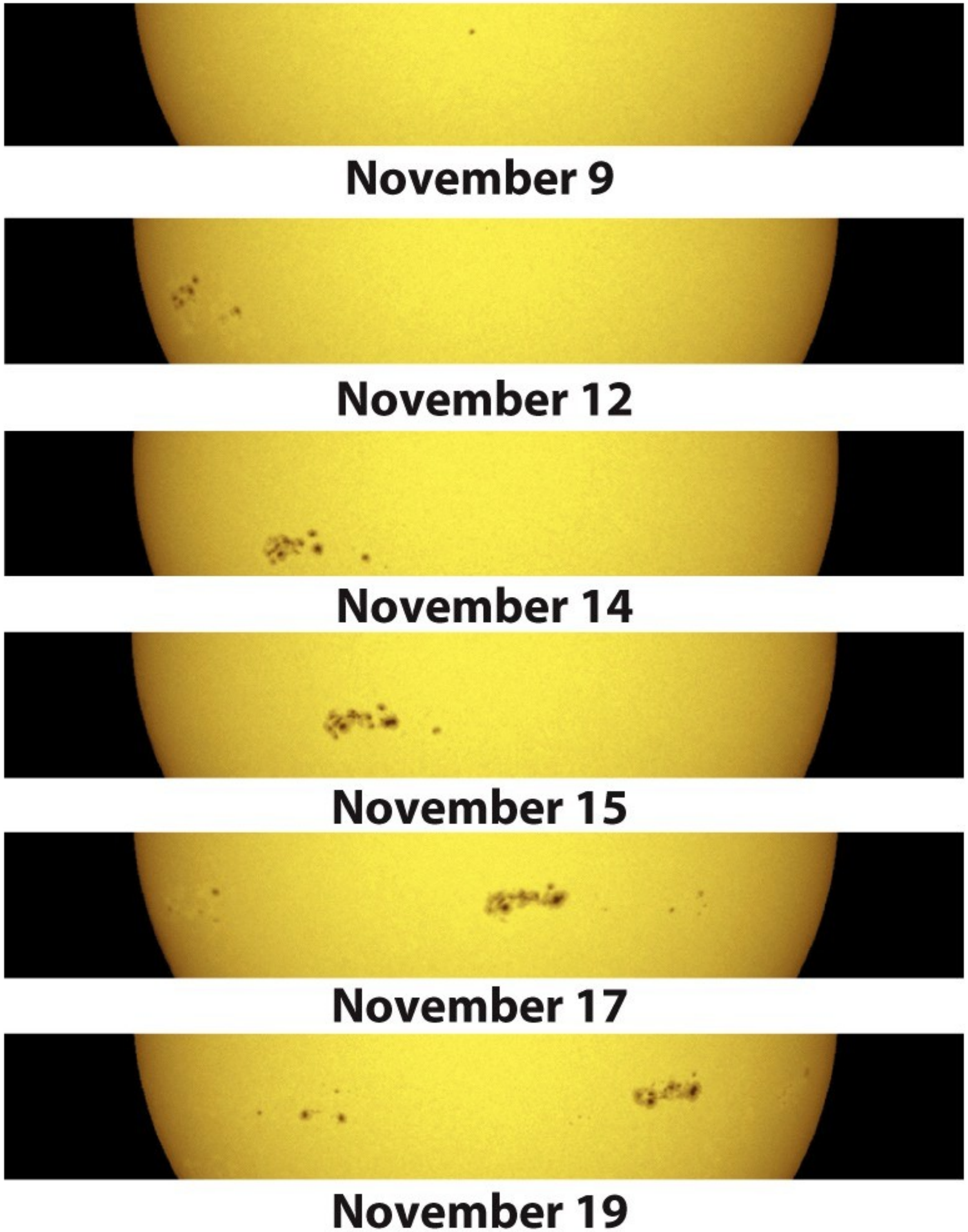
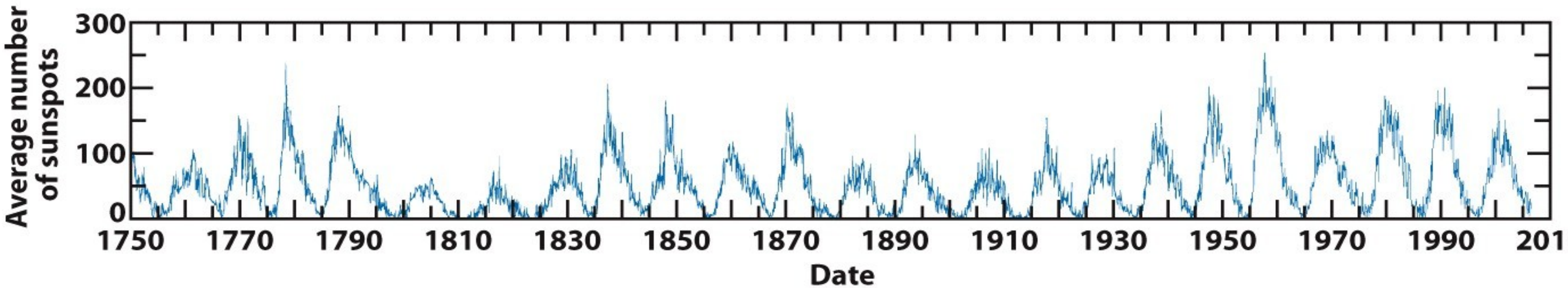


Figure 16-18
Universe, Tenth Edition
The Carnegie Observatories

Galileo used the motion of sunspots to determine the rotation rate of the Sun. Galileo's measurement was about 4 weeks. Later in the 1800, sunspots showed that the Sun does not rotate as a rigid body. The equatorial regions rotate faster than the poles. This is the same differential rotation we saw with the Jovian planets. The equator rotates in about 25 days while the poles rotate about one every 35 days.

The Sunspots



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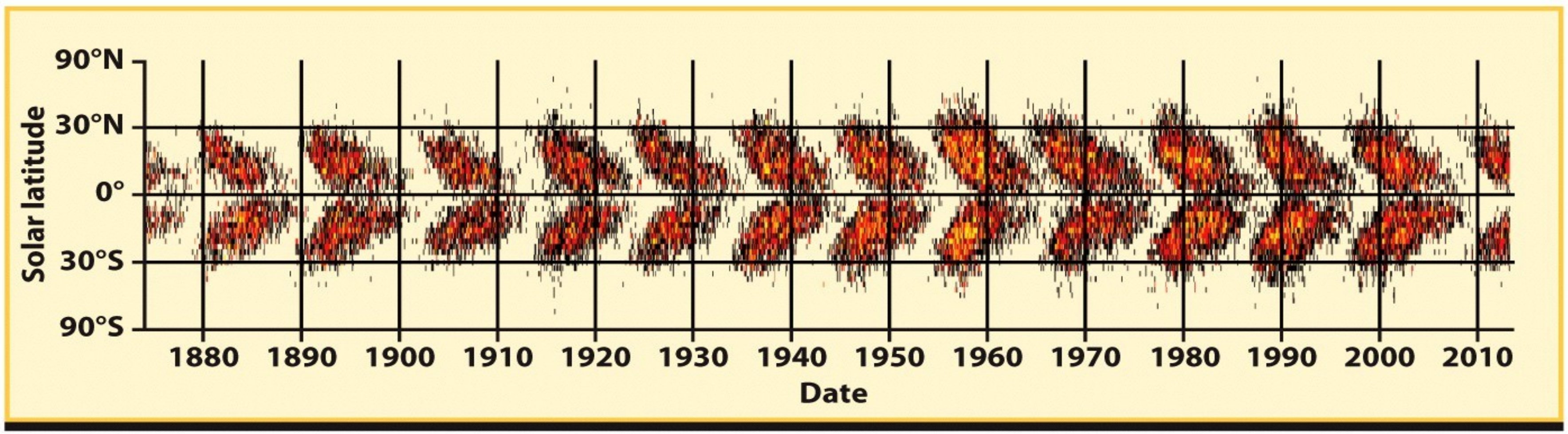
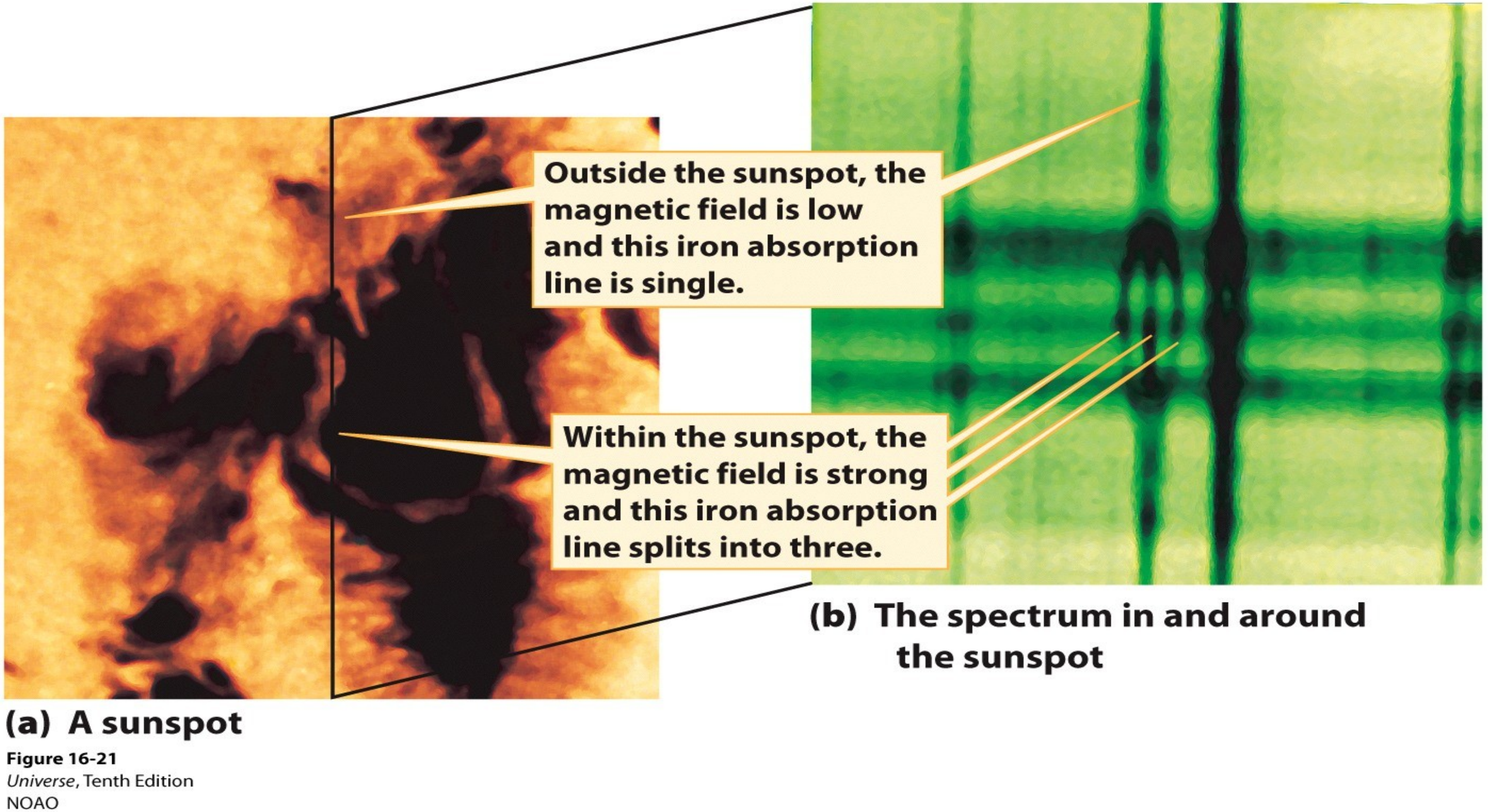


Figure 16-20
Universe, Tenth Edition
NASA Marshall Space Flight Center

Sunspots do not appear at a constant rate but the number varies over time. Sunspots vary with a period of about 11 years. Sunspots also vary in location. At a Sunspot minimum the first appear at about 30^{o} north and south latitude. As the cycle reached a maximum sunspots appear closer to the equator.

The Sun's Magnetic Cycle and Sunspots



Hale in 1908, showed sunspots are associated with large magnetic fields on the Sun. This spectrum of iron shows the absorption line split into three lines (the Zeeman effect) in the strong magnetic field in the region of a sunspot. This indicates a field 5000 times the magnetic field of the Earth.

The Sun's Magnetic Cycle and Sunspots

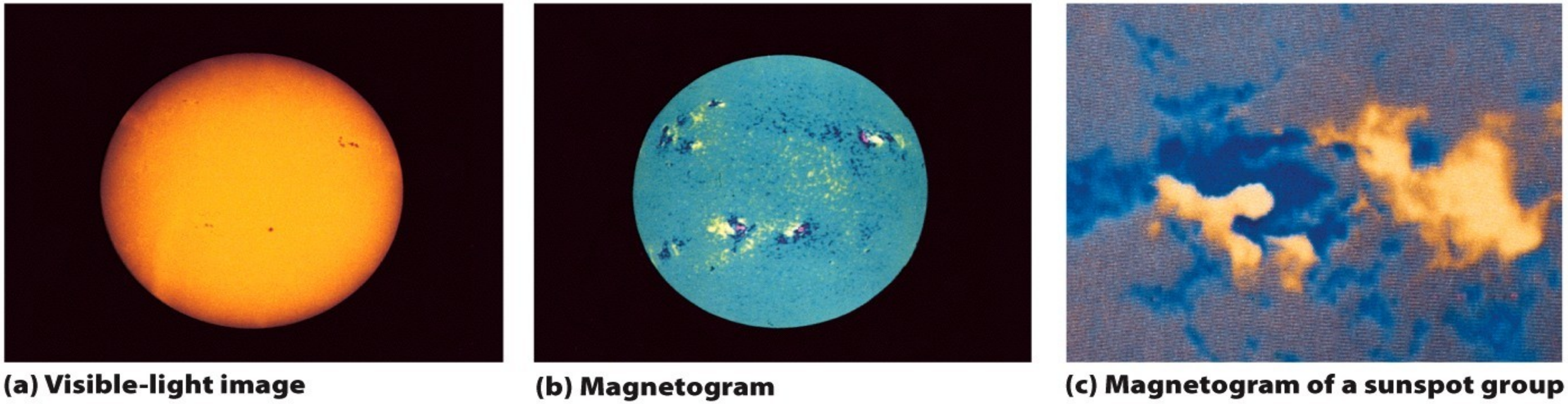


Figure 16-23
Universe, Tenth Edition
NOAO

The gas in the Sun is actually a plasma where the electrons move independently from the ions. A magnetic fields deflect electrical charged particles. On the Sun where the magnetic field is particularly strong, the charged ions of the hot convection plasma are pushed away leaving a cooler region.

By taking images of the Sun at two different wavelengths which are slightly lower and slightly higher than the wavelength of a magnetically split spectral line, an image of the magnetic field can be produced called a magnetogram.

The Sun's Magnetic Cycle and Sunspots

Groups of sunspots look like giant bar magnets with a north and south pole. Hale discovered that there is a regularity in the magnetization of sunspot groups. As the Sun rotates, the first or 'proceeding members' are trailed by 'following members'. Hale compared the northern and southern hemispheres. He found the 'proceeding members' all had the same polarity in one hemisphere and the opposite polarity in the other hemisphere. In the northern hemisphere of the Sun with the north magnetic pole the 'proceeding members' all had a north magnetic polarity and in the southern hemisphere the proceeding members had a south magnetic polarity. Hale and his collaborator discovered the Sun's magnetic field completely reverses every 11 years. The hemisphere that has north proceeding members will reverse every 11 years. The Sun's pattern repeats only during two Sunspot cycles so astronomers call it the 22-year solar cycle.

The Magnetic Dynamo Model

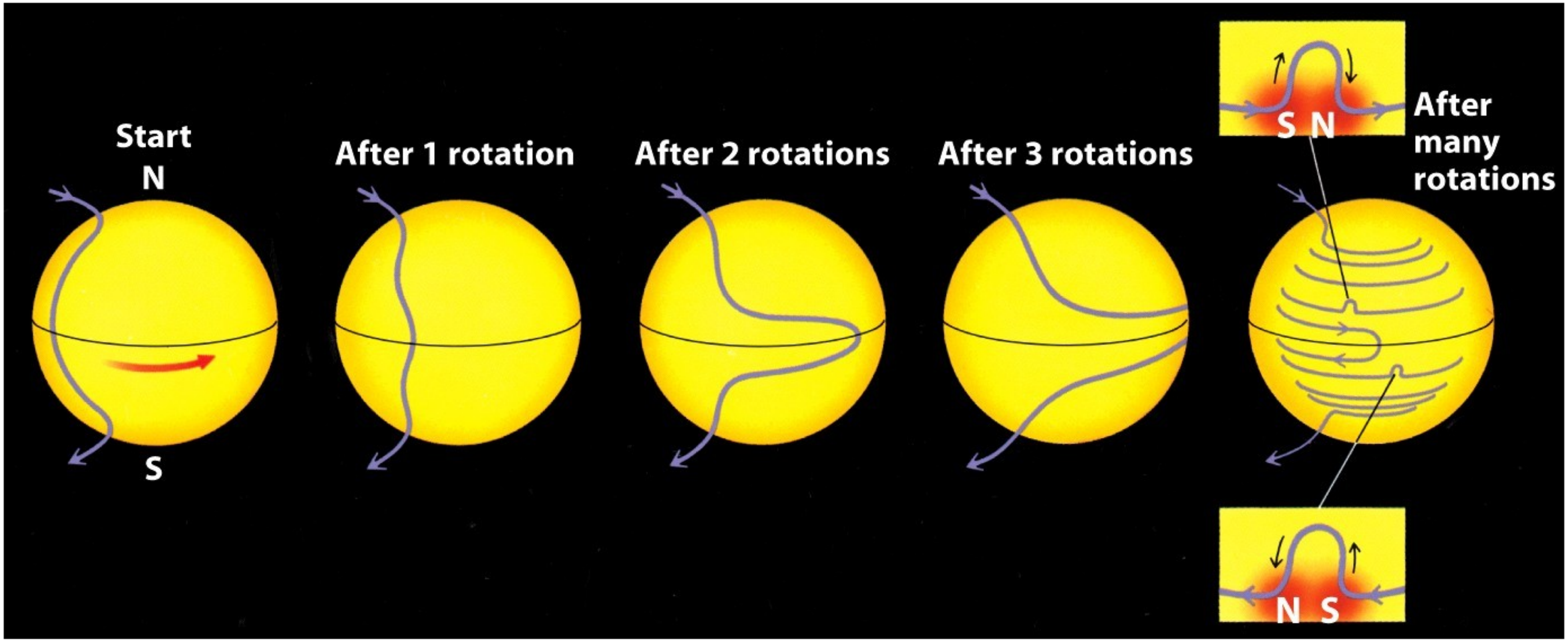
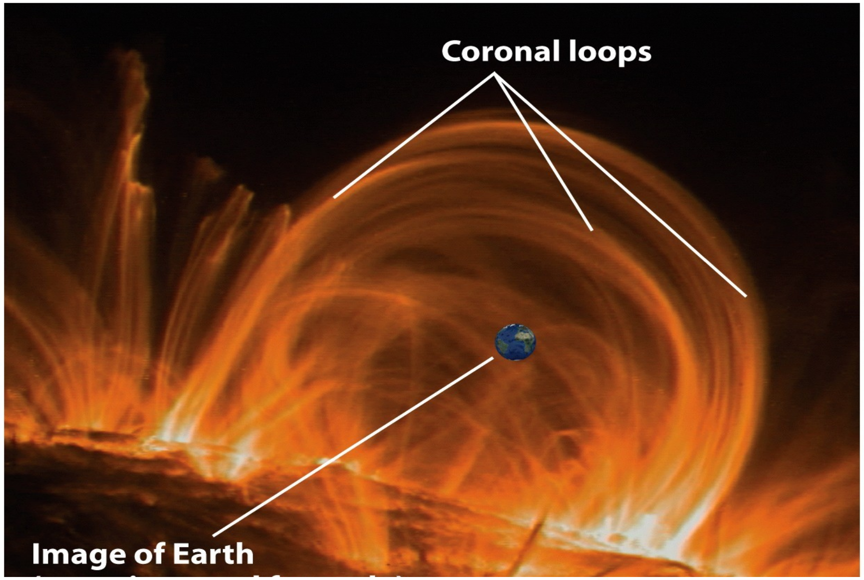


Figure 16-24
Universe, Tenth Edition

The magnetic dynamo model uses two basic properties of the photosphere: differential rotation and convection. Differential rotation cause the magnetic field to wrap around the Sun. The field become concentrated at latitudes around the equator. Convection causes kinks that erupt through the photosphere where sunspots appear.

Magnetic Reconnection



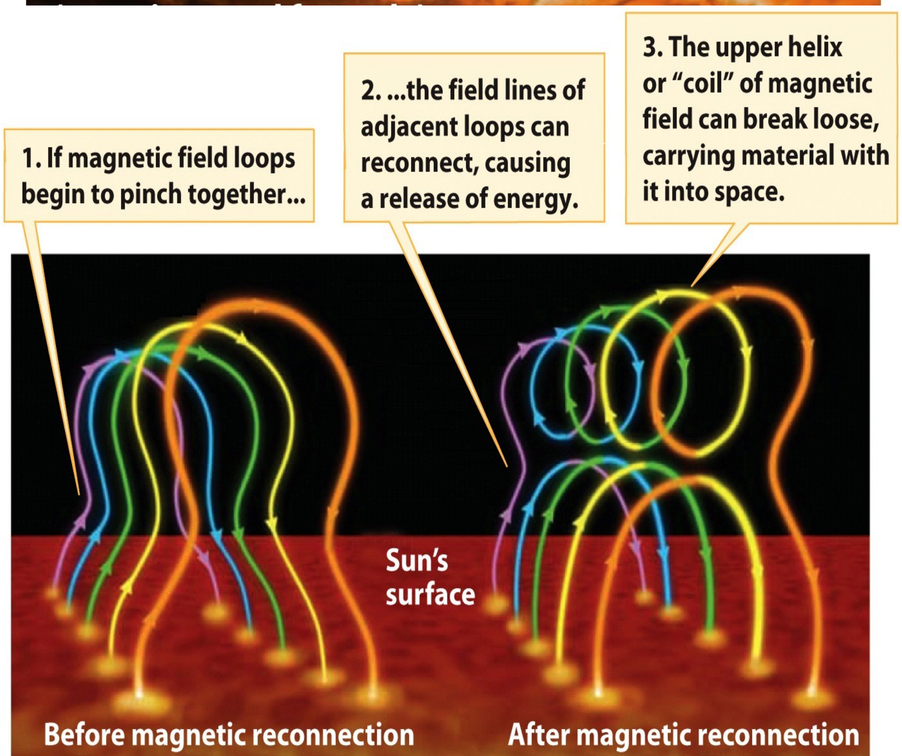


Figure 16-26b
Universe, Tenth Edition

Magnetic field lines and plasma move together. When convection pushes up plasma, it pushes up magnetic field lines as well. This explains why the chromosphere and corona is so hot. Observations show magnetic field arches 10^4 km into the corona. If two arches come close to one another the field lines will re-arrange in a magnetic reconnection. This releases huge amounts of energy which heats the corona and chromosphere.

Prominences, Flares & Coronal Mass Ejections

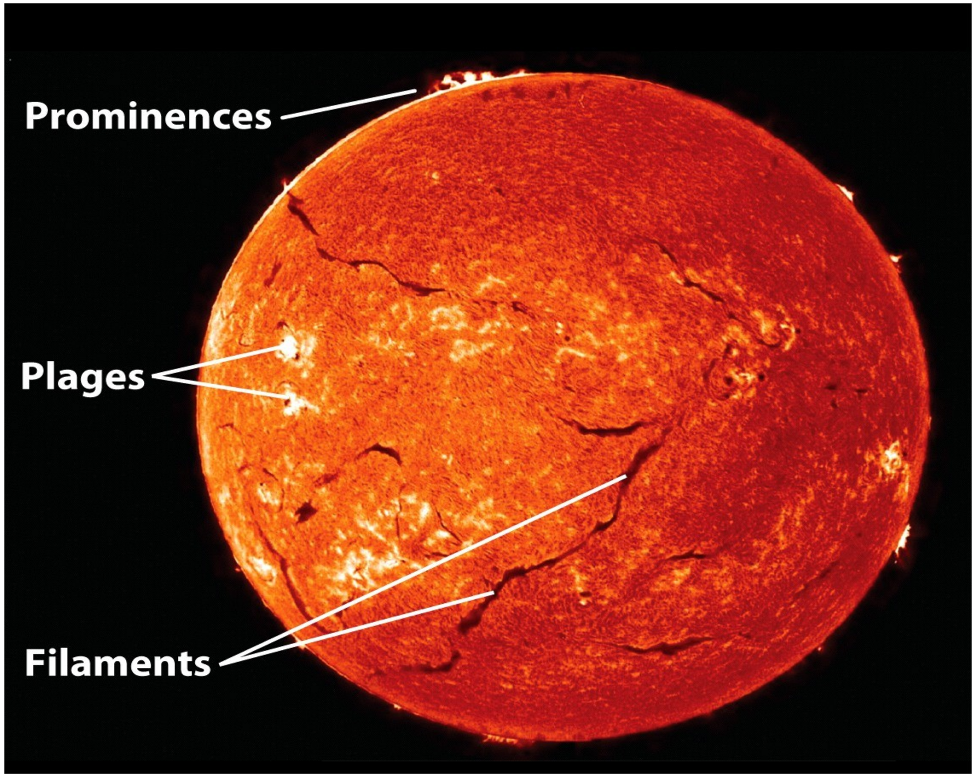
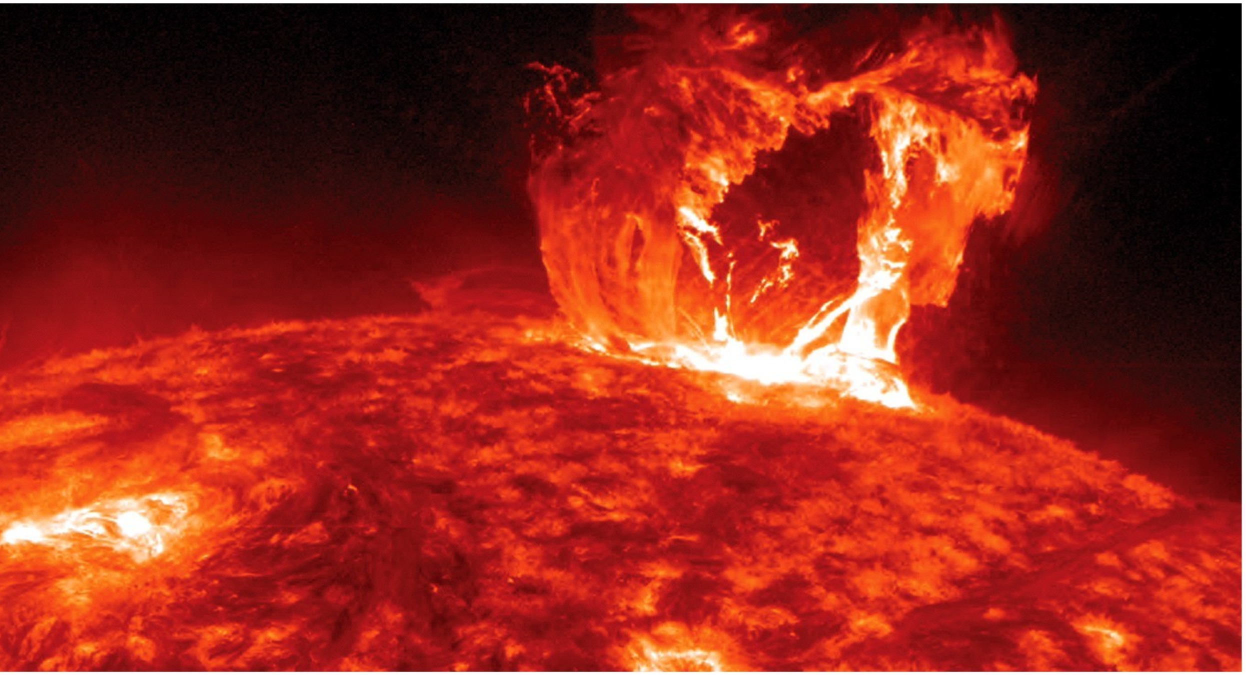


Figure 16-27
Universe, Tenth Edition
NASA

The chromosphere is shown in this image using the H_α line. Plages are bright areas that form before sunspots where magnetic fields push up from the interior. The dark filaments are relatively cool and dense where parts of the chromosphere is pulled along with magnetic field lines as they arch upward. From the side they form prominences. Prominences can extend tens of thousands of km.

Prominences, Flares & Coronal Mass Ejections



gure 16-30
iverse, Tenth Edition
SA

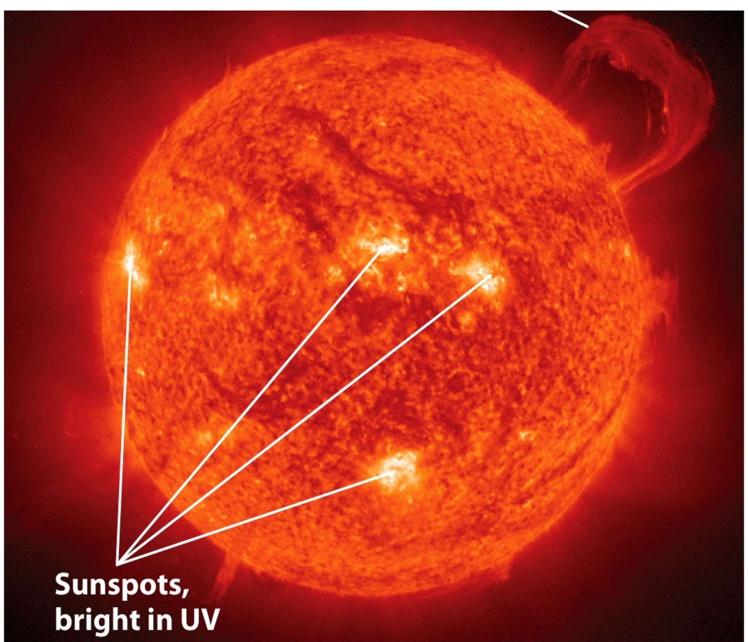
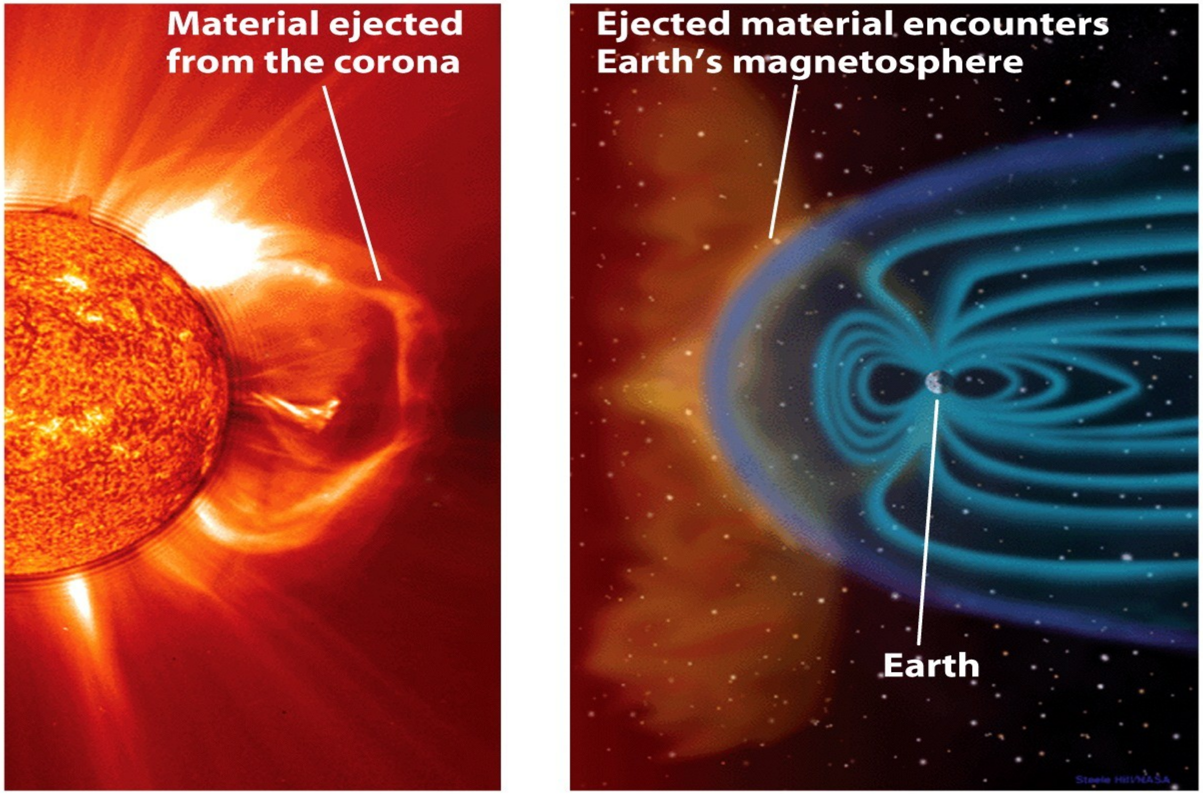


Figure 16-29
Universe, Tenth Edition

Prominences can extend tens of thousands of kilometers into space. Magnetic reconnection also causes violent solar flares. In minutes, the temperature is a small region may reach 5 million K. Vast amounts of radiation and particles are ejected. The most energetic flares can release 10^{30} joules of energy.

Prominences, Flares & Coronal Mass Ejections



(a) A coronal mass ejection (b) Two to four days later

Figure 16-31
Universe, Tenth Edition
SOHO/EIT/LASCO/ESA/NASA

If a solar flare or coronal mass ejection is pointed at Earth, the plasma of electrons and ions can disrupt satellites and electrical equipment and communication equipment on the ground. Solar flares and coronal ejections are monitored to provide early warning.